CONSOLIDATION BEHAVIOUR OF GASSY MUD: 
THEORY AND EXPERIMENTAL VALIDATION
STELLINGEN

behorende bij het proefschrift:

CONSOLIDATION BEHAVIOUR OF GASSY MUD:
THEORY AND EXPERIMENTAL VALIDATION

auteur:

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Stellingen

1. Ten gevolge van de aanwezigheid van biogas in baggerslib treedt er een significante vertraging op van de consolidatie, zodat bij ontwerpberekeningen niet kan worden volstaan met het inschatten van de te verwachten ophoping van gas alleen.

2. De eigengewichtsconsolidatie van slib, bestaande uit gas, water en korrels, kan beschreven worden in termen van twee componenten: gasbellen en verzadigde slibmatrix, waarbij verondersteld wordt dat het gas zich in grote holten bevindt die vast zitten in het korrelskolet.

3. De vertraging van de consolidatie wordt veroorzaakt door het feit dat de drijvende kracht voor consolidatie t.g.v. de aanwezigheid van gas kleiner is, terwijl de drainagepaden langer worden.

4. Er is een natuurlijke begrenzing van het gasgehalte in de gebruikte modellering, t.w. het gasgehalte waarbij het korrelskolet met gas gaat opdrijven.

5. Scheurvorming in de slibmatrix speelt een belangrijke rol bij het ontsnappen van gas, zodat het gasgehalte beperkt blijft tot ca. 20% voor Ketelmeerslib en ca. 10% voor Slufter slib.

6. Het bepalen van geschikte parameterrelaties t.b.v. de consolidatieberekening voor slib is geen eenvoudige zaak, waardoor de kosten van de benodigde laboratoriumproeven een orde hoger uitvallen dan voor grond.

7. Consolidatieberekeningen zijn essentieel voor het inschatten van milieueffecten van diverse depotontwerpen, zowel op land als onder water.

8. In de praktijk is het vaak onduidelijk welk type slib er later geborgen gaat worden, wat het inschatten van de benodigde depotruimte bemoeilijkt. Daarom is een goed monitoringsplan essentieel.
9. Aanbevolen wordt om op locaties die mogelijk zullen worden gebaggerd, niet alleen te kijken naar de verontreinigingsgraad, maar ook de grondmechanische klassificatie-eigenschappen te bepalen, zodat op basis hiervan een schatting kan worden gemaakt van de consolidatie-eigenschappen.

10. Het grootschalig saneren van de Nederlandse bio-industrie is alleen betaalbaar als de boeren de mogelijkheid wordt geboden om te schakelen naar milieu- en diervriendelijker produceren en de consument bereid is minder vlees te eten voor dezelfde kosten.

11. De kosten gemoeid met het ontwikkelen van een zuiniger en milieuvriendelijker auto worden door de fabrikant doorberekend aan de consument. Het gebruik van zo’n auto kan worden bevorderd door bijvoorbeeld de BPM te verlagen of een lager BTW tarief te hanteren.

12. Bij veel grootschalige en complexe werken, zoals bijvoorbeeld een stormvloedkering is het menselijk falen de grootste risico factor. De mens moet zich dus tegen zichzelf leren beschermen.

13. Voor het behalen van een doctorstitel zou een 45-urige werkweek voldoende moeten zijn. Aangezien dit vaak niet het geval is, loopt men het risico zich teveel op details te concentreren en van zijn omgeving te vervreemden.
CONSOLIDATION BEHAVIOUR OF GASSY MUD: THEORY AND EXPERIMENTAL VALIDATION

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"Waar een wil is, is een weg."

Voor mijn ouders.

Voor Herman.
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Contents:

Acknowledgements 7
Table of contents 9

Chapter 1 Introduction
  1.1 background 13
  1.2 previous research 15
  1.3 research aims 18

Chapter 2 Treatment of finite strain theory for gassy mud
  2.1 assumptions 21
  2.2 basic equations 25
  2.3 the finite strain differential equation 29
  2.4 calculation of $e_g$ 30

Appendix 2.1 Derivation of finite strain differential equation 32
Appendix 2.2 A general definition of the storage equation for gassy soil 33
Appendix 2.3 Comparison with compressible fluid theory
  A2.3.1 geometry 35
  A2.3.2 gas pressure 36
  A2.3.3 consolidation parameters 37
  A2.3.4 limitation of bubble sizes 38
  A2.3.5 other assumptions 39

Chapter 3 Numerical implementation 41
  3.1 FDM discretisation
    3.1.1 all cases 42
    3.1.2 case (3): compressible gas only 44
    3.1.3 cases (3) and (4) 45
    3.1.4 boundary conditions for all cases 46
  3.2 stability 47
  3.3 comparison of FDM with FEM method 48

Chapter 4 Experimental verification 51
  4.1 general 51
  4.2 self weight column tests 53
  4.3 oedometer tests 54
  4.4 analysis of experimental results
    4.4.1 distribution of gas void ratio
      4.4.1.1 column tests 57
      4.4.1.2 oedometer tests 57
    4.4.2 operative stress
      4.4.2.1 column tests 58
      4.4.2.2 oedometer tests 58
    4.4.3 permeability
      4.4.3.1 column tests 59
      4.4.3.2 oedometer tests 59
4.5 results from computer simulations
   4.5.1 column tests with biogenic gas production
   4.5.2 column tests with artificial gas production
   4.5.3 saturated reference column NK2
   4.5.4 constant rate of loading oedometer tests
      4.5.4.1 general input for computer simulations
      4.5.4.2 results for test FY-S5
      4.5.4.3 results for test FY-6
      4.5.4.4 results for test FY-3
      4.5.4.5 general interpretation of constant rate of loading tests

4.6 concluding remarks
   acknowledgements

Chapter 5 Effect of biogenic gas on consolidation parameters of sludge
   5.1 general
   5.2 experimental
      5.2.1 GASCON set-up and user possibilities
      5.2.2 experiments
   5.3 results
      5.3.1 consolidation behaviour
      5.3.2 visual inspection of the side walls
      5.3.3 determination of gas content
   5.4 analysis of parameter relations $\sigma_{op}(e_f)$ and $k(e_f)$

5.5 conclusions

5.6 further applications of GASCON-test
   acknowledgement

Chapter 6 sensitivity analysis for a typical disposal site
   6.1 general
   6.2 variation of gas distribution
   6.3 variation of $\sigma_{op}(e_f)$ and $k(e_f)$
   6.4 variation of gas content
   6.5 variation of other input variables
   6.6 conclusions

Chapter 7 Validation of computer calculations
   7.1 general
   7.2 the Slufter disposal site
   7.3 monitoring data
   7.4 computer calculations with FSCongas: derivation of input data
   7.5 computer calculations with FSCongas: results
   7.6 conclusions
   7.7 recommendations
Chapter 8 Conclusions

8.1 validation and verification 139
8.2 parameter determination 140
8.3 sensitivity analysis 140
8.4 comparison with field measurements 141
8.5 future research 142
8.6 final conclusion 143

List of symbols 145
References 147
Summary 153
Samenvatting 155
List of Publications 157
Curriculum vitae 159
Chapter 1 Introduction

1.1 background

In The Netherlands, sediments originating from the rivers Rhine and Meuse are heavily polluted. The sediments are polluted with for example heavy metals, PCB's, PAH's and organic pesticides. In the mid eighties, efforts to reduce the disposal of untreated industrial waste water began to pay off, and the sediments carried by the rivers became less polluted. It then became opportune to consider ways of reducing the effects of the polluted sediments. Removal of the sediments was often considered as the most effective way to reduce the environmental effects. In addition, sediments have to be dredged for nautical reasons. Investigations have been carried out into cleaning up of these sediments. Only a limited amount of mud can be cleaned at reasonable cost, whereas the main part has to be stored in disposal sites. As the space available is limited, these disposal sites have to be deep. For this purpose special disposal sites have been designed, consisting of a deep excavation, surrounded by a protective dyke. The hydraulic conditions during filling are shown in Figure 1.1.

At the Maasvlakte (at the west of Rotterdam), the Slufter disposal site is located, which is used to store contaminated mud from the Rotterdam harbour. The required storage capacity of the depot was set at 150 Mm³ (Deibel et al. 1996). The depot is in use since 1987 and is estimated to be filled until 2010. In the Ketelmeer (near Kampen in the IJsselmeer), the depot IJsselooog is under construction and will be finished in 1999. This depot can contain 20 million cubic meters of dredge spoil. Other large scale depots are to be located in the Hollands Diep and in Zeeland. In total 203 million m³ of heavily polluted mud has to be dealt with.

Environmental impact assessment studies are essential to estimate the environmental impact and to obtain the necessary permits. An important aspect is minimising the release of contaminants to the subsoil.

The mud is deposited at a relatively low density, and consolidates under its own weight, starting from the bottom. In this way, an isolating layer is formed at the bottom. The storage capacity is determined by the way the mud consolidates. If the mud consolidates more, the storage capacity may be considerably larger.
Figure 1.1: Hydraulic conditions in a disposal site

In order to predict the release of contaminated water to the subsoil and the storage capacity of these disposal sites, calculations were made with a saturated finite strain consolidation program, called FSCOnbag (Greeuw & van Ommen 1992). FSCOnbag is a one dimensional model. As the width of the site is much larger than the depth, this model can be used by defining vertical blocks of material (Vonk & Vink 1993). Consolidation parameters were determined by means of the HYDCON-test (Wichman et al. 1993, van Essen & Greeuw 1995).

In the Slufter site significant amounts of gas, up to 18% volume percentage at atmospheric pressure, are present (Deibel et al. 1996). The gas is produced biogenically under anoxic conditions. Field measurements in the Ketelmeer indicated that around 4% of gas at atmospheric pressure was present (Opstal 1995). During dredging this gas escapes and causes problems with pumping the mud. In addition, laboratory tests on Ketelmeer mud showed a large gas accumulation up to 20% at atmospheric pressure (Wichman & Greeuw 1997 and Chapter 5). The gas was observed to be present in large voids that are much larger than the void spaces of the surrounding soil. Several laboratory tests (Sills & Yuan
1993 and Sills 1994a) indicate that the presence of gas retards the consolidation under self weight and reduces the storage capacity of the site.

It was concluded that further research was necessary. A STW proposal was set up as part of a collaboration between Delft University of Technology, Delft Geotechnics, Oxford University and The Dutch Ministry of Transport, Public Works and Water Management, Road- and Hydraulic Engineering Division. This thesis reports on the progress of this project.

1.2 previous research

In the past, extensive research was performed on the mechanical properties of soft gassy sediments (see for example: Thomas 1987, Wheeler 1988b, Gardner & Goringe 1988, Wheeler et al. 1990, Wheeler 1991, Sills et al. 1991, Wheeler et al. 1991 and Duffy et al. 1994). The gassy samples have been prepared by means of a special zeolite technique, in which methane saturated zeolite powder is thoroughly mixed with the mud (Sills et al. 1991). After some hours, the methane in the zeolite pores has been replaced by water and the methane has accumulated in large gas voids in a rather uniform manner throughout the sample volume. The gas voids that are formed are similar to voids that have been observed in natural samples (Sills et al. 1991), apart from the natural gas voids being larger in some cases. The amount of zeolite powder added was typically about 20% by solid volume for both the gassy and the saturated samples. For the saturated samples the zeolite powder was water saturated and for the gassy samples the zeolite powder was saturated with methane in different proportions depending on the required gas content.

It was found that the gas voids are much larger than the void spaces in the surrounding soil (Gardner & Goringe 1988). In addition, the voids were found to be fixed inside the soil skeleton. The mechanical behaviour of the gassy soil could be expressed in terms of the mechanical behaviour of the gas voids and the surrounding saturated soil matrix, which can be considered as a continuum (Wheeler 1988a). The consolidation behaviour has been investigated by means of oedometer testing (Thomas 1987). It was found that the saturated matrix consolidates in a similar manner as a saturated soil and that the operative stress and permeability as functions of matrix void ratio (or simply fluid void ratio) control the consolidation behaviour. The operative stress is defined as vertical total stress minus pore water pressure. The operative stress is different from the effective stress in a saturated soil.
in that it is not the exclusive cause of all the measurable effects of a change in stress, such as compression, distortion and a change in shearing resistance (Sills et al. 1991). The total stress is of importance as well. The fluid void ratio, \( e_f \) is defined as the fluid volume divided by the solids volume, whereas the gas void ratio, \( e_g \) is defined as the gas volume divided by the solids volume. It was concluded from oedometer tests on Comwich mud with a variable gas fraction that the gas pressure is controlled by the vertical total stress (Thomas 1987). It was found that the relative gas pressure, \( u_g \) is more or less linearly dependent on the vertical total stress under continuous loading conditions. Thomas calculated the gas pressure from changes in gas volume by means of Boyle’s Law and Henry’s Law. Boundaries on the gas pressure minus the mean total stress were derived by Wheeler et al. (1990), considering one gas void in an undrained isotropic linear elastic, perfectly plastic medium. In case the gas pressure is equal to the upper limit cavity expansion occurs, whereas cavity contraction occurs when the gas pressure is equal to the lower limit. Experimental evidence for this effect follows from oedometer tests (Thomas 1987). It was found that surface tension effects limit the difference between gas pressure and pore water pressure at lower gas contents. If the gas pressure lies well inside these surface tension and cavity expansion and contraction limits, it should remain almost unaffected by changes to the total stress or pore water pressure, because the deformation of the cavities remains small. The escape of large gas bubbles was investigated by Wheeler (1991). It follows from theoretical considerations as well as from simple tests that the shear strength has to be very small for the bubbles to escape (0.02 kPa for bubbles with a bubble radius of 1 cm). This means that it usually may be assumed that the position of the gas bubbles is fixed inside the soil skeleton. From other research it follows that all elastic moduli are significantly affected by the gas, whereas in the case of a fluid, containing very small isolated gas bubbles, the bulk modulus \( K \) is affected only (Wheeler & Gardner 1989). Wheeler (1988b) and Sham (1989) found that the undrained shear strength can be reduced significantly due to the presence of gas, depending on the specific values of the total stress and the operative stress. Gas bubbles were shown to have a major influence on the acoustic behaviour of fine grained offshore soils (Gardner 1988), confirming the large effect of gas on the elastic properties of the soil. Sills et al. (1991) give a useful summary of this research.
The research that has been performed on the self weight consolidation of gassy soils is limited however. Column tests on Ketelmeer mud with an artificial gas production show that the consolidation is significantly retarded (Sills & Yuan 1993, Sills 1994a). A column test on mud with a natural gas production (Greeuw 1992) shows that the consolidation is heavily affected.

Many researchers recognised that the consolidation behaviour with large deformations under self weight has to be described by means of finite strain consolidation theory (see for example Lee & Sills 1981, Monte & Krizek 1976, Schiffman et al. 1984, Toorman 1996). A one dimensional finite strain theory was developed by Gibson et al. (1967) and Mikasa (1965). It is recognised that especially during the disposal of material use of Lagrangian coordinates is required. In this way, the amount of dry material is directly included in the coordinate system. In case Eulerian coordinates are used, the boundaries follow from the consolidation process and have to be adjusted during the calculation, which is a cumbersome procedure.

Numerical simulations were made by several researchers. Greeuw & van Ommen (1992) developed a computer program that is based on one dimensional finite strain theory for saturated sludge. A partly implicit numerical procedure was used. This program was an improvement of the saturated consolidation program developed by Cargill (1985). Thomas (1987) developed a computer program for the consolidation of gassy soft soil by means of which accurate simulations were obtained of oedometer tests. This program was based on the so called double compressibility model, consisting of the two compressible components: gas voids and saturated soil matrix. It was assumed that the self weight of the soil can be neglected and the deformations are relatively small. The governing equations were written in terms of $e_f$ and $e_g$. Petrusczak & Pande (1992 and 1996) propose a model for large gas inclusions, that are larger than the void spaces of the surrounding soil. They found that the difference between the gas pressure and pore water pressure is dependent on the average bubble size, the porosity of the surrounding matrix and the surface tension of the air-water interface.

Several researchers used a saturated finite strain model to predict the consolidation behaviour in the field (Poindexter 1988, Greeuw 1994). Apart from the effects caused by the gas, the predictions were reasonable.

1.3 research aims

Research data on the self weight consolidation of gassy soils are scarce, despite the fact that significant amounts of gas can be produced and can be expected to have a considerable influence on the consolidation behaviour. Preliminary research indicated that the self weight consolidation is retarded due to the presence of the gas. Further research was considered to be necessary, which should finally lead to a more accurate prediction of the storage capacity of disposal sites with gassy mud. It is recognised that knowledge about the production and escape of gas is also needed for such a prediction. This research focuses on the consolidation behaviour, however. This research has several aims.

The first aim is to investigate the self weight consolidation of gassy soils in order to obtain the quantities that determine consolidation. At low stress levels this can be done by means of advanced column tests. At higher stress levels there is a need for hydraulic consolidation tests and oedometer tests. The existing saturated finite strain theory has to be extended for gassy soft soils. This is treated in Chapter 2: Treatment of finite strain theory for gassy mud.

The second aim is to develop a finite strain consolidation model that includes the effects caused by the presence of gas. The gas voids are much larger than the void spaces in surrounding soil skeleton. The voids seem to be fixed in the soil skeleton. Two mechanisms are responsible for the retardation of the consolidation. The first is the reduction in specific weight of the soil skeleton with gas inclusions, due to the presence of the gas. The second mechanism is the increase of the drainage path length, as compared to a saturated soil. The model has to be verified by choosing different numerical discretisations (see Chapter 3: Numerical implementation.). In addition, advanced laboratory tests have to be simulated by means of this model, in order to validate it (see Chapter 4: Experimental verification). The model has to be as realistic as possible, by including gas accumulation, compression, dissolution and advection. As sedimentation is a relatively fast process compared to consolidation, this is assumed to occur instantaneously.
The third aim is to develop an accurate and practical parameter determination for gassy soils. These parameters can then be used in the finite strain consolidation model. The effect of gas on these parameters has to be investigated. The gas production should be natural. This is treated in Chapter 5: Effect of biogenic gas on consolidation parameters of sludge.

The fourth aim is to investigate the sensitivity of the output of the consolidation model, such as height, fluid void ratio and excess pore pressure, to changes in input data, such as gas content and material properties. These calculations give insight in the interaction between gas content and consolidation. Chapter 6: Sensitivity analysis for a typical disposal site, deals with this.

The fifth research aim is to validate the consolidation model by means of field measurements. The Slufter disposal site is the most suitable, as many field data are available. Conclusions will be drawn about the practical applicability of the consolidation model, using parameters from suitable laboratory tests. This is treated in Chapter 7: Validation of computer calculations.

Other points of interest are:
The biogenic gas accumulation is an input relation to the consolidation model. The escape of gas bubbles is not directly included, but it is possible to limit the gas content, depending on experimental evidence. Diffusion of gas through the mud layer has to be considered as well. During consolidation, diffusion is much smaller than advection, however. Therefore diffusion is not taken into account.

Secondary consolidation, i.e. creep, has to be considered too, as the effect might be significant, due to the long time scales involved. Experimental evidence for creep will be considered in Chapter 4. Time dependent irreversible changes in mud properties, without a change in water content, are called aging. Due to aging the mud becomes stiffer and will consolidate less. In addition, the mud will be less sensitive to changes in gas pressure, due to the gas production. Aging might be of importance as well, as the time scales involved are long. This is not included in this research. Stepkowska et al. (1995) investigated the dependence of effective stress and permeability on microstructure, which turned out to be dependent on the type of test. This might explain the differences in finite strain parameter relations, that were obtained from column tests, oedometer tests, HYDCON-tests and GASCON-tests.
Chapter 2 Treatment of finite strain theory for gassy mud

2.1 assumptions

The theory that is described here is applicable to soft soils with a gas content below a certain critical value (estimated around 20% for Ketelmeer mud and around 10% for Slufter mud). At higher gas contents the gas might escape or the driving force of one-dimensional self weight consolidation, which is proportional to $\gamma_s - \gamma_f (1 + e_g)$, becomes zero. This happens if $e_g \approx 1.5$. The sand content has to be limited as well, estimated below 50%. At higher sand contents gas bubbles may exist in larger pores in the saturated soil skeleton without deformation of the surroundings. In this case the pore fluid is compressible, which gives a different expression for the gas pressure (see appendix 2.3). The following assumptions are made:

It is assumed that the gas accumulates in large gas bubbles or voids that are much larger than the average pore size of the surrounding soil (Gardner & Goringe 1988, Sills et al. 1991). A geometrical representation is given in Fig.2.1a. This assumption has been verified by Gardner & Goringe (1988) for artificial and natural samples. As the gas bubbles are much larger than the pore sizes, the common compressible fluid theory is inadequate (see appendix 2.3).

Wheeler (1991) derived two theoretical expressions, from which it followed that, in case the gas bubbles do escape, the shear strength should be very small (i.e. 0.02 kPa for a bubble radius of 1 cm). Therefore, it is assumed that the large bubbles are fixed inside the soil skeleton, i.e. the bubbles cannot escape.

The number of gas voids is not fixed, as additional bubbles may be formed in a later stage as a result of gas production.
As is shown in Fig. 2.1b, the gassy soil can be idealized as a two component system, consisting of compressible gas bubbles that are completely embedded in a saturated soil matrix. Many soil particles are surrounding the gas voids, and small menisci are bridging the gaps between them.

Fig. 2.1:

schematic representation of soil structure (a) and simplification to large bubble model (b) (Wheeler 1988a)
The difference between the gas pressure and pore water pressure equals $2T/r$, with $T =$ surface tension and $r =$ radius of curvature of menisci. The radius of curvature of these menisci is much smaller than the bubble radius, except in case the gas pressure is only slightly larger than the pore water pressure. As the diffusion among the bubbles is fast as compared to the time scales of loading and pore pressure dissipation, it is assumed that the local gas pressure is the same in all bubbles that are located in a horizontal plane. In the vertical direction the gas pressure is depending on the vertical total stress (see further).

As the vapor pressure of water is small within the expected range of 5 to 15 °C, it is not considered here. The main part (82% to 90%, Martens & Val Klump 1980) of the biogenic gas consists of methane. Therefore, only methane is considered here.

The consolidation behaviour is described in terms of the two components: gas voids and saturated soil matrix with holes in it (see Fig. 2.1b), using mechanical concepts for the saturated soil matrix similar to the purely saturated case (Thomas 1987, Sills et al. 1991).

The basic concept of the mechanical behaviour of the material considered here is as follows: Suppose that in an elementary volume the total stress is increased in a very short time. Because the fluid can not be expelled from the element in such a short time, the fluid void ratio $e_f = V_f/V_s$ is initially constant. $V_f$ and $V_s$ are the volumes of fluid and solid, respectively. The volume of the gas bubbles, however, will be reduced, because the pressure in the surrounding soil (including water) is increased. This means that the degree of saturation $S_r$ increases, which in turn implies that the total void ratio $e$ decreases, as $e_f = S_r e$ is constant. This decrease of the total void ratio represents the volume reduction of the gas bubbles, not the flow of the fluid. On the other hand there will be no volume change in the saturated part of the soil, so that the increment of pore water pressure will be equal to the increment of the total stress in that region, which completely surrounds the gas
bubbles. Thus both the operative stress $\sigma_{op} = \sigma - p$ and the fluid void ratio $e_f$ remain constant, which suggests the application of a constitutive relation of the form $\sigma_{op} = f(e_f)$, because it has been shown that $\frac{\partial \sigma_{op}}{\partial \alpha} = 0$ if $\frac{\partial e_f}{\partial \alpha} = 0$.

Therefore, it is assumed that the operative stress controls the fluid void ratio $e_f$, which is defined in terms of porosity $n$ and degree of saturation $S_r$ as $e_f = S_r n/(1-n)$. In this respect the operative stress acts in a similar way as the effective stress for a saturated soil (Sills et al. 1991). A corresponding gas void ratio $e_g$ is defined as $e_g = (1-S_r)n/(1-n)$.

In addition, it is assumed that the permeability $k$ as a function of $e_f$ controls the speed of consolidation in a similar manner to that of $k(e)$ for a saturated soil. From constant rate of loading oedometer tests it appeared that $\sigma_{op}(e_f)$ and $k(e_f)$ are roughly the same for samples with different gas contents (Thomas 1987, Sills & Yuan 1995, Wichman 1997b). Parameter relations as functions of $e_f$ obtained from GASCON-tests with variable gas content were roughly the same as well (see Chapter 5).

During the disposal of soft mud, the vertical total stress increases, which causes a significant compression of the gas voids, as the strength of the surrounding soil matrix is small. The saturated soil surrounding the gas voids is acting to transmit the total stress change to the gas. This is called cavity contraction. In this case it can be assumed that the gas pressure is equal to its upper limit: the vertical total stress plus atmospheric pressure. A lower limit is the pore water pressure plus atmospheric pressure, which is approximated when the radius of curvature of the menisci is equal to the bubble radius. These limits on the gas pressure follow from theoretical considerations (Wheeler et al. 1990) and laboratory tests, with conditions that are typical for a deep disposal site (Sills et al. 1991 and Sills & Yuan 1995, Wichman 1997b). Only in case the gas production rate is very high or the
sample is unloaded, the gas cavities tend to expand, which means that the gas pressure has to be significantly larger than the vertical total stress plus atmospheric pressure in order to deform the surrounding soil skeleton (Wheeler et al. 1990).

If the self weight consolidation of a gassy sludge is compared with that of a saturated sludge containing the same mass of water and solids, the bulk density is reduced, which gives a smaller driving force for consolidation and a smaller initial excess pore water pressure. In addition, the drainage path lengths are increased. These effects combine to retard the consolidation process and reduce the final amount of consolidation. It is reminded that the gas voids are assumed to be connected to the soil grains.

One dimensional finite strain consolidation theory, as derived by Gibson et al. (1967, 1981) and Mikasa (1965) has to be extended, in order to include these effects. In previous unsaturated models, such as in Thomas (1987), this self weight consolidation was not included.

This new theory is fundamentally different from compressible fluid theory as is explained in appendix 2.3.

2.2 basic equations

As finite strain theory is applied to the case of disposal and self weight consolidation of sludge, the use of material coordinates is required. When using material coordinates, the basic equations are described with reference to the position of the solids. In continuum mechanics the material (Lagrangian) coordinate is normally defined as the initial position of a certain mass of solids with reference to the bottom plane. In case the soil deforms in the vertical direction only, this initial position represents a definite mass of solids with reference to the bottom plane. If it is assumed that the specific weight of solids, $\gamma_s$ is
constant, this solids mass can be identified by the height of the solids with reference to the bottom plane, which is a more convenient definition of the material (Lagrangian) coordinate. The relation between the spatial (Eulerian) coordinate $\xi$ and this material coordinate $z$ is explained in Fig. 2.2, in which the gassy sludge is represented by its solids, pore water and gas fraction. At a later time, the pore water volume has decreased because of consolidation, while the free water has increased by the same amount. The amount of solids remains constant. As the gas voids are assumed to be connected to the soil grain skeleton, consolidation causes compression of the gas voids, as the soil grains are moving towards a lower position inside the water column at which the vertical total stress is higher. In addition, a larger fraction of the gas is dissolved, according to Henry’s Law. Therefore, for a certain material coordinate $z$, i.e. for a fixed height of solids, $\xi(z,t)$ changes in time due to consolidation and a decrease in gas volume.

Fig. 2.2: Illustration of relation of spatial (Eulerian) coordinates with material (Lagrangian) coordinates. Explanation is given in text.
In this sense, $\zeta(z, t)$ is a convective coordinate. It is assumed that the specific weight of fluid $\gamma_f$ is constant. The definition of the material (Lagrangian) coordinate $z$ is given in equations (2.1) and (2.2) with $\gamma_s = \text{constant}$:

$$
\begin{align*}
  z(\zeta, t) &= \frac{\xi}{1 + e_f(\zeta', t) + e_g(\zeta', t))} \\
  \xi(z, t) &= \int_{0}^{z} (1 + e_f(z', t) + e_g(z', t)) dz'
\end{align*}
$$

(2.1) (2.2)

with $\xi$ is the spatial (Eulerian) coordinate. The definitions are written for a unit surface bulk area perpendicular to the $z$ and $\zeta$ directions.

From equations (2.1) and (2.2) a differential form is derived:

$$
\frac{\partial \xi(z, t)}{\partial z} = \left(1 + e_f(z, t) + e_g(z, t)\right)
$$

(2.3)

The vertical total stress $\sigma$ at height $\zeta$ is derived from the weight of the layers on top and a possible surface load. $h_{\text{water}}$ is the height of the free water layer on top and $\zeta_{\text{max}}$ is the height of the sludge layer. Neglecting the weight of the gas this gives:

$$
\sigma = \int_{\zeta}^{\zeta_{\text{max}}} \left(\frac{\gamma_s + e_f(\zeta', t) \cdot \gamma_f}{1 + e_f(\zeta', t) + e_g(\zeta', t)}\right) d\zeta' + \gamma_f h_{\text{water}} - \zeta_{\text{max}} (z_{\text{max}}, t) + \text{load}
$$

(2.4)

Inserting $\partial \xi(z, t) / \partial z$ from (2.3) into (2.4) leads to:

$$
\sigma = \int_{z}^{z_{\text{max}}} \left(\gamma_s + e_f(z', t) \cdot \gamma_f\right) dz' + \gamma_f h_{\text{water}} - \zeta_{\text{max}} (z_{\text{max}}, t) + \text{load}
$$

(2.4a)

with $z_{\text{max}}$ is the total solids height, which is derived from the volume of solids present in
The layer with the surface area under consideration. At this stage it is not yet necessary to assume that the gas voids are large.

The specific discharge of liquid, \( q \), can be derived from the change in height \( \xi(z, t) \) of the solids mass indicated by \( z \) with reference to the bottom plane. Changes in height are caused by outflow of pore water as well as compression and dissolution of the gas. Therefore, changes in gas volume have to be subtracted from changes in total volume in order to get the outflow of pore water at a certain height \( \xi(z, t) \):

\[
q = -\left( \frac{\partial \xi}{\partial t} \right)_{z=\text{const}} + \int_{0}^{z} \frac{\partial}{\partial t} e_{g}(z', t) dz' + q_{\xi=0} \tag{2.5}
\]

The term \( q_{\xi=0} \) has been added to allow for a drained boundary at the bottom.

Substitution of \( \xi \) from equation (2.2) into equation (2.5) gives:

\[
q = -\int_{0}^{z} \frac{\partial}{\partial t} e_{f}(z', t) dz' + q_{\xi=0} \tag{2.5a}
\]

Equation (2.5a) describes the outflow of pore water. For the derivation of equation (2.5) it is not yet necessary to assume that the gas voids are large.

Gibson et al. (1967) use the definition \( q = n(v_{f} - v_{s}) \) for saturated sludge, with \( n \) = porosity and \( v_{f} \) and \( v_{s} \) are the average velocities of the fluid and solid phases, respectively. In appendix 2.2 it is shown that \( q \) can be defined as \( q = S_{r} \cdot n(v_{f} - v_{s}) \) in case the gas bubbles are fixed in the soil skeleton and that this definition is equivalent to equation (2.5a).

As the consolidation of the saturated matrix can be described in a similar way as for a saturated sample, it is proposed to use Darcy's Law:
Chapter 2

\[ q = -\frac{k}{\gamma_f} \frac{1}{1 + e_f(z, t) + e_g(z, t)} \frac{\partial p}{\partial z} - k \]  \hspace{1cm} (2.6)

with \( p \) = pore water pressure and \( k \) = permeability. Equation (2.6) originates from the more familiar equation \( q = -\frac{k}{\gamma_f} \frac{\partial u}{\partial z} \) by substitution of \( \frac{\partial u}{\partial z} = \frac{\partial}{\partial z} \left( p - \gamma_f \left( e_{\text{max}} - e \right) \right) \) and \( \frac{\partial}{\partial z} = \frac{1}{(1 + e_f + e_g)} \frac{\partial}{\partial z} \) with \( u = \) excess pore water pressure. At this stage it has not been specified yet whether \( k \) is depending on \( e_f \), only. This is treated in appendix 2.1.

### 2.3 the finite strain differential equation

Equations (2.1) to (2.6) are used to obtain the following finite strain differential equation for gassy sludge (see appendix 2.1):

\[
\frac{\partial e_f}{\partial t} = -\frac{\partial e_f}{\partial z} \frac{\partial}{\partial e_f} \left[ \frac{k(e_f)}{\gamma_f(1 + e_f + e_g)} \left( \gamma_s - \gamma_f(1 + e_g) + \frac{\partial \sigma_{\text{op}}(e_f)}{\partial z} \right) \right]
\]

\[
+ \frac{\partial e_g}{\partial z} \left( \frac{k(e_f)}{\gamma_f} \right) \left[ \gamma_s + e_f \gamma_f \frac{\partial}{\partial z} \left( \frac{\partial \sigma_{\text{op}}(e_f)}{\partial e_f} \right) \right]
\]  \hspace{1cm} (2.7)

In case \( e_g \) is uniform across the height of the sludge layer: \( \frac{\partial e_g}{\partial z} = 0 \), which gives the finite strain differential equation for uniform \( e_g \):

\[
\frac{\partial e_f}{\partial t} = -\left( \frac{\gamma_s - \gamma_f(1 + e_g)}{\gamma_f} \right) \frac{\partial e_f}{\partial z} \frac{\partial}{\partial e_f} \left[ \frac{k(e_f)}{\gamma_f(1 + e_f + e_g)} \right]
\]

\[
- \frac{\partial}{\partial z} \left[ \frac{k(e_f)}{\gamma_f(1 + e_f + e_g)} \frac{\partial e_f}{\partial z} \frac{d \sigma_{\text{op}}(e_f)}{de_f} \right]
\]  \hspace{1cm} (2.8)

If \( e_g \) is put equal to zero, this equation becomes the same as the finite strain consolidation equation for fully saturated sludge, as derived by Gibson et al. (1967).

Thomas (1987) assumed that \( e_g \) is uniform in his oedometer tests. He used an equation
equivalent to (2.8) without the first term, which is the contribution from the self weight of the soil.

2.4 calculation of \( e_g \)

The finite strain differential equation (2.7) is solved numerically (see Chapter 3) in the following four cases. In case (1) \( e_g \) is a constant, giving a uniform distribution of \( e_g \) across the height. In case (2) \( e_g \) is increasing linearly in time during a given period, \( t^{\text{prod}} \) until a maximum, \( e_g^{\text{max}} \) is obtained. For simplicity, only a linear increase is considered. Without compression or dissolution, this means that the mass of gas accumulating in the mud bed increases linearly in time. In cases 3 and 4 \( e_g \) is calculated from the gas pressure \( p_g \) by using Boyle’s and Henry’s Law. The assumptions are that \( p_g = \sigma + u_{\text{atm}} \) and in case (3) that no dissolution takes place, i.e. Henry’s coefficient \( H \) equals zero, whereas in case (4) dissolution takes place with \( H = 0.041 \), i.e. the value for tap water at 10°C (Yamamoto et al. 1976). The assumption that \( p_g = \sigma + u_{\text{atm}} \) is only valid for large gas voids. The temperature is assumed to be constant, which is normally the case for the main part of the sludge in a deep disposal site.

In cases (3) and (4) the following equation for \( e_g \) is used:

\[
(e_g(z,t) + H \cdot e_f(z,t)) \cdot p_g(z,t) = (e_g(z,t_0) + H \cdot e_f(z,t_0)) \cdot p_g(z,t_0) - \Delta_{\text{gas}}
\]  

(2.9)

with \( \Delta_{\text{gas}} \) is the loss of dissolved methane due to the outflow of pore water:

\[
\Delta_{\text{gas}} = -\frac{RT}{V_s} \int_{t_0}^t \frac{d}{dt'} N(z,t') dt'
\]

(2.10)
with $R$ is the gas constant and $T$ is the absolute temperature. $V_s$ is the volume of solids that is associated with the part of the sludge layer under consideration. The symbol $N$ represents the number of moles of gas at each point and $t_0$ is a reference time at which the conditions are known. In case (3) $\Delta_{\text{gas}} = 0$. It is assumed that the initial mass of gas is the same for each part of the sludge, directly after deposition. From this assumption and equations (2.9) and (2.10) $e_g$ at each point and at each time can be calculated. In case 4 an upper limit for the outflow of methane due to advection was taken, as it is assumed that for each node the dissolved methane flows directly out of the mud layer, without passing the mud thickness between this node and the boundaries. This assumption implies that the in-situ gas pressure at the node determines the mass loss of methane, which might not be the case when the dissolved methane passes other parts of the mud bed, where the gas pressure is different. Most pore water is expelled at the top, where the gas pressure is lowest. Therefore, this assumption implies an upper limit for the outflow of dissolved methane.

In reality, biogenic gas is produced by methanogenic bacteria which decompose organic matter, which is part of the solids mass. As a consequence, the solids mass decreases as a function of time. It follows from experimental observations as well as approximate calculations that the amount of organic matter that is decomposed on a time scale of a few years is very small (Olie 1994). However, the gas volume that is produced is significant.
Appendix 2.1 Derivation of finite strain differential equation.

From equation (2.5a) the following differential form is derived:

\[ \frac{\partial e_f(z,t)}{\partial t} = -\left(\frac{\partial q}{\partial z}\right)_{t=\text{constant}} \]  \hspace{1cm} (2.11)

Equation (2.11) is considered as the storage equation for gassy sludge.

Experimental observations indicate that in most cases it is a reasonable approximation to assume that the operative stress and permeability are functions of fluid void ratio, only, i.e. \( \sigma_{op}(e_f) \) and \( k(e_f) \). It follows from constant rate of loading oedometer tests that \( \sigma_{op}(e_f) \) and \( k(e_f) \) are roughly the same for samples with different gas content (Sills & Yuan 1995, Wichman 1997b). In Chapter 5 GASCON-tests are treated on samples with varying gas content. These tests indicate that the \( \sigma_{op}(e_f) \) and \( k(e_f) \) relations are roughly the same as well. This assumption has proven to be valid only in case the gas voids are large. Time dependent effects such as creep and aging are not implemented.

Pore water pressure \( p \) is written as vertical total stress minus operative stress, i.e. \( \sigma - \sigma_{op} \), according to the definition of operative stress. In equation (2.6) \( \frac{\partial p}{\partial z} \) is written as

\[ \frac{\partial \sigma}{\partial z} - \frac{\partial \sigma_{op}}{\partial z} \], with \( \frac{\partial \sigma}{\partial z} = -(\gamma_s + e_f(z,t)\gamma_f) \) (see equation 2.4a):

\[ q = \frac{k(e_f)}{\gamma_f} \frac{1}{1 + e_f + e_g} \left[ (\gamma_s - \gamma_f(1 + e_g)) + \frac{\partial \sigma_{op}(e_f)}{\partial z} \right] \]  \hspace{1cm} (2.12)

The notation \((z,t)\) for \( e_f \) and \( e_g \) is left out.

Equation (2.12) is substituted in (2.11), leading to:

\[ \frac{\partial e_f}{\partial t} = -\frac{\partial}{\partial z} \left[ \frac{k(e_f)}{\gamma_f(1 + e_f + e_g)} \left( (\gamma_s - \gamma_f(1 + e_g)) + \frac{\partial \sigma_{op}(e_f)}{\partial z} \right) \right] \]  \hspace{1cm} (2.13)

Equation (2.13) is written as:
\[
\frac{\partial \epsilon_f}{\partial t} = \frac{\partial F(e_f, e_g)}{\partial e_f} \cdot \frac{\partial e_f}{\partial t} + \frac{\partial F(e_f, e_g)}{\partial e_g} \cdot \frac{\partial e_g}{\partial t}
\]

with \( F(e_f, e_g) = -q(e_f, e_g) \) (see 2.12). The partial derivatives can be expanded in order to obtain equation (2.7).

Appendix 2.2 A general definition of the storage equation for gassy soil.

The storage equation in formula (2.11) can be derived from a general equation, in which \( \rho_s \) and \( \rho_f \) are not constant. This equation is written in Eulerian coordinates and use is made of the so called substantial derivative \( \frac{D}{Dt} \), which is defined as a partial derivative with respect to time, while the same solids mass is being considered. The storage equation is based on a mass balance for the liquid phase. It is assumed that all gas bubbles are fixed in the soil skeleton. In this case it makes sense to consider the liquid phase separately. No assumption is made yet concerning the size of the gas bubbles. The following general storage equation can be derived, by considering the net mass flux of liquid into the elementary volume \( U \) of moving soil particles (of fixed identity):

\[
- \nabla \cdot \left( \frac{\rho_f V_p S_r (v_f - v_s)}{U} \right) = \frac{1}{U} \frac{D}{Dt} \left( S_r V_p \rho_f \right) \tag{2.14}
\]

with \( V_p \) is the volume of pores within \( U \), including large voids which may be present. It is noted that \( U \) is not fixed in time, as its dimensions change depending on the deformation of the gas bubbles and the outflow of pore water. \( v_f \) and \( v_s \) are the average velocities of the fluid and solid phases, respectively. \( \rho_f \) is affected by the amount of methane in solution. As \( U \) is infinitesimally small, the gas pressure is assumed to be uniform. By means of
Henry's law it follows that $\rho_f$ is uniform within U. Next, it is assumed that the liquid flows in one main direction, i.e. in the vertical direction, which means that the Eulerian coordinate $\xi$ can be used. As the mass of solids $(V_s \rho_s)$ is constant within U and $U = V_s (1 + e)$, the following equation can be obtained from (2.14):

$$-rac{\partial}{\partial \xi} \left( \rho_f n S_f (v_f - v_s) \right) = \frac{V_s \rho_s}{V_s (1 + e)} \frac{D}{Dt} \left( S_r e \frac{\rho_f}{\rho_s} \right)$$  \hspace{1cm} (2.15)

In case $\rho_s = \text{constant}$, equation (2.15) can be written in terms of Lagrangian coordinates by means of equation (2.3):

$$-rac{\partial}{\partial \xi} \left( \rho_f q \right) = \frac{D}{Dt} \left( S_r e \rho_f \right)$$  \hspace{1cm} (2.16)

with the specific discharge of liquid $q = S_r \cdot n (v_f - v_s)$. Since $S_r = \frac{e_f}{e_f + e_g}$ and $e = e_f + e_g$, equation (2.16) reduces to equation (2.11), if $\rho_f$ is constant. This implies that the definition of $q$ used here is equivalent to equation (2.5a).

**Appendix 2.3 Comparison with compressible fluid theory.**

In this section a comparison is made between large bubble theory and small bubble theory, i.e. compressible fluid theory. The size of the gas bubbles is strongly dependent on the properties, such as grain size, of the surrounding soil. During gas production in soft soils with a limited sand content (estimated below 50%), the gas was observed to accumulate in voids that are much larger than the surrounding void spaces, but that have a limited size. In GASCON-tests on mud from the Ketelmeer and Slufter disposal site, the bubbles were very small at the beginning, gradually the bubbles became larger, and more bubbles became
visible as gas production continued (see Chapter 5). The bubble size was smaller than 2
mm. In addition, it was observed that in case the gas content is high, a significant amount
of gas flushes out of the sample through the bottom drain (Wichman 1997a and Greeuw &
van Essen 1998). It is likely that apart from methane in solution, also small gas bubbles
move with the pore liquid out of the drain.

In case the gas bubbles are stationary, i.e. fixed to the soil skeleton, the assumptions that
are normally made in compressible fluid theory can be compared with the assumptions
made in the finite strain theory for gassy soft soil that has been treated here. In appendix
2.2 it is shown that, in case the gas bubbles are stationary, the same storage equation in
terms of the liquid phase can be used in both theories.

A2.3.1 geometry

In compressible fluid theory at higher saturation levels \((S_r \geq 0.85)\), it is assumed that the
gas bubbles are discrete, which is also the case for the large bubble theory. If the diffusion
in the pore water between the gas bubbles is fast compared to the loading speed, it is
assumed that the gas bubbles in compressible fluid theory have equal size and are spherical
(see section A2.3.2). The bubbles are supposed to be smaller than or equal to the smallest
size of the pores that contain them. The soil skeleton around the bubbles is not disturbed,
i.e. similar to a saturated soil. In large bubble theory, the gas is present in large voids only,
with sizes that are much larger than the average pore size of the surrounding soil. In this
case, the soil skeleton around the voids deforms, depending on its strength. The gas voids
are not equal in size and might be non spherical. Small menisci bridge the gaps between the
surrounding soil particles. Normally, the radius of curvature of these menisci is not equal to the bubble radius. The minimum bubble radius equals the radius of curvature of the menisci (Wheeler et al. 1990).

### A2.3.2 gas pressure

In case of equilibrium, the difference between the gas pressure and the absolute pore water pressure is equal to $2T/r$, with $T$ = surface tension and $r$ = radius of curvature of the contact face(s) between the water and gas phase. In case the vertical total stress and pore pressure vary gradually, the gas pressure is approximately equal in all gas bubbles, as diffusion in the surrounding pore water is fast enough to equalize differences in gas pressure. This is the case for both theories.

In compressible fluid theory, the gas bubbles are completely surrounded by water. Therefore, the radius of curvature of the gas/water interface equals the bubble size. As it can be assumed that the gas pressure is equal in all bubbles, the bubbles have the same size.

In large bubble theory, the bubbles are not necessarily equal in size, as the difference between the gas pressure (approximately equal to the vertical total stress, $\sigma$ plus atmospheric pressure) and the absolute pore water pressure determines the curvature of the small menisci bridging the pores around the large void, only. This implies that within certain limits the pore water pressure can vary independently from the gas pressure, without changes in bubble size. In case the mud is very soft, the radius of curvature of the gas/water menisci is approximately equal to the bubble size, as the difference between the vertical total stress and pore water pressure is small, i.e. around 0.1 kPa. In this case, it is
possible to calculate the size of the gas bubbles, when the surface tension $T$ is known. In case $\sigma - p = \frac{2T}{r} = 0.1$ kPa and $T = 74 \cdot 10^{-3}$ N / m (for an air/water interface, Schuurman 1966), the bubble radius $r = 1.48$ mm. In section 2.3.4 an upper limit to the bubble size around 2 mm is mentioned, which is of the same order of magnitude.

A2.3.3 consolidation parameters

In compressible fluid theory (at high saturation levels) it is assumed that the effective stress in its normal sense can be used. In large bubble theory, the quantity “operative stress” has been defined as $\sigma_{op} = \sigma - p$ (Sills et al. 1991). This definition differs from Terzaghi’s definition, in that $\sigma_{op}$ is not the exclusive cause of all the measurable effects of a change in stress, such as compression, distortion and a change in shearing resistance (Terzaghi 1936).

In compressible fluid theory, it might be necessary to correct the permeability in case a certain fraction of the gas bubbles is stationary. Barends (1980) suggested a correction factor $(1 - b)^3$ in terms of pore fraction of stationary bubbles $b$. In large bubble theory, the flow paths close to the voids are more curved than the flow paths between the bubbles. Thomas (1987) calculated the reduction in permeability in case the bubbles are large, assuming vertical flow around voids that are not permeable. For a volume fraction of spherical bubbles of 5% the reduction in permeability is 7%. In case the width of the voids is 5 times larger than the height, the calculated reduction is 17%, for the same gas content.

In Chapters 4 and 5 attention is given to the variation of $k(e_f)$ as a function of gas content.
A2.3.4 limitation of bubble sizes

Next, a discussion on the maximum size of the gas voids is included in this section. In small bubble theory, the size of the gas bubbles is limited by the smallest size of the pores that contain gas. In large bubble theory, the size of the gas voids is variable. It was observed in GASCON-experiments on samples of mud from the Ketelmeer and the Slufter disposal site with a natural gas production that the gas bubbles were smaller than approximately 2 mm (see Chapter 5 and Greeuw & van Essen 1998). This was also the case at gas contents as high as 19%. One might expect that there should have been fewer but larger gas bubbles. From observations of samples taken from the Slufter site it follows that the bubble sizes range from 2 cm to 5 cm, however. At the start of gas production, the gas voids were small and gradually additional gas voids became visible, as they were growing. While the gas production continued, still more bubbles were formed, whereas the final size was limited. In addition, it followed that the bubbles in parts of the mud bed with a lower water content were smaller than those in parts with a higher water content (Wichman 1997a and Chapter 5).

A possible explanation for the limitation on the size of the large bubbles might be as follows:

At the start of biogenic gas production, small gas voids are formed, that are expanding as gas accumulates. As the voids are fixed in the soil skeleton, the surrounding soil is deforming and the distances between the soil particles tend to become larger. At a certain stage, it is likely that attractive forces between the soil particles hinder further expansion of the cavity. As gas is still being produced, the gas pressure in the voids is increasing as
compared to the pore water pressure. This causes an increase of the curvature of the small menisci that are bridging the gaps between the surrounding soil particles. This allows for smaller gas bubbles to be produced on locations where this was not possible before, i.e. in smaller pores, as the minimum bubble size is equal to the radius of curvature. Next, new voids start to grow, for example at the edges of a large void, and still more undissolved gas is accumulating. In case small fissures are present, gas bubbles might be formed at these locations. From observations of the side wall of the GASCON-cell (see Chapter 5) it follows that this mechanism is likely to occur.

A2.3.5 other assumptions

In both theories, it is normally assumed that the local diffusion time scales are much smaller than the time scale of loading. This is also the case when biogenic gas production occurs, which is a relatively slow process as well. Therefore, equilibrium can be assumed. Henry’s Law can be used in both theories under equilibrium conditions, in order to calculate the volume fraction of gas that dissolves. In both theories, the vapor pressure of water is neglected, as it is small.
Chapter 3 Numerical implementation.

In Chapter 2 the derivation of a storage equation for gassy sludge is explained, which is expressed in terms of the specific discharge \( q \) of the fluid phase:

\[
\frac{\partial e_f(z, t)}{\partial t} = - \left( \frac{\partial q}{\partial z} \right)_{t=\text{constant}}
\]  

(2.11)

Darcy's Law, constitutive equations for the saturated matrix and Terzaghi's principle were used to obtain equation (2.12):

\[
q = \frac{k(e_f)}{\gamma_f} \frac{1}{1 + e_f + e_g} \left[ \left( \gamma_s - \gamma_f(1 + e_g) \right) + \frac{\partial \sigma_{op}(e_f)}{\partial z} \right]
\]  

(2.12)

In Chapter 2 it is shown that (2.11) and (2.12) can be combined to obtain the following finite strain differential equation for gassy sludge:

\[
\frac{\partial e_f}{\partial t} = - \frac{\partial e_f}{\partial z} \frac{\partial}{\partial e_f} \left[ \frac{k(e_f)}{\gamma_f(1 + e_f + e_g)} \left( \left( \gamma_s - \gamma_f(1 + e_g) \right) + \frac{\partial \sigma_{op}(e_f)}{\partial z} \right) \right]
\]

\[
+ \frac{\partial e_g}{\partial z} \frac{k(e_f)}{\gamma_f(1 + e_f + e_g)^2} \left[ \left( \gamma_s + e_f \gamma_f \right) + \frac{\partial \sigma_{op}(e_f)}{\partial z} \right]
\]  

(2.7)

In this chapter a partly implicit finite difference method (FDM) is explained by means of which equation (2.7) can be solved, using various assumptions on the behavior of \( e_g \).

An existing finite strain computer program FSConbag (Greeuw & van Ommen 1992) has been modified, using a number of different discretisations. Next, the stability of this solution method is discussed. The cases that are treated below are described in Chapter 2.4.

In addition, equations (2.11) and (2.12) have been used for a finite element method (FEM), which is substantially different from the finite difference method (de Vries 1995). This is treated in section 3.3.
3.1 FDM discretisation

3.1.1 all cases.

Equation (2.7) is discretised, using the finite difference scheme from FSConbag (Greeuw & van Ommen 1992): superscript j indicates the time step number and subscript n indicates the node number.

\[
\frac{e^{j+1}_{f,n} - e^{j}_{f,n}}{\tau} = \frac{1}{\gamma_f} \left( \frac{(\alpha(e^{j}_{f,n+1}) - \alpha(e^{j}_{f,n-1}))}{2\Delta z} \right) \left( \frac{(e^{j+1}_{f,n+1} - e^{j+1}_{f,n-1})}{2\Delta z} \right) \\
- \frac{1}{\gamma_f} \left( \frac{\alpha(e^{j}_{f,n+1})}{2\Delta z} - \frac{\alpha(e^{j}_{f,n-1})}{2\Delta z} \right) + \frac{1}{\gamma_f} \left( \frac{\alpha(e^{j}_{f,n+1})}{(\Delta z)^2} - \frac{2e^{j+1}_{f,n} + e^{j+1}_{f,n-1}}{(\Delta z)^2} \right) + \text{RHSGAS} (3.1)
\]

with:

\[
\beta(e_f) = \frac{\partial}{\partial e_f} \left( \frac{k(e_f)}{1 + e_f + e_g} \right); \alpha(e_f) = \frac{k(e_f)}{(1 + e_f + e_g)} \frac{d\sigma_{op}(e_f)}{de_f};
\]

\[
\frac{\partial e_f}{\partial z} = \frac{e_{f,n+1} - e_{f,n-1}}{2\Delta z}; \frac{\partial^2 e_f}{\partial z^2} = \frac{e_{f,n+1} - 2e_{f,n} + e_{f,n-1}}{(\Delta z)^2};
\]

Equation (3.1) is written in a matrix form as follows:

\[(1 - \tau M) e^{j+1} = e^j + \tau \cdot r\]

with \( \tau \) is the magnitude of the time step and \( r \) is the inhomogeneous right hand side term, arising from the discretisation of RHSGAS, i.e. the second term in equation (2.7), and the boundary conditions.

The RHSGAS term has been discretised partly implicitly as well as explicitly in order to investigate the stability of the solution.
The simplest discretisation is the explicit one, for which a difference of 2 node distances, i.e. $2\Delta z$ is taken:

$$\text{RHSGAS} = \frac{1}{\gamma_f} \frac{1}{2\Delta z} \frac{k(e_f, n)}{(1 + e_f, n)^2} \left[ (\gamma_s + e_f, n) \gamma_f \sigma_{op}(e_f, n+1) - \sigma_{op}(e_f, n-1) \right]$$

(3.2)

As all $e_f$ values are calculated at time step $j$, this expression is totally included in the inhomogeneous right hand side term, i.e. explicit.

By writing $\frac{\partial \sigma_{op}(e_f)}{\partial z} = \frac{d \sigma_{op}(e_f)}{d e_f} \cdot \frac{\partial e_f}{\partial z}$ in RHSGAS it is possible to include parts in the matrix $M$. This is a partly implicit discretisation of RHSGAS (see equation (3.3)).

$$\text{RHSGAS} = \frac{1}{\gamma_f} \frac{1}{2\Delta z} \frac{k(e_f, n)}{(1 + e_f, n + e_g, n)^2} \left[ \gamma_s + \gamma_f e_f, n \right]$$

$$+ \frac{\alpha(e_f)}{\gamma_f(1 + e_f, n + e_g, n)} \frac{\sigma_{op}(e_f)}{2\Delta z} \frac{(e_g, n+1 - e_g, n-1)(e_f, n+1 - e_f, n-1)}{\partial z}$$

(3.3)

with $\alpha(e_f) = \frac{k(e_f)}{1 + e_f + e_g} \cdot \frac{d \sigma_{op}(e_f)}{d e_f} \cdot$.

Equations (3.2) and (3.3) can be used in all 4 cases. In case (1), i.e. $e_g$ = constant, the $e_g, n$ values are constant and RHSGAS=0. In case (2), i.e. for $e_g$ increasing linearly in time during a given period, the $e_g, n$ values are calculated from

$$e_g, n = e_g^{\text{max}} + e_g^{\text{max}} \cdot \left(j \cdot \tau - t_{ini} - t_{prod}\right) / t_{prod}$$

with $t_{prod}$ is the period in which the gas production takes place after deposition of the respective nodes at times $t_{ini}$. $e_g^{\text{max}}$ is the maximum gas void ratio at time $t_{prod}$, $\tau$ is the magnitude of the time step. From this
follows that during deposition the nodes have different $e_{g,n}^j$ values and therefore RHSGAS is non zero.

### 3.1.2 case (3): compressible gas, only.

In case (3), i.e. for a compressible gas with gas pressure $p_g = \sigma + u_{atm}$ and no dissolution, two other discretisations have been investigated, in which the derivative of $e_g$ has been calculated analytically using Boyle's Law. It is assumed that the water level equals the mud level. $\sigma$ can be calculated from equation (2.4a), taking $\varepsilon_{max} = h_{water}$, $H=0$ and load=0. One might expect that an analytic calculation of $e_g$ improves the stability.

Equation (3.4) contains the resulting expression for $e_g$:

$$e_g = \frac{e_{g,atm}^0 \cdot u_{atm}}{u_{atm} + \int_{z}^{z_{max}} (\gamma_s + e_f(z',t)\gamma_f)dz'}$$

Equation (3.4) contains the resulting expression for $e_g$.

$\varepsilon_{g,atm}^0$ is the gas void ratio at atmospheric pressure $u_{atm}$, with $u_{atm} = 100$ kPa. For each node the mass of gas is assumed to be the same, i.e. $e_{g,atm}^0$ is constant.

From (3.4) $\frac{\partial e_g}{\partial z}$ is calculated and substituted in RHSGAS:

$$\text{RHSGAS} = \frac{e_g^2}{e_{g,atm}^0 u_{atm}} \frac{(\gamma_s + e_f \cdot \gamma_f)}{(1 + e_f + e_g)^2} \cdot \frac{k(e_f)}{\gamma_f} \left[ (\gamma_s + e_f \gamma_f) + \frac{\partial \sigma_{op}(e_f)}{\partial z} \right]$$

Equation (3.5) has been discretised both explicitly and partly implicitly, analogous to equations (3.2) and (3.3). $\frac{\partial e_g}{\partial z}$ is taken at time step $j$. This gives:
Chapter 3

\[
\text{RHS GAS} = \frac{(e_{g,n}^j)^2}{e_{g}^{\text{atm}} u_{\text{atm}}} \frac{(\gamma_s + e_{f,n}^j \gamma_f)}{(1 + e_{f,n}^j + e_{g,n}^j)^2} \frac{k(e_{f,n}^j)}{\gamma_f} \cdot \left[ \frac{(\gamma_s + e_{f,n}^j \gamma_f)}{2 \Delta z} \right]^{(3.6)}
\]

which is the explicit method.

The partly implicit method gives:

\[
\text{RHS GAS} = \frac{(e_{g,n}^j)^2}{e_{g}^{\text{atm}} u_{\text{atm}}} \frac{(\gamma_s + e_{f,n}^j \gamma_f)}{(1 + e_{f,n}^j + e_{g,n}^j)^2} \frac{k(e_{f,n}^j)}{\gamma_f} \left[ \frac{(\gamma_s + e_{f,n}^j \gamma_f)}{2 \Delta z} \right]^{(3.7)} + \frac{(1 - \alpha(e_{f,n}^j))}{\gamma_f} \frac{(e_{f,n}^{j+1} - e_{f,n}^{j+1})}{(1 + e_{f,n}^j + e_{g,n}^j)}
\]

3.1.3 cases (3) and (4)

In cases (3) and (4), i.e. for a compressible gas with a variable solubility, equation (2.9) is evaluated numerically (see equation (3.8)). It is assumed that the gas pressure

\[p_g = \sigma + u_{\text{atm}}, \text{ with } u_{\text{atm}} = 100 \text{ kPa}.\]

\[
\left( e_{g,n}^j + H \cdot e_{f,n}^j \right) p_{g,n}^j = \left( e_{g,n}^{j-1} + H \cdot e_{f,n}^{j-1} \right) p_{g,n}^{j-1} - H \cdot \left( e_{f,n}^{j-1} - e_{f,n}^{j} \right) \frac{(p_{g,n}^{j-1} + p_{g,n}^{j})}{2}^{(3.8)}
\]

with \(j = \text{time step number}, n = \text{node number} \) and \(H = \text{Henry's coefficient} \).

The second term on the right hand side in equation (3.8) is \(-\Delta_{\text{gas}}\), with \(\Delta_{\text{gas}}\) is the loss of dissolved methane due to the outflow of pore water (advection). In \(\Delta_{\text{gas}}\) an average gas pressure for two subsequent time steps is taken. At the time the respective nodes are deposited, the initial mass of gas is the same for each of them. During consolidation this
changes, due to the outflow of dissolved methane gas. The advection term that is used here is an upper limit to the outflow of dissolved methane, as it is assumed that the loss of methane is proportional to the local gas pressure (see Chapter 2). In case (3), \( H=0 \) and no loss of methane occurs.

As \( \sigma \) can be calculated from equation (2.4a) for time steps \( j \) and \( j-1 \), the \( p_g \) values can be calculated as well. By means of equation (3.8) \( e_g^j \) values are calculated from the \( e_g^{j-1} \) values, which can be substituted in RHSGAS (equation (3.2) or (3.3)). Equation (3.1) can be solved now for \( e_{f,n}^{j+1} \). For \( H=0 \) and in case the water level equals the mud level, this calculation of \( e_g \) can be compared with the special case in section 3.1.2 for a typical disposal scenario. In section 3.1.2 \( e_g \) is calculated directly from \( e_g^{\text{atm}} \) for each time step. In equation (3.8) \( e_g \) is calculated from \( e_g \) at the previous time step, which is less accurate.

Both methods gave approximately the same results, however.

### 3.1.4 boundary conditions for all cases.

Equations (3.2), (3.3), (3.6) and (3.7) can only be applied for the internal nodes. Boundary conditions have to be considered separately.

The case of a drained boundary has been implemented in the same way as for the saturated model: At a drained boundary pore water pressure \( p \) is equal to the hydrostatic pressure.

The operative stress is calculated from \( \sigma - p = \sigma - p_{\text{hydrostatic}} \). The void ratio of fluid \( e_f \) follows from inversion of \( \sigma_{op}(e_f) \).

For an undrained bottom boundary \( q_{\xi=0} = 0 \). Equation (2.5a) shows that \( q \) only depends on changes in \( e_f \). Therefore, the undrained boundary condition has been implemented in the
same way as for the saturated case (Greeuw & van Ommen 1992), by using \( e_r \) instead of \( e \) as a variable.

### 3.2 Stability

The discretisation shown in equation (3.1) combined with equations (3.2), (3.3), (3.6) or (3.7) has been tested empirically for stability. In can be expected that physical instability occurs when \( e_g \) approaches \( \frac{\gamma_s}{\gamma_f} - 1 \), which means that the driving force for consolidation is equal to zero. Indeed, in case \( e_g \) exceeds \( \frac{\gamma_s}{\gamma_f} - 1 \), the computer program becomes numerically unstable. In this case, the first term in brackets in equation (2.12) is taken to be zero.

In case (1), this limitation of \( e_g \) is sufficient to ensure stability. In cases (2), (3) and (4) swell of the saturated matrix might occur due to gradients in \( e_g \). This can be explained as follows: In cases (2), (3) and (4) RHSGAS, i.e. the second term with \( \frac{\partial e_g}{\partial z} \) in equation (2.7), becomes non zero. Swell of the saturated matrix occurs, when the second term with \( \frac{\partial e_g}{\partial z} \) in (2.7) is larger than the modulus of the first term, which means that \( \frac{\partial e_r}{\partial z} \) is larger than zero.

In cases (3) and (4), swell occurs when \( e_g \) exceeds a certain critical value, depending on the disposal scenario and the material characteristics. This can be explained as follows: From equation (2.12) it follows that the specific discharge \( q \) is smaller than in the saturated case when \( e_g \) is non zero. In cases (3) and (4), \( e_g \) decreases as a function of depth, due to compression and dissolution. In addition, \( e_r \) decreases as a function of depth due to consolidation under self weight. The choice of the finite strain parameter relations and
initial fluid void ratio for a typical disposal scenario determines the speed of consolidation and therefore the shape of the $e_f$ against depth profile. Gradients in $e_g$ might lead to significant changes in specific discharge across the mud layer. Swell occurs when the discharge in the lower part of the mud layer is larger than the discharge in the top part, which causes $\frac{\partial e_f}{\partial z}$ to be positive, according to equation (2.11). It was found that this happens mainly in the top part of the mud layer when the gradients in $e_f$ are small. Small gradients in $e_f$ occur when the mud layer is deposited relatively fast, as consolidation under self weight starts from the bottom.

The author believes that this swell is a real physical phenomenon. However, the definition of the $\sigma_{op}(e_f)$ relation does not include swell. Normally, the swell is around 10% of the corresponding compression. As a first approximation, swell has been disregarded.

Under the restrictions that have been mentioned here, the explicit discretisations of RHSGAS (equations (3.2) and (3.6)) are as stable as in the saturated case. The partly implicit discretisations (equations (3.3) and (3.7)) turned out to be less stable at higher values of $e_g$. An analytic calculation of $e_g$, as performed for equations (3.6) and (3.7) did not improve the stability. All four FDM discretisations gave the same results for lower values of $e_g$ so that no swell occurs. Therefore, equation (3.2) was implemented in the FSCongas computer program, as this is the simplest discretisation.

3.3 comparison of FDM with FEM method.

In order to test the FDM program, a Finite Element Code was established. This FEM method has been applied on equation (2.11), into which equation (2.12) was substituted, using so called "roof functions" (de Vries 1995). The FEM code has been implemented
such that the range of applicability corresponds to that of the FSCongas computer program. Using a finite element discretisation leads to a rather different numerical formulation of the field equations and the boundary conditions.

Calculations with different distributions of the gas across the bed height (see Chapter 2 for cases (1) to (4)) were made, consisting of a saturated calculation, case (1), i.e. with $e_g = \text{constant}$, case (2), i.e. with a linear increase of $e_g$ in time, and case (3), i.e. for a constant mass of gas. In case (3), the gas is compressed due to changes in gas pressure $p_g$.

As mentioned before, it was assumed that $p_g$ is equal to the vertical total stress plus atmospheric pressure $u_{atm}$, with $u_{atm} = 100$ kPa. The free water level was supposed to be equal to the mud level. Therefore, equation (3.4) has been used. Trial runs were made to check whether both numerical methods gave the same output. It was found (de Vries 1995) that FDM and FEM, give similar results. A few minor corrections were necessary in the FDM code, concerning a consistent application of the Trapezoidal rule in the calculation of the vertical total stress.
Chapter 4 Experimental verification

4.1 general

In order to test the assumptions underlying the finite strain theory for gassy sludge, experimental tests are necessary with test conditions similar to the conditions in a typical disposal site. Settlements, excess pore water pressures, as well as densities can be compared with computer simulations. In addition, the gas content, defined as \( e_g/(1 + e_f + e_g)*100\% \), should be determined accurately. This gives a need for specialised tests. Computer simulations that have been performed on such tests are presented in section 4.5. Thus it will be investigated whether \( \sigma_{\text{op}}(e_f) \) and \( k(e_f) \) are independent of gas content and it will be investigated whether it is reasonable to assume that the gas pressure is equal to the vertical total stress plus atmospheric pressure. It is possible to make a sensitivity analysis for the gas content as well as for the distribution of the gas across the bed height (for column tests).

In the framework of this project a series of tests has been performed by dr. Sills and collaborators at Oxford University, Department of Engineering Science, consisting of self weight column tests and oedometer tests. The tests were performed on mud from the Ketelmeer and the Slufter disposal site in The Netherlands. Samples with different gas contents have been compared with saturated samples. The column tests were most suitable to investigate the self weight consolidation behaviour and structural changes in the consolidating mud bed. The gas voids are embedded in the most natural way. However, the stress level is necessarily low. For some column tests the stress range was increased by applying a hydraulic pressure difference across the mud bed by means of a peristaltic pump (see Fig.4.1). This is not considered here, as the computer simulation is much more complex. In addition, oedometer tests have been performed, starting from a low stress level, i.e. a few kPa, in which the load and in some cases also the backpressure was increased at a constant rate up to operative stresses of ca. 100 kPa. This is close to the maximum operative stress in a depot of 40 m depth with an average density of 1.3 g/cc, which is 120 kPa.

The mud properties are shown in Table 4.1.

The most recent column tests, called BIOx, with \( x = \)integer, were performed on Slufter mud with a biological gas production. BIO7 was performed at room temperature, whereas the other columns were cooled or heated by means of water filled jackets that were
covering part of the column wall (see Fig. 4.1). As the temperature across the mud bed was most uniform at room temperature, BIO7 has been simulated. The experimental conditions are given in section 4.2. More details are given in Gonzalez & Sills (1997).

Table 4.1: mud properties

<table>
<thead>
<tr>
<th>mud from:</th>
<th>PL (%)</th>
<th>LL(%)</th>
<th>grain sizes (%)</th>
<th>organic content (%)</th>
<th>$\rho_s$ g/cc</th>
<th>$\rho_f$ g/cc</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$&lt;2\mu m$</td>
<td>$&lt;16\mu m$</td>
<td>$&gt;63\mu m$</td>
<td></td>
</tr>
<tr>
<td>Ketelmeer</td>
<td>41</td>
<td>137</td>
<td>32</td>
<td>77</td>
<td>1.2</td>
<td>7.2</td>
</tr>
<tr>
<td>Slufter</td>
<td>29</td>
<td>110</td>
<td>34</td>
<td>66</td>
<td>8.4</td>
<td>6.8</td>
</tr>
</tbody>
</table>

(*) The liquid limit was determined by means of the Casagrande method (ASTM D4318).
(**) determined by Delft Geotechnics with K$_2$CrO$_4$ method.

Simulations of two other column tests, NK1 and NK2 are presented here, which were performed on one single batch of Ketelmeer mud. The experimental conditions are given in section 4.2. NK1 had an artificial gas production with NK2 being the saturated reference column. Also simulations were made of constant rate of loading oedometer tests, that were performed on samples from the same batch of Ketelmeer mud. A selection of three typical experiments is presented in section 4.3. These oedometer tests were performed on samples with an artificial gas production.

In case of artificial gas production, the samples were mixed with a toxic additive, called BES, which stops the natural gas production. The gassy samples have been prepared by means of a special zeolite technique, in which methane saturated zeolite powder is thoroughly mixed with the mud. After one day, the majority of the methane in the zeolite pores has been replaced by water and the methane has accumulated in large gas voids in a rather uniform manner throughout the sample volume. The gas voids that are formed are similar to voids that have been observed in natural samples (Sills et al. 1991), apart from the natural gas voids being larger in some cases. The amount of zeolite powder added was 24% by weight of solids for both the gassy and the saturated samples. For the saturated samples the zeolite powder was water saturated and for the gassy samples the zeolite
powder was saturated with methane in different proportions depending on the desired gas content.

4.2 self weight column tests

In order to verify the self weight consolidation model for samples with varying gas contents and gas production rates, up to 10 column tests have been used (Wichman 1997b). The apparatus at Oxford University consisted of an accurate X-ray facility, by means of which bulk density profiles can be obtained, and a system which allows for the measurement of pore water pressure at several fixed positions at the column wall (Bowden 1988) (see Fig. 4.1).

Fig. 4.1: experimental set-up for column test
The accuracy of the density measurement is 0.002 g/cc and has a vertical resolution of 1 mm. The accuracy of the pore water pressure measurement is 0.01 kPa (Sills, 1994c). This gives an overall accuracy of 0.03 kPa for the effective stress (Sills & Yuan 1993).

After being mixed thoroughly, the mud was deposited quickly in one time. The initial mud height was approximately 60 cm for all tests. The internal column diameter was 102 mm. During self weight consolidation the bottom was undrained. During test NK1 the gas production was artificial, with a saturated reference column NK2 (see Table 4.2). These tests were performed at room temperature. In test BIO7 biogenic gas production occurred at room temperature. The experimental conditions are given in Table 4.2.

Mud height, water height, pore water pressures and density profiles were measured at suitable time intervals. The heights of the water layer and the mud bed were determined by eye against a rule. Pore water pressures were measured at 11 heights across the mud bed. The density profiles were calculated from the X-ray absorption profiles. The total gas volume inside the mud bed was calculated from the increase in water height. The threshold gas content in Table 4.2 is taken at the time that the gas volume stays constant.

**Table 4.2: conditions column tests (Sills 1994a, Gonzalez & Sills 1997)**

<table>
<thead>
<tr>
<th>test</th>
<th>origin</th>
<th>initial sludge height (m)</th>
<th>initial density (g/cc)</th>
<th>threshold gas content (%)</th>
<th>duration of self weight period (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BIO7</td>
<td>Slufter 0.6</td>
<td>1.18</td>
<td></td>
<td>8</td>
<td>94</td>
</tr>
<tr>
<td>NK1</td>
<td>Ketelmeer 0.6</td>
<td>1.178</td>
<td></td>
<td>5</td>
<td>68</td>
</tr>
<tr>
<td>NK2</td>
<td>Ketelmeer 0.6</td>
<td>1.174</td>
<td></td>
<td>0</td>
<td>60</td>
</tr>
</tbody>
</table>

4.3 oedometer tests

The oedometer tests are based on the tests Thomas has performed on Combwich mud (Thomas 1987). They consisted of incremental loading tests, in which the load was increased instantaneously and constant rate of loading tests, in which the load was increased at a constant rate up to a maximum value at which the load was kept constant. The constant rate of loading tests are most suitable to simulate the conditions in a disposal site, and are considered here. The experimental set-up at Oxford University consisted of a 108 mm
diameter cylindrical consolidation cell that allowed for accurate measurements of total sample volume as well as the volume of water draining from the sample. The gas volume change can be calculated from the change in total sample volume minus the change in the volume of expelled pore water. The load was applied by means of a hydraulically activated piston at the bottom of the cell and drainage was allowed at the top and bottom parts of the sample. During consolidation, drainage of pore water and gas occurred at the top face only, where gas and water were separated by collecting the gas at the apex of a cone-shaped chamber above the porous filter (Thomas 1987). Changes to the construction of the experimental set-up and data registration have been made by F. Yuan (Sills & Yuan 1993) in order to allow for the application of backpressure and low stresses of order of 1 kPa (see Fig. 4.2).

Fig. 4.2: experimental setup of oedometer test

Notes:
- load applied with oil for lubrication of piston movement
- drainage is only allowed through top surface
- drained fluid volume is measured by transducer attached to burette
- gas trap and volume measurement is applied on drainage line
- low load stress application
Additional facilities for permeability determination by means of the flow-pump method have also been included (Sills & Yuan 1993). Accurate permeability measurements turned out to be essential as the computer simulations are very sensitive to changes in permeability. Low initial stress levels are considered as the sludge remains soft for a long time after disposal. Sample thickness, the outflow of pore water, vertical total stress and pore water pressures at the top and the bottom of the cell were registered electronically. The initial sample thickness before loading was 4 to 5 cm, because the soft samples have a large compression index. The tests were performed at a temperature around 20 degrees.

Tests have been performed at operative stress levels ranging from 2 kPa to 250 kPa.

The constant rate of loading oedometer tests have been performed with loading rates ranging from 1 kPa/hour to 33 kPa/hour (Sills & Yuan 1993, 1994, 1995). The slower loading rates are the most accurate, as the excess pore water pressures remain relatively low, resulting in a uniform sample. For the later tests also backpressure has been applied at a constant rate as well (Sills & Yuan 1995). Before loading at a constant rate, the sample was allowed to consolidate at a stress level of a few kPa.

The pore water pressure difference across the sample height was measured directly by means of a differential pore pressure transducer (see DT1 in Fig. 4.2). This measurement gives the (maximum) excess pore water pressure at the undrained bottom, neglecting the small hydrostatic component. It has been found that the slower loading rates provide a more accurate calculation of operative stress and permeability as functions of void ratio during consolidation, as the excess pore water pressures are lower and therefore assumptions on the shape of the pore water pressure profile are less critical. In total 6 constant rate of loading oedometer tests have been simulated (Wichman 1997b). Simulations of three typical examples, i.e. FY-S5, FY-6 and FY-3 are presented here. The experimental conditions are given in Table 4.3.
Table 4.3: constant rate of loading oedometer tests (Sills & Yuan 1994 and 1995)

<table>
<thead>
<tr>
<th>test</th>
<th>origin</th>
<th>initial conditions:</th>
<th>loading conditions:</th>
<th>back pressure:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>sludge</td>
<td>height (mm)</td>
<td>density (g/cc)</td>
<td>gas content (%) after preloading</td>
</tr>
<tr>
<td>FY-S5</td>
<td>Ketelmeer</td>
<td>49.7</td>
<td>1.2</td>
<td>14</td>
</tr>
<tr>
<td>FY-6</td>
<td>Ketelmeer</td>
<td>49.99</td>
<td>1.185</td>
<td>8</td>
</tr>
<tr>
<td>FY-7</td>
<td>Ketelmeer</td>
<td>49.99</td>
<td>1.185</td>
<td>8</td>
</tr>
<tr>
<td>FY-2</td>
<td>Ketelmeer</td>
<td>49.28</td>
<td>1.186</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FY-3</td>
<td>Ketelmeer</td>
<td>51.76</td>
<td>1.182</td>
<td>0</td>
</tr>
</tbody>
</table>

4.4 analysis of experimental results

The analysis consisted of the calculation of $\sigma_{op}(e)$, $\sigma_{op}(e_f)$, $k(e)$ and $k(e_f)$ relations and $e_g$ profiles as a function of time, with $e = e_f + e_g$. These parameters have been used as input for the computer simulations.

4.4.1 distribution of gas void ratio

4.4.1.1 column tests

In order to calculate $e_g$, assumptions on the spatial distribution of gas voids have to be made. For the column tests it has been assumed that the local gas volume is proportional to the solids volume, i.e. $e_g$ is constant across the height of the mud bed. This means that the gas bubbles are supposed to be fixed in the soil skeleton and that the change in $e_g$, due to changes in vertical total stress, is supposed to be negligible (at maximum $\pm 4\%$ for a bed thickness of 60 cm). The $e_g$ values are assumed to be equal to the average across the height of the mud bed. This average $e_g$ value is obtained from the rise in free water level, representing the gas height. The shape of the density profiles suggest that the assumption $e_g$ is constant is reasonable (see section 4.5). Unfortunately, it has not been possible to determine the distribution of $e_g$ across the sample height directly, as it was not possible to extrude parts of the sample.

4.4.1.2 oedometer tests

For the oedometer tests photographs from air dried samples after unloading show a nearly
uniform distribution of gas voids. Therefore, for the oedometer tests it is assumed as well that \( e_g \) is constant across the height of the sample.


4.4.2. operative stress

4.4.2.1 column tests

For the column tests \( \sigma_{op}(e_f) \) profiles were obtained at regular intervals by integrating the density profile in order to calculate the vertical total stress, and subsequently, by subtracting pore water pressure from the vertical total stress. As the pore water pressure data are only available at the pressure ports, interpolation is necessary in order to match the density profiles. \( e_f \) profiles have been calculated on the assumption that the local gas volume is proportional to the solids volume, i.e. \( e_g \) is constant. Least squares fits of the resulting data were used as input for the computer simulations (see Figure 4.3a and in Fig. 4.4a, line labelled with NK1_simulation). In Fig. 4.3a the measured operative stress profile after 77 days shows a strange behaviour below 0.06 kPa. This is caused by the denser non gassy layer on top of the sediment bed and can be ignored. The same feature is visible in Fig. 4.4a for the NK1 curve after 37 days below 0.02 kPa. For NK2 creep effects are visible, as the initial operative stress profiles have a higher fluid void ratio, especially in the lower stress range. It was found that the \( \sigma_{op}(e_f) \) profile marked with NK2_simulation in Fig. 4.4a gave a good fit of the measured height, density profiles and pore water pressures.

4.4.2.2 oedometer tests

For the constant rate of loading tests the (changing) gas volume was calculated from changes in total sample volume and the amount of expelled pore water, using the water content determination at the end of the test. Average \( e_g \) values were calculated from the gas volume and the known volume of solids in the oedometer. Continuous profiles of \( \sigma_{op}(e_f) \) were obtained by assuming a uniform void ratio distribution and a parabolic pore water pressure distribution. These assumptions are reasonable for the main part of the experiment when the loading rate is sufficiently slow. Typical lines have been drawn in the summary graph of fluid void ratio against operative stress, in order to obtain input relations for the computer simulations (see Fig. 4.5a). Table 4.4 gives the parameter values \( m_1 \) and \( m_2 \) that were used for the computer simulations that gave the best agreement with the
measurements. In all cases these relations had the following form:
\[ \sigma_{op}(e_f) = \sigma_0 \exp(m_1 + m_2 \cdot e_f), \] with \( \sigma_0 = 1 \text{ kPa}. \)

4.4.3 permeability

4.4.3.1 column tests

From the column tests permeability values were obtained as follows. The pore water pressure data were interpolated linearly or by means of a quadratic fit, in order to obtain continuous profiles against height. From two subsequent density profiles the average velocity \( U_s \) of a given set of solid particles can be obtained by subtracting heights with constant excess vertical total stress, i.e. vertical total stress minus hydrostatic pressure. As the gas voids affect the height of the water level, and therefore the excess vertical total stress, it is necessary to assume that \( e_g \) is constant across the height of the mud bed. Other distributions of \( e_g \) result in an excess vertical total stress that is not constant. In case of an undrained lower boundary, the specific discharge at a certain height is equal to \(- U_s\). The corresponding pore water pressure gradients are calculated from the average of the continuous pore water pressure profiles, that belong to the two sequential density profiles that have been used to calculate \( U_s \). Permeability values can be obtained from the specific discharges and pore water pressure gradients by using Darcy's Law. For test NK1 the permeability analysis was not entirely consistent, as \( e_g \) was assumed to be proportional to \( e_f \), contradicting the implicit assumption that \( e_g \) is constant, following from the assumption that the excess vertical total stress is constant (see above). The results are shown in Figures 4.3b and 4.4b. In addition to the permeability values that were obtained from the density and excess pore water profiles, the initial permeability at the start of the experiment was calculated from the initial settlement of the saturated bed height. This is included in Figures 4.3b and 4.4b. Input relations for \( k(e_f) \) were obtained from least squares fits of the data (excluding the start values), that were slightly rotated in some cases, in order to optimise the computer simulation. The lines that gave the optimum computer simulation are within the range of the measurements.

4.4.3.2 oedometer tests

For the constant rate of loading oedometer tests, flow-pump tests were performed after the initial loading and after consolidation under maximum load. For test FY-S5 this was not possible, as the design had been changed. Several flow rates have been used, and average
permeability values were calculated from outflow and inflow. The results are shown in Figure 4.5b, including results from tests FY-2 and FY-7 (see Table 4.3 for the experimental conditions). Least squares fits were made of fluid void ratio against permeability, giving input relations for the computer simulations (see Fig. 4.5b). It is visible that the $k(c_f)$ values are within the same range, except those from the saturated experiments FY-2 and FY-3. In section 4.4 it is investigated whether the differences in permeability are significant for the simulations of the laboratory tests. Table 4.4 gives the parameter values $m_3$ and $m_4$ that were used for the optimum computer simulations. In all cases these relations had the following form: $k(c_f) = k_0 \exp(m_3 + m_4 \cdot c_f)$ with $k_0 = 1 \text{ m/sec}$.

**Table 4.4: optimum parameter values for all tests**

<table>
<thead>
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<th>test</th>
<th>$m_1$</th>
<th>$m_2$</th>
<th>$m_3$</th>
<th>$m_4$</th>
</tr>
</thead>
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<td>-26.25</td>
<td>1.47</td>
</tr>
<tr>
<td>NK1</td>
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<td>-1.72</td>
<td>-21.54</td>
<td>1.04</td>
</tr>
<tr>
<td>NK2</td>
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<td>-22.47</td>
<td>1.30</td>
</tr>
<tr>
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<td>-24.07</td>
<td>1.78</td>
</tr>
<tr>
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<td>-24.07</td>
<td>1.78</td>
</tr>
<tr>
<td>FY-3</td>
<td>9.05</td>
<td>-2.68</td>
<td>-23.70</td>
<td>1.86</td>
</tr>
</tbody>
</table>
Fig. 4.3a: $\sigma_{op}(e_r)$ for test BIO7. *Least square fits were used as input for simulations.*

![Graph showing fluid void ratio vs operative stress (kPa).]

Fig. 4.3b: $k(e_r)$ for test BIO7. *Lines indicated by BIO7-8 and BIO7-10 were used as input for simulations.*

![Graph showing fluid void ratio vs permeability (*10^-8 m/sec).]
Fig. 4.4a.1: $\sigma_{op}(e_f)$ for test NK2. Line indicated by NK2-simulation was used as input for the simulation.

Fig. 4.4a.2: $\sigma_{op}(e_f)$ for test NK1. Line indicated by NK1-simulation was used as input for the simulation.
Fig. 4.4b: $k(e_f)$ for tests NK1 and NK2. *Lines indicated by NK1-simulation and NK2-simulation were used as input for simulations.*

Fig. 4.5a: $\sigma_{op}(e_f)$ for tests FY-S5, FY-6, FY-3. *Lines indicated by boundary1 and boundary2 were used as input to the computer simulations.*
Fig. 4.5b: $k(e_f)$ for tests FY-S5, FY-6 and FY-3. *Lines indicated by fy-6 and fy-s5 simulation and fy-3 simulation were used as input to simulations.*

4.5 results from computer simulations

4.5.1 column tests with biogenic gas production

Results from column test BIO7 are compared with computer simulations in Figures 4.6a, 4.6b and 4.6c, showing mud height (or "height" in Fig. 4.6a), water height ("h water" in Fig. 4.6a) and gas height ("h gas" in Fig. 4.6a), density profiles and excess pore water profiles after suitable time intervals. In Fig. 4.6a also the saturated part of the mud height ("h sat" in Fig. 4.6a) is shown. More details are given in Gonzalez & Sills (1997).

The BIO7 test was performed on Slufter mud at room temperature and is most suitable to simulate, as the temperature profile was more uniform, i.e. with a variation within a few degrees, than for the other BIOx tests. In this test the gas was produced gradually by bacteria and it is considered to give a more natural mud bed structure than the tests with an artificial gas production. The experimental conditions are given in Table 4.2. Initially, no gas is present and a gradual increase in water height indicates that gas is accumulating in the mud bed (see Fig. 4.6a). After 70 days the increase in water height diminishes, which indicates that in total no gas is accumulating any more. This might be explained by gas bubbles escaping from parts of the mud bed. At that time the gas content was 8%.
Figures 4.3a and 4.3b show the $\sigma_{op}(e_f)$ and $k(e_f)$ relations that were used as input for the computer simulations. The $\sigma_{op}(e_f)$ and $k(e_f)$ relations were obtained by means of a least squares fit of the measurement data. The least squares fits for $\sigma_{op}(e_f)$ were taken over the range $> 0.1$ kPa, as at lower stresses the void ratios are unreliable. The sensitivity to changes in these relations was investigated. In Fig. 4.6a it is visible that the simulation BIO7_10 gives the best results. In this case $\sigma_{op}(e_f)$ was equal to the least squares fit after 46 days. In simulation BIO7_8 a $k(e_f)$ relation was used that was slightly rotated and intersects one of the two permeability points that were calculated from the initial settlements, indicated by “BIO7_start value” in Fig. 4.3b. $\sigma_{op}(e_f)$ was the same as for BIO7_10. Also the same gas accumulation curve was used. In simulation BIO7_11 $\sigma_{op}(e_f)$ was equal to the least squares fit of the measured profile after 77 days, starting from 0.1 kPa. $k(e_f)$ was the same as in BIO7_10. Again the same gas accumulation curve was used.

Fig. 4.6a: (gas) height for test BIO7

It is concluded that these simulations are significantly different from the optimum simulation BIO7_10. The outcome is very sensitive to changes in permeability. However, after 50 days the simulated height increases for all simulations, due to the assumed gas production.
Simulation BIO7_10 is compared with the measured density profiles in Figure 4.6b. The agreement is good, except for the top part of the mud bed. The measurement showed a higher density layer. It is likely that almost no gas is present here. For the simulations a constant $c'_g$ value across the mud bed was used.

A comparison between the optimum simulation BIO7_10 and the measured excess pore pressure profiles is shown in Fig. 4.6c. Starting from 46 days, the experimental excess pore pressure profiles do not decrease gradually any more, but show unexplainable jumps. The simulated profiles show a gradual decrease in excess pore water pressure, initially starting at the bottom. When comparing measurements and simulation, it follows that 7 out of 12 profiles are reasonably close, with the best agreement at times smaller than 46 days. Profiles that are in reasonable agreement are shown separately from those that are in less agreement in Figures 4.6c.1 and 4.6c.2.

Fig. 4.6b: density profiles for BIO7 with simulation BIO7-10
Fig. 4.6c: excess pore water pressures for BIO7 with simulation BIO7-10

c.1: profiles that are in reasonable agreement

![Graph showing the relationship between excess pore water pressure and height with data points and lines indicating measurements and simulations.](image)

- Measurements: time elapsed (days)
  - 0, 3, 14, 19, 38, 46, 77
- Simulation: time (days)
  - 0, 3, 14

Simulation: time (days)
- 19, 38, 46, 75

![Graph showing the relationship between excess pore water pressure and height with data points and lines indicating measurements and simulations.](image)

- Measurements: time elapsed (days)
  - 10, 30, 55, 66, 94
- Simulation: time (days)
  - 10, 31, 58, 68, 91, 100

c.2: profiles that are in less agreement
When looking more closely at the results, it is visible that at the time the rise in water level levels off, the measured mud height is decreasing faster than the simulated height (see Fig. 4.6a). This indicates that the consolidation might be enhanced. From later BLOx tests it appeared that the biogenic gas production is likely to go on, at the time the water level stays constant, and that significant amounts of gas are escaping. This might cause the enhancement of consolidation.

The computer simulations were made with $e_g$ constant across the mud bed, i.e. the local gas volume is proportional to the local solids volume, which means that the gas bubbles move with the solids. As the agreement between the measured and simulated density profiles is good for the bulk of the mud bed, also at later stages, it is likely that $e_g$ is constant is not an unreasonable assumption. The gas production should be rather uniform as the temperature was rather uniform. As $e_g$ is constant, this implies that the same escape mechanism occurs everywhere in this bulk area. When the density profiles are compared, it is visible that they become more spiky, even when consolidation is almost finished. As the resolution of the X-ray facility is high, the spikes in density are attributed to the gradual development of fissures that are partly filled with gas bubbles. As this results in a inhomogeneous gas distribution spikes in density are measured. At the side walls, the fissures were observed to be more or less horizontal with diagonal connections. Drainage through these channels enhances consolidation. The fissuring is still increasing as the gas escapes. A possible cause of the increase in fissuring might be that the gas bubbles are accumulating in the fissures and at some stage gas bubbles start to escape through preferential channels that stay more or less opened. The fissures developed similarly over the bed height, except at the bottom, where the density had been larger initially.

Summarising, it is concluded that at the time the rise in water level levels off, consolidation is enhanced due to the formation of preferential drainage channels, that stay opened as gas escapes and can become even wider. It is likely that these channels develop over the whole depth of the mud bed, and perhaps less in the bottom region, where the density had been larger initially. As in the bottom region the measured density is somewhat larger than the simulation, probably less gas bubbles are accumulating. It should be noted that the mud bed had a limited height of 60 cm. In addition, the outcome of the simulation with $e_g$ is constant is in very good agreement with the measured height, density profiles and excess.
pore water pressures.
It seems reasonable to maintain this simple approach in which \( e_g \) is obtained by dividing the increase in total accumulated gas volume by the total solids volume, even when the gas is escaping. When the mud bed is thicker, differences in \( e_g \) due to compression of the gas voids and dissolution should be taken into account. In test BIO7 the gas content increases gradually from 0\% up to values of 8\%. As the simulation was in good agreement with the measurements at all intermediate gas contents, it appears that the use of unique \( \sigma_{op}(e_f) \) and \( k(e_f) \) relations is successful, implying that these relations are independent of gas content.

4.5.2 column tests with artificial gas production

Column tests NK1 and NK2 were performed on Ketelmeer mud. NK1 had an artificial gas production in which the methane was released from a zeolite powder within the first few days. NK2 was a saturated reference column in which the zeolite was completely saturated with water. The experimental conditions are given in Table 4.2. NK2 is treated in section 4.5.3. A maximum gas content of 5\% was obtained within 13 days of initial gas production. A comparison between the outcome of the optimum computer simulation and the measurements is shown in Figures 4.7a, 4.7b.1, and 4.7c. In Figures 4.4a and 4.4b the parameter relations are shown that were used as input. They are within the experimental range. In Fig. 4.4a.2 the \( \sigma_{op}(e_f) \) profile that was measured after 37 days is shown, from which a least squares fit was made that served as the input of the optimum simulation. The other \( \sigma_{op}(e_f) \) profiles were within the same range.

The agreement between simulation and measurement is good, except for the early density profiles, that have a different shape. This is reflected in the differences between the early operative stress- fluid void ratio profiles and the later ones. The initial profiles have higher fluid void ratios. For another test on Slufter mud, CTP1 this was very clear (Wichman 1997b).

In Fig. 4.7a also the mud height from a saturated simulation, using the same parameter relations as in NK1 is shown. It is clearly visible that the saturated part of mud height, i.e. bed height minus gas height, from the simulation that includes gas decreases slower than the height from the saturated simulation. This indicates that in this case the consolidation is
retarded by the gas. In addition, the final bed height minus gas height is larger than the height from the saturated simulation. This can be explained by the fact that, in case gas is present, the initial excess pore water pressures are lower, which causes smaller final operative stress values and therefore a higher fluid fraction.

Fig. 4.7a: (gas) height for tests NK1, NK2

In Fig. 4.7b.1 the later density profiles have the same roughness as the initial one, which might be interpreted as follows. The initial density in test NK1 was 1.18 g/cc, which was also the case for test BIO7. The gas content in NK1 was 5% after 13 days and stayed constant afterwards. The same gas content was obtained in BIO7 after 46 days. At that time the BIO7 profile was more spiky than the initial one, whereas NK1 did not develop additional spikes at all. The differences between both experiments might be explained by a lack of layering in NK1 and a more homogeneous gas production. Even at a similar gas content as in BIO7 this is the case. A reason for the lack of layering might be that NK1 was performed on Ketelmeer mud, whereas BIO7 was performed on Slufter mud. Another reason might be that the gas production in BIO7 is biogenic and in NK1 it is artificial, more homogeneous and also faster.
Fig. 4.7b.1: NK1: density with $e_g = \text{constant}$

Fig. 4.7b.2: NK1: density with $e_g/e_f = \text{constant}$.
Fig. 4.7c: excess pore water pressures for NK1

The latter reason is more likely, because fissures were observed in GASCON-tests for Ketelmeer mud with a natural gas production as well (see Chapter 5). However, from GASCON-tests (see Chapter 5) it followed that Ketelmeer mud with a biogenic gas production might contain very large amounts of gas, up to 20%, and it was found that little gas escaped. This mud was sampled from the same location as the mud that was used for test NK1. As it is likely that the escape of gas is related to the formation of fissures, the fissures in the Ketelmeer mud are likely to be smaller than in the Slufter mud.

In order to investigate the sensitivity of the simulation to the distribution of gas void ratio, also a simulation with \( e_g \) proportional to \( e_f \) was made. The simulated mud height was the same as for \( e_g = \text{constant} \), as the total gas volume in the bed was the same. However, major differences in density profiles were found (see Fig. 4.7b.2). It is clearly visible that as consolidation proceeds, the simulated density profiles are much too steep, as the gas content in the bottom part is decreasing as \( e_f \) is decreasing. It is concluded that the assumption that \( e_g = \text{constant} \) is the better choice. Simulations for other sets of column tests were satisfying as well (Wichman 1997b). The mud originated from the Ketelmeer as well as from the Slufter disposal site and had a artificial gas production.
4.5.3 saturated reference column NK2

NK2 was performed on the same batch of Ketelmeer mud as test NK1 and contained a zeolite fraction that was fully saturated with water (see Table 4.2). Figures 4.8a, 4.8b and 4.8c show a comparison between the simulated profiles and the measurements. The agreement between the simulation and the measurements is reasonable. The input parameter relations are shown in Figures 4.4a and 4.4b. In Figure 4.4a creep effects are clearly visible as the initial profiles have a higher fluid void ratio, especially in the lower stress range. A line has been drawn that gives a good outcome of the computer simulation. The differences in shape between the initial density profiles and the simulation are due to creep. In Figure 4.7a a saturated simulation with parameters from the optimum simulation for NK1 is shown as well as the measured mud height for column NK2. The two curves are clearly different. This might be due to thixotropy or mixing effects, especially in the initial stage of both column tests, during which the gas produced in NK1.

Fig. 4.8a: height against time for NK2
Fig. 4.8b: density profiles for NK2

Fig. 4.8c: excess pore water pressures for NK2
Due to the fast production of gas the mud settles slower and acquires a stiffer skeleton. In Fig. 4.4a the operative stress profile for NK1 is clearly different from those for NK2. From column tests on Slufter mud (tests BIOx, see section 4.1) with a biological gas production it followed that $\sigma_{op}(e_f)$ and $k(e_f)$ are not systematically dependent on gas content, however (Gonzalez & Sills 1997).

4.5.4 constant rate of loading oedometer tests

4.5.4.1 general input for computer simulations

Simulations of three typical oedometer tests are shown here, in which the load, and in case of test FY-S5 also the backpressure, was increased at a constant rate. The tests were performed on samples of Ketelmeer mud with an artificial gas production, with FY-3 being saturated (see Table 4.3). Sills & Yuan (1995) reported additional tests, in which a backpressure was applied and the gas content was varied. In Wichman (1997b) satisfying simulations of other tests are reported, in addition to the three tests that are mentioned here. Test FY-S5 is considered as the most successful, as it was possible to measure the gas volume more accurately. The test conditions are more realistic than tests FY-6 and FY-3 as backpressure was applied. In test FY-6 no backpressure was applied and it is interesting to investigate what difference this makes. FY-3 serves as a saturated reference test. Sills & Yuan (1995) reported that parameter relations from other tests with similar loading rates and backpressure rates as in test FY-S5, but with variable gas contents, are close to the ones shown in Figures 4.5a and 4.5b. In Fig. 4.5a two boundaries are shown that served as input for the computer simulations. Fig. 4.5b shows typical input $k(e_f)$ relations.

The initial $e_g$ values that were used in the computer simulations were obtained as follows: by means of back calculation, using the final water contents (see section 4.4.2), an initial gas volume was obtained after initial loading (i.e. at a few kPa). Also gas volumes at intermediate times were obtained in the same manner. When these are divided by the oedometer area, gas heights follow (see Figures 4.9b and 4.10b). Experimental gas pressures were obtained from the changes in gas volume by means of Boyle's and Henry's law. It was assumed that Henry's coefficient $H=0.033$ (Sills & Yuan 1994 and 1995). However, Sills & Yuan (1995) reported that the sensitivity of the experimental analysis to changes in $H$ is large. As the changes in load are gradual, it is reasonable to assume that local equilibrium between the gas voids is obtained. $H=0.033$ is the value for methane in
tap water at 20°C (Yamamoto et al. 1976) and it gives a gas pressure that is slightly smaller than the absolute vertical total stress (see Fig. 4.9a). H=0.033 is considered to be the most realistic and was used in the computer simulation. In addition, it was assumed in the computer simulation that the gas pressure $p_g$ was equal to the absolute vertical total stress, i.e. $p_g = \sigma + 100$ kPa.

In the simulation the input value for $e_g$ is $e_g^{\text{atm}}$, with a gas pressure equal to an atmospheric pressure of 100 kPa. In order to define a value that is independent of the initial water content, it was assumed that no gas was in solution at atmospheric pressure. Next, $e_g^{\text{atm}}$ was calculated from $e_g$ after initial loading, taking into account that part of the methane was in solution after initial loading. During the simulation, $e_g$ after initial loading is calculated by assuming that part of the gas goes into solution. Boyle’s and Henry’s Law were used to calculate $e_g$. This procedure gives a initial gas volume (gas height in Fig. 4.9b) that is very close to the experimental one. In the simulation advection has been included, which implies that part of the dissolved methane leaves the sample. The advection loss was calculated from the change in fluid void ratio times the average gas pressure between two time steps (see Chapter 3).

The initial load that was put into the computer simulation was obtained by substitution of $e_f$ after initial loading into the input $\sigma_{op}(e_f)$ relation. In this way the simulated initial height, which is depending on $\sigma_{op}(e_f)$, is in agreement with the measured height. This initial value of operative stress can be compared with the difference between the initial experimental load and initial backpressure. Only small differences were found. The input loading rate was calculated by dividing the difference between the maximum (averaged) load minus backpressure and the initial input load by the time needed to reach the maximum load level.

4.5.4.2 results for test FY-S5

Figures 4.9a and 4.9b show a comparison between the optimum simulation and the measurements for test FY-S5. In Fig. 4.9a the measured pore pressure difference can be compared with the simulated excess pore water pressure at the undrained face, as the hydrostatic component is negligible. The agreement between both is good. The simulated gas pressure is not in this graph, as it is an input relation to the simulation. It is visible that the difference between the load and the relative gas pressure is gradually increasing. This can be explained by the increase in strength of the soil matrix around the gas voids, due to
Fig. 4.9a: loading conditions for FY-S5

![Graph showing loading conditions for FY-S5](image)

Fig. 4.9b: (gas) height for test FY-S5

![Graph showing gas height for FY-S5](image)
consolidation. As the strength increases the voids are compressed less easily, and the gas pressure increases less. This effect was not included in the computer simulation. In Fig. 4.9b the agreement between the simulated and measured sample height and gas height is good. At constant load the gas height stays constant and only a minor decrease in sample height is visible, as consolidation is almost finished. This also follows from the excess pore water pressure in Fig. 4.9a.

The gas content has decreased to one half of its initial value at constant maximum load (see Fig. 4.9b). The input $\sigma_{op}(e_f)$ for this simulation of FY-S5 is indicated by boundary1 in Fig. 4.5a, and is closest to the measured profile. The input $k(e_f)$ relation is similar to the relation that was used for test FY-6 (see Fig. 4.5b), and is equal to a least squares fit of the flow-pump data from tests FY-6 and FY-7 (not treated here). This curve is indicated by "fy-6 simulation" in Fig. 4.5b. Sills & Yuan (1995) showed that the permeability values from flow-pump tests with different gas contents and also with backpressure are very close to the input $k(e_f)$ relation that was used for test FY-S5.

For test FY-S5 it is concluded that the computer simulation is close to the measurement using parameter relations that are within the experimental range. The optimum parameter values are shown in Table 4.3.

4.5.4.3 results for test FY-6

Figures 4.10a and 4.10b show the results for test FY-6. For the optimum computer simulation $\sigma_{op}(e_f)$ indicated by boundary2 was used. $k(e_f)$ was the same as for the previous simulation, i.e. equal to the line indicated by "fy-6 simulation" in Fig. 4.5b, which is a least squares fit of the flow pump data of tests FY-6 and FY-7.

FY-6 and FY-7 were combined as they gave very similar results. The agreement between the simulated and measured sample height and excess pore water pressure is good. Again, the simulated excess pore water pressure at the undrained face can be compared with the measured pore pressure difference, as the hydrostatic component is negligible. The (relative) gas pressure in Fig. 4.10a is deviating significantly from the load, which is related to the difference between the experimental and simulated gas height in Fig. 4.10b. This effect is caused by gas coming out of solution in the water filled chambers on the top and bottom sides of the oedometer, which are not part of the actual oedometer sample.
Fig. 4.10a: loading conditions for FY-6

![Graph showing pressure vs. time with various lines and markers for load, backpressure, gas pressure, pore pressure difference, simulated excess pwp (optimum), and simulation with parameters from fy-s5.]

Fig. 4.10b: (gas) height for test FY-6

![Graph showing height vs. time with various lines and markers for sample height, simulated height (optimum), height with parameters from fy-s5, gas height, simulated gas height (optimum), and hgas with parameters from fy-s5.]
These chambers were not used in test FY-S5, which inhibited the flow-pump testing however. In addition, a simulation was made by using $\sigma_{op}(e_f)$ from the FY-S5 simulation, in order to investigate the sensitivity of the outcome. In Fig. 4.10b it is visible that the sample height from this simulation is clearly less as compared to the optimum simulation of this test. The gas height is very similar to the optimum simulation. In Fig. 4.10a it is visible that the excess pore water pressure is higher, which is logical as the sample is more compressible.

It is concluded that a sensible simulation could be made, that is quite sensitive to changes in parameters.

4.5.4.4 results for test FY-3

Results for the saturated reference test FY-3 are shown in Figures 4.11a and 4.11b. The optimum simulation is in good agreement with the measurements. The input $\sigma_{op}(e_f)$ relation is indicated by “boundary1” in Fig. 4.5a and is equal to the input relation for simulation FY-S5. The input $k(e_f)$ relation is indicated by “FY-3 simulation” in Fig. 4.5b. In order to investigate the sensitivity of the simulation to changes in permeability, also a simulation was made with $k(e_f)$ equal to the input value for the simulation of test FY-S5. It is visible that the excess pore water pressure is much higher, which is caused by the slower consolidation speed due to the lower permeability values. This is also visible in Fig. 4.11b as the sample height decreases more slowly. The final height is the same for both simulations. The overall consolidation behaviour is very similar to the gassy tests, including those with backpressure. It is concluded that the simulation is sensitive to changes in permeability within the range that was found for all tests. The optimum parameter values are shown in Table 4.4.
Fig. 4.11a: loading conditions for test FY-3

Fig. 4.11b: height for test FY-3
4.5.4.5 general interpretation of constant rate of loading tests

When the findings for tests FY-S5, FY-6 and FY-3 are combined, it is clear that the computer simulations are very successful. However, there are significant differences between \( \sigma_{op}(e_f) \) and \( k(e_f) \) from different experiments. In Chapter 2 it was mentioned that the shape of the gas voids significantly affects permeability. From a theoretical analysis it followed that in case the gas voids are flattened with an aspect ratio of 5, the presence of 5% of gas causes a decrease of 17% in permeability (Thomas 1987). When comparing \( k(e_f) \) from tests FY-3, FY-6 and FY-S5, the global decrease in permeability is even larger, i.e. 46%. It is expected that the application of backpressure affects the shape of the gas voids as well, as the cavities contract more under loading conditions, while obtaining the same operative stress level. However, no systematic differences between \( k(e_f) \) relations from tests with and without backpressure were found. The differences between \( \sigma_{op}(e_f) \) and \( k(e_f) \) from different experiments are significant however, which was demonstrated by simulating tests FY-3 and FY-6 with parameters from test FY-S5.

4.6 concluding remarks

In this Chapter the emphasis was on the verification of the assumptions that form the basis of the finite strain theory for gassy sludge. The theory has been implemented numerically in a computer program, FSCongas. As the ultimate aim is to make predictions of the self weight consolidation in deep disposal sites, it is essential to verify the self weight solution. This was done by means of small scale column tests. As the stress range is necessarily limited, a major experimental effort was made to simulate the higher stress conditions by means of constant rate of loading oedometer tests, including backpressure. All tests were successfully simulated by means of the computer program FSCongas, using the same basic assumptions. The parameters that give the optimum simulation are within the experimental range. In case of the constant rate of loading tests independent measurements of permeability were made by means of a flow pump, which confirmed the \( k(e_f) \) relations that were used in the computer simulations.

It followed that unique \( \sigma_{op}(e_f) \) and \( k(e_f) \) relations can be used and that it is likely that the gas voids move with the solids. Even when gas escapes, as in test BIO7, it is reasonable to assume that \( e_g = \text{constant} \), which means that the local volume of gas is proportional to the
solids volume. Differences in $\sigma_{op}(e_f)$ and $k(e_f)$ between experiments occur, which are affected by a number of factors that are difficult to quantify. For example, the bubble shape significantly affects the permeability, as well as the manner in which the initial gassy mud bed was formed. In addition, the experiments have a limited accuracy. No systematic dependence of $\sigma_{op}(e_f)$ and $k(e_f)$ on gas content, defined as $e_g/(1+e_f+e_g)*100\%$ was found. Research is currently executed that comprises the study of sludge with a biogenic gas production by means of oedometer testing. Also Scanning Electron Microscopic images will be made, to investigate the gassy soil structure (SERC-proposal, University of Oxford).

acknowledgements:
The author is thankful to Dr. Sills and collaborators from Oxford University for the useful discussions on the interpretation of the experimental research that is presented here. The author is thankful to the Netherlands Technology Foundation (STW) for sponsoring the main part of this work. In addition, the Ministry of Transport, Public Works and Water Management as well as the British Research Council (EPSERC) are gratefully acknowledged for the allowance they gave to quote results from the research that was funded by them.
Chapter 5 Effect of biogenic gas on consolidation parameters of sludge

5.1 general

In the past, a major effort was spent to develop a practical test, by means of which consolidation parameters could be obtained at low stress levels and with the accuracy required. Several laboratories developed a testing procedure (van Essen & Greeuw 1995, van der Meer et al. 1995, Elprama 1994). These tests were suitable for saturated soils only. It was found that during the filling of a deep disposal site the pore pressures dissipate slowly (Deibel et al. 1996), which implies that the operative stress levels in the main part of the layer are still low, i.e. below 20 kPa. Major settlement occurs in this stage already, determining the storage capacity of the site. In addition, significant quantities of gas were measured, up to 18% volume percentage at atmospheric pressure.

A new testing facility had to be built in order to investigate the effects of gas in this range of low stresses, as existing facilities could not cope with the disturbing effects caused by the presence of gas. In addition, the new equipment should be suitable to test mud with a natural gas production at a broad range of temperatures. Accurate measurements of gas content should be possible, and a distinction has to be made between the fraction of gas that is accumulating in the mud bed and the fraction that is escaping. In addition, the final distributions of water content and gas content against height have to be determined. A major research aim was to investigate whether the consolidation of mud with a biogenic gas production at low stress levels can be described in terms of unique $\sigma_{op}(e_f)$ and $k(e_f)$ relations, which are independent of gas content. Visual inspection of the mud sample at the side walls was thought to be essential.

On the basis of the good experience that was made by means of the HYDCON procedure for saturated sludge (van Essen & Greeuw 1995), a new testing facility, the so called GASCON cell, was developed at Delft Geotechnics in which the gassy mud layer consolidates under the action of a hydraulic gradient. The pressure difference across the mud layer is smaller than 15 kPa, as side wall leakage might occur at higher hydraulic gradients. At first, a series of tests on Ketelmeer mud was performed. The experimental set-up is explained in section 5.2.
5.2 experimental

5.2.1 GASCON set-up and user possibilities

The apparatus is placed in a temperature controlled room. The main part of the set-up is a 25 cm diameter and 1 m height transparent perspex cell in which a mud layer with a maximum thickness of 50 cm can be tested (see Fig. 5.1). The height of the mud layer is measured by means of a laser-reflector system. Two pressure regulated balances can be connected to the top and bottom parts of the cell. The upper part of the headspace is transparent and has a mm-scale in order to follow the accumulation of gas bubbles that escape from the mud layer. Pore pressures are measured at seven heights, with transducer 1 at the top and transducer 7 at the bottom drain (see Fig. 5.1).

Fig. 5.1: GASCON set-up
Pore pressure ports 6, 4 and 2 are located at 2 cm intervals. Before test KET6, two additional pore pressure transducers were mounted at 2 cm intervals from port 5. In the middle of the bottom plate a large diameter (23 mm) total stress transducer is mounted. Temperature is measured at three different places: outside the cell, in the headspace and in the water layer above the sludge.

By means of the GASCON set-up (see Fig. 5.1) three types of experiments can be performed. 1. The first type of test is to measure the gas production under constant atmospheric pressure by means of the gas bladder system. Balance 1 is connected to the gas bladder and balance 2 is not used. Before the gas production measurement, the cell is partially filled with nitrogen gas. The accumulation of gas causes an increase in water height, which is measured by means of a differential transducer. All the gas that is produced causes a flow of gas to the gas bladder. This occurs under nearly constant pressure, since the total volume of gas is large. As the bladder expands, water flows to balance 1. The water height in balance one has to be kept fairly constant. Thus, a distinction can be made between the fraction of the gas that is accumulating in the mud bed, and the fraction that is escaping. In case the gas production is very low, the gas bladder is not needed, as the gas mainly accumulates in the mud. In the head space a small perspex cylinder allows for volume measurement of small amounts of gas that are escaping. In this case, the cell is filled with water and balance 1 is connected to the side wall.

2. The second type of test is a compression/decompression test, by means of which the gas content of the entire sample can be determined. The upper part of the cell is completely filled with water and balance 1 is connected to the cell water. Balance 2 is not used. The gas bladder is not used either. A pressure is maintained on balance 1, which measures the associated water flow. Locally, the change in height of the mud layer can be measured by means of the laser-reflect system. In case gas escapes, this accumulates in the small perspex cylinder on top of the cell.

3. The third type of test is a hydraulic consolidation test. A constant hydraulic pressure difference is applied, which causes the mud to consolidate. The upper part of the cell is completely filled with water. Balance 1 is connected to the cell water and balance 2 is connected to the bottom drain (see Fig. 5.1). The water pressure on top of the mud layer is higher than the bottom pressure, which causes a downward flow. Balance 1 measures the inflow of water, whereas balance 2 measures the outflow of pore water from the mud layer.
The back pressure can be increased up to 150 kPa. In case gas is escaping, this accumulates in the small perspex cylinder on top of the cell. At the end of the test, when consolidation is finished, the bottom drain is closed and the bottom plate can be elevated step by step, in order to extrude the sample layer by layer for water content determination. On each layer a miniature vane test is performed, in order to determine the undrained shear strength. The local gas content can be determined from the water content, volume and weight of the extruded layers. Further specifications of the experimental set-up are given in Schaminee (1996).

5.2.2 Experiments
Initially, two tests have been performed in order to optimise the measurement procedure and the experimental set-up. Next, four tests, KET3 to KET6, have been performed on one single batch of mud. The mud was sampled from a small pit in the Ketelmeer with coordinates X:178240; Y:511798 at the end of February 1996. The gas content was varied by means of temperature regulation. In test KET4 the sample was mixed with a toxic additive, called BES, which stops the natural gas production, but has little influence on the chemical bonds between soil particles. A summary of the experimental conditions is given in Table 5.1 and the mud properties are given in Table 5.2.

<table>
<thead>
<tr>
<th>Test</th>
<th>Initial Density (g/cc)</th>
<th>Average Gas Volume% from Extrusion</th>
<th>Pressure Difference Across Mud Layer (kPa)</th>
<th>Temperature (°C) During Period of:</th>
</tr>
</thead>
<tbody>
<tr>
<td>KET3</td>
<td>1.23</td>
<td>6</td>
<td>2-5-8-10</td>
<td>10 and 20</td>
</tr>
<tr>
<td>KET4</td>
<td>1.25</td>
<td>0</td>
<td>2-5-8-10</td>
<td>10</td>
</tr>
<tr>
<td>KET5</td>
<td>1.24</td>
<td>19</td>
<td>2-5-8-12</td>
<td>20</td>
</tr>
<tr>
<td>KET6</td>
<td>1.25</td>
<td>13</td>
<td>2-5-8-12</td>
<td>10 and 20</td>
</tr>
</tbody>
</table>

The initial sample height was around 30 cm for all experiments, which corresponds to 14.7 liters of mud. At 3 heights white spots of spearswhite clay were injected from the side wall in order to mark the settlement of the solids.
Table 5.2: classification properties for Ketelmeer mud

<table>
<thead>
<tr>
<th>plastic limit (%)</th>
<th>liquid limit (%)</th>
<th>grain sizes (%)</th>
<th>organic content (%) by means of $K_2CrO_4$</th>
<th>$\rho_s$ (g/cc)</th>
<th>$\rho_f$ (g/cc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>39.0</td>
<td>105.9</td>
<td>48.3</td>
<td>79.1</td>
<td>1.1</td>
<td>7.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.1</td>
<td>7.4</td>
<td>2.50</td>
<td>1.00</td>
</tr>
</tbody>
</table>

(*) The liquid limit was determined by means of the Casagrande method (ASTM D4318).

A typical experiment consists of a separate gas production phase and a hydraulic consolidation phase and lasts at least 4 weeks. Compression/decompression tests were performed regularly, in order to determine the amount of gas that was produced. The loading and unloading takes place within a period of one hour. The pressure increment varied between 50 kPa and 100 kPa. Miniature vane tests were performed with a rotation speed of 0.16 turns per minute, which was similar to the value used by Gonzalez & Sills (1997). A column test was performed in parallel to the GASCON tests, in order to measure the accumulation of gas in a mud bed that consolidates under the action of self weight, only. The initial bed height was approximately the same as in the GASCON cell. For tests KET3 and KET4 a small cylinder was used. For tests KET5 and KET6 a cylinder with an internal diameter of 18.8 cm was used.

5.3 results

5.3.1 consolidation behaviour

Results from experiment KET6 are shown as an example in Figure 5.2a to 5.2c. In Figure 5.2a the mud height and the height of the white clay spots are shown during the last phase of the experiment, when hydraulic consolidation occurs. Initially, all white spots follow the surface settlement, which indicates that mainly the bottom part is becoming denser. After 150 hours, the bottom spot moves less than the other spots, which indicates that the middle part of the layer is consolidating as well. Figure 5.2b shows the cumulative discharges and the sludge volume change during the hydraulic consolidation period. From the difference between the cumulative outflow and cumulative inflow the extra volume of gas that has been produced can be obtained. This volume can be added to the initial gas volume. The gas contents thus obtained are shown in Table 5.3. It is also visible in Fig. 5.2b that up to 370 hours the inflow is smaller than the volume change of the mud layer, which means that pore
water is expelled from the mud surface. After 370 hours part of the pore water that had been expelled before is entering the mud again. This means that the chemical composition of the pore water is not seriously affected. In Fig. 5.2c the pore water pressures are shown with reference to pore pressure 1. The height indicated is with reference to the bottom of the mud sample.

The sudden drops in the bottom pore water pressure, i.e. the lowest curve in Fig. 5.2c, indicate the start of the subsequent hydraulic loading steps. The top pore pressures are very close together, as the increase in hydrostatic pressure as a function of depth is almost balancing the decrease in excess pore pressure due to the hydraulic loading. It is visible that the bottom pore pressures show the largest drop, as the local hydraulic gradient in this region is larger. In addition, during the last two loading steps the top pore water pressures are dropping to a larger extent than during the previous loading steps. This means that a larger part of the mud height is significantly consolidating. This is in agreement with the observations made in Fig. 5.2a. Similar results were obtained from the other GASCON tests (Wichman, 1997a).

Fig. 5.2: results from test KET6 during hydraulic consolidation.

(a) height of mud layer and white clay spots
(b) cumulative flow and volume change

(c) pore pressures relative to pore pressure 1 for test KET6

The accuracy of the pore pressure transducers was determined by connecting them to a reference container regularly. It followed that the accuracy is 0.1 kPa. At larger gas
contents the actual accuracy might be less, as the pore pressures are sometimes fluctuating (see the bottom pore pressures in Fig. 5.2c). The worst case was obtained for the test with the highest gas content, i.e. KET5, in which the accuracy of the bottom pore pressure is ±0.5 kPa. The fluctuations in pore water pressures are probably caused by gas bubbles that are blocking the bottom drain. These fluctuations were investigated in more detail by using a sample time of 30 seconds and it was found that the fluctuations occur on a time scale of 15 minutes.

5.3.2 visual inspection of side walls
The sides of the sample were inspected regularly and photographs were taken. In general, after a few days small gas bubbles with a diameter smaller than 0.5 mm became visible. At that time small fissures became visible, that were more or less horizontally oriented. The formation of these fissures is probably related to the production of gas, as fewer fissures were visible in the saturated test KET4. The fissures in test KET4 were mainly located around the injection points of the speswhite spots and the pore pressure ports. During tests KET5 and KET6 fewer gas bubbles were visible in the bottom part of the mud layer. Gradually, the diameter of the bubbles increased to approximately 1 mm and many more bubbles became visible. The length of the fissures increased.

With a gas content as high as 20% (test KET5) the bubbles were still small, i.e. smaller than 1 mm (see Figure 5.3). Hardly any gas escaped from the mud layer. After the final compression tests for KET5 and KET6, a small amount of gas escaped
from fissures in the mud layer. The gas consisted of trains of small bubbles. However, at the side walls larger bubbles escaped, which is not surprising as larger voids had been created at the side wall, due to the sliding of the mud along the wall.

5.3.3 determination of gas content

From KET3, KET5 and KET6 sets of gas production curves were obtained at temperatures of 10°C and 20 °C. Figure 5.4 shows the results at 10°C.

For KET3 two compression/decompression tests were performed at the start of the test and after the self weight period. The results from these are connected with a dotted line in Figure 5.4. The continuous line was obtained from the difference between outflow and inflow.

For test KET6, the production curve was obtained by adding the gas volume from the rise in water level to the initial gas content from the first compression test. It is visible that the tests that were performed at a later date have a smaller gas production rate. The mud was stored at a temperature between 5 and 10°C, at which the gas production probably still takes place.

Fig. 5.4: gas production curves at 10°C
The following assumptions were made for the analysis of the compression/decompression tests (Wichman, 1997a). It was assumed that the gas pressure is equal to pore water pressure 1 plus an atmospheric pressure of 100 kPa. Boyle's law was used to calculate the gas volume at atmospheric pressure from changes in gas volume that were measured by means of the top balance. Dissolution of the gas, consisting mainly of methane, was not taken into account, leading to an overestimate (100 cc to 200 cc) of the gas volume.

If it was assumed that the gas pressure is equal to the vertical total stress plus atmospheric pressure, the gas contents were 2% (relative difference) larger than the gas contents that followed when it was assumed that the gas pressure is equal to pore water pressure 1 plus atmospheric pressure. In Chapter 4 it is shown that the first assumption is reasonable. In this analysis the compliance of the GASCON cell was taken into account, being 30 cc at 100 kPa and 10°C. Most gas volume percentages from the compression/decompression tests are in good agreement, i.e. with an error bound in gas volume % of ±1, with the other measurements of gas content (see Table 5.3). The gas contents from extrusion of the sample have an absolute accuracy of ±1%. The gas contents that were obtained from extrusion tend to be about one percent smaller than the other values. In addition, the gas production rates that followed from the rise in water level in the reference columns were similar.

<table>
<thead>
<tr>
<th>test</th>
<th>gas volume % from outflow - inflow</th>
<th>from compression test</th>
<th>from extrusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>KET3</td>
<td>7.1</td>
<td>9.2</td>
<td>6</td>
</tr>
<tr>
<td>KET5</td>
<td>20.3</td>
<td>19.6</td>
<td>19</td>
</tr>
<tr>
<td>KET6</td>
<td>13.6</td>
<td>13.5</td>
<td>13</td>
</tr>
</tbody>
</table>

Figure 5.5 shows the local gas volume percentages that were obtained for the extruded layers for tests KET3, KET5 and KET6. The average gas volume percentages from extrusion are mentioned in Tables 5.1 and 5.3. An estimate of the accuracy of the local gas contents follows from the saturated test KET4. It follows that the absolute variations are within ±2%. This seems to be consistent with the variation in gas content in Fig. 5.5.
It is visible that the gas content in the top 2 cm layer is lowest for all tests, which might be explained by the presence of an oxidised layer on top of the sludge, and by small amounts of gas escaping. The gas content in the 10 cm below this layer is relatively high. For test KET5, i.e. the test with the highest average gas content of 19%, the gas content in the bottom part is significantly lower. The same is visible to a lesser extent for test KET6. It is likely that fewer gas bubbles had accumulated in the bottom region. The bubbles appeared to be smaller. Fissures that can contain gas bubbles are formed less easily in the bottom layer, because this layer acquires the highest density.

5.4 analysis of parameter relations $\sigma_{op}(e_f)$ and $k(e_f)$.

After one week of hydraulic consolidation at maximum load, the pore pressures hardly dropped and the bottom drain was closed. For the analysis the final pore water pressures were used. Vertical total stress values at the pore pressure ports were calculated by adding the weight of the water layer and mud layer to water pressure one, measured in the overlying water. The total stress measurement at the centre of the bottom plate was not always reliable. The effects of wall friction tend to be large as the height and the diameter of the sample are approximately equal. The total stress measurements indicate that the effect
of wall friction might be as large as 1 or 2 kPa. Close to the cell walls the weight loss due to wall friction is proportional to the shear strength and the adhesion. This was found to be a major effect. It was not possible to correct the total stress values for wall friction.

Operative stresses were calculated at the pore pressure ports by subtracting pore water pressure from the vertical total stress. By means of linear interpolation of the measured data from extrusion suitable values for the total void ratio \( e_{\text{tot}} \) and fluid void ratio \( e_f \) were obtained. The results are shown in Figures 5.6a and 5.6b. In Figure 5.6a the local variation in \( e_{\text{tot}} \) is caused by the inaccuracy of the extrusion. When \( e_f \) is plotted against operative stress (see Fig. 5.6b), the data points reduce almost to a single curve. The differences at low stress levels are mainly due to the inaccuracy in pore water pressure measurements. For test KET4 results from an oedometer test are shown, that was performed on part of the bottom layer. These results are in good agreement with the GASCON results.

In the middle between the pore pressure ports, permeabilities were calculated from gradients in excess pore water pressure and the specific outflow by means of Darcy's law. At the end of consolidation, the specific outflow is almost constant and the value that was used for the analysis was obtained by means of linear regression of the cumulative outflow for the last 20 hours. By means of linear interpolation of the measured data from extrusion, suitable values for the total void ratio \( e_{\text{tot}} \) and fluid void ratio \( e_f \) were obtained. The results are shown in Figures 5.6c and 5.6d. When \( e_f \) is plotted against permeability, the data points reduce almost to a single curve. As the excess pore pressure gradients are small in the top part of the mud layer, the inaccuracy of the pore pressure measurement affects the higher permeability values very much. For test KET4 results obtained from an oedometer test and a constant head test are included, which were performed on parts of the bottom layer. These data are in reasonable agreement with the GASCON data. An attempt was made to calculate permeabilities from the initial settlements in the reference column and the GASCON cell. The settlements in the reference column were much too small, which might be due to wall friction. The GASCON results were affected by the initial compression/decompression test. For test KET6 a permeability value could be obtained, which was much smaller than was expected from Figure 5.6d.

It is visible that all sets of parameter relations have roughly a log-linear behaviour. When plotted as a function of \( e_f \), they are independent of gas content.
Fig. 5.6: parameter relations from GASCON tests

(a) total void ratio against operative stress

(b) fluid void ratio against operative stress
(c) total void ratio against permeability

(d) fluid void ratio against permeability
The undrained shear strength, $C_u$ from the vane-tests is very similar for all tests, which implies that it is independent of gas content. In Figure 5.7 $C_u$ is plotted against operative stress for tests KET3 to KET6, and a reasonable least squares fit could be made ($R^2 = 0.89$). It was found that the shear strength increased significantly in the bottom part of the layer.

**Fig. 5.7: shear strength against operative stress**

5.5 conclusions
The GASCON tests on samples of Ketelmeer mud with a gas content ranging from zero to 20%, can be considered as successful for the following reasons: The gas content and gas production rate were measured accurately. The accuracy is depending on the testing procedure, however. From measurements of height, profiles of excess pore water pressure and cumulative discharge it followed that the hydraulic consolidation behaviour is very similar for all tests. At the end of the tests, the samples were successfully extruded for the determination of profiles of water content, shear strength and gas content. Even at an average gas content as large as 20%, the gas voids seemed to remain fixed in the soil skeleton.

It was found that the relations of fluid void ratio against operative stress and fluid void ratio against permeability are independent of gas content, i.e. they form unique curves. These
observations confirm results that follow from oedometer tests on artificially prepared samples with varying gas content at higher stress levels (Sills & Yuan 1995). In addition, it was possible to make useful observations of the mud structure through the side wall. This has given insight in the escape mechanism of the gas bubbles. The formation of fissures is essential for the gas bubbles to escape. This conclusion is different from the theory as discussed by Wheeler (1991), as soil matrix is not homogeneous, but consists of fissures, that weaken the structure at specific places and that are affected by the amount of gas bubbles. When these results are compared with the column tests on Ketelmeer mud with an artificial gas production (see Chapter 4), it follows that the natural gas production causes fissuring, while the artificial gas production does not. This difference is probably due to the fact that the artificial gas production takes place within a few days, at the time that the soil structure is still weak and behaves more like a fluid. The biogenic gas production takes place at the time that the mud is behaving like a soil, with a small shear strength. In a soil fissures can develop, whereas in a fluid this is not possible.

5.6 further applications of GASCON-test

Other types of mud, such as mud from the Slufter disposal site, have been tested (Greeuw & van Essen 1998). The design of the bottom drain had been altered, in order to collect the gas that is draining from the sample and to determine its volume. These results also suggest that unique $\sigma_{op}(e_f)$ and $k(e_f)$ relations exist independent on gas content. Measurements of biogenic gas production at higher levels of backpressure up to 150 kPa, representing a water depth of 15 meters, are also under consideration.

acknowledgement

This research was done as a part of a joint research project, that is supported by The Netherlands Technology Foundation, The Ministry of Transport, Public Works and Water Management and Delft Geotechnics.
Chapter 6 Sensitivity analysis for a typical disposal site

6.1 general

The computer program FSCongas can be used as a monitoring tool for disposal sites, such as the Ketelmeer depot, which is located in the Ketelmeer and the Slufter depot, which is located at the Maasvlakte. In addition, the program can be used for design purposes. In order to perform a simulation, it is necessary to determine the input characteristics, such as the relation between the operative stress and fluid void ratio, $\sigma_{op}(e_f)$ and the relation between the permeability and fluid void ratio, $k(e_f)$, and the initial distribution of the gas across the bed height. For the temporary Ketelmeer depot these characteristics have been determined, but additional information over a longer period is necessary. The main depot is still under construction. In Chapter 7 simulations are shown for the Slufter site, which exists for 10 years now. At the Slufter several distributions of the gas across the bed height were found. It makes sense to investigate the sensitivity of quantities, such as settlements, bulk density and pore water pressures, to changes in gas distribution and gas content. Some simplified cases for a typical disposal scenario are treated in this chapter. In Chapter 7 these quantities are compared with the measurements from the Slufter site. In addition, the sensitivity of the simulation to changes in $\sigma_{op}(e_f)$ and $k(e_f)$ is treated.

6.2 variation of gas distribution

For a typical disposal scenario a sensitivity analysis for different assumptions for the distribution of gas void ratio $e_g$ versus height has been performed. In all cases, in total 20 meters of Ketelmeer mud, consisting of solids and water, is deposited within 10 years (see Fig. 6.1). In practice, the deposition takes place by means of a diffusor and the deposited mud heap levels off gradually, due to fluid mud flow. The height of the water level is 25m and the bottom condition is drained.

The parameter relations are supposed to be of the following form:

$$\sigma_{op}(e_f) = \sigma_0 \exp(m_1 + m_2 * e_f) \quad \text{and} \quad k(e_f) = k_0 \exp(m_3 + m_4 * e_f);$$

with $\sigma_0 = 1 \text{ kPa}$, $k_0 = 1 \text{ m/sec}$, $m_1 = 9.047$, $m_2 = -2.677$, $m_3 = -24.072$ and $m_4 = 1.776$ (see Chapter 4 for classification of this type of Ketelmeer mud).

The initial fluid void ratio is 4.25, corresponding with $\sigma_{op} \approx 0.1 \text{ kPa}$ and with $k \approx 7E-08$
m/sec. At this stress level, the sludge was observed to be strong enough to contain significant amounts of gas bubbles, but is still in an early stage of consolidation. In addition, it is expected that the fluid mud flow has stopped at this stress level. The specific weights of the solids and water are 25 kN/m$^3$ and 10 kN/m$^3$, respectively.

For cases 1 to 4 the input was as follows:

*case 1:*

case 1 uses $e_g = 0.62 = \text{constant}$, which corresponds to an initial gas content of 10.6%. $e_g = 0.62$ equals the average $e_g$ after compression in case 3, without consolidation.

*case 2:*

case 2 has a linear gas production with a maximum gas void ratio, $e_{g \text{max}} = 0.62$ and a production time, $t^{\text{prod}} = 60$ days. 60 days is observed to be sufficiently long to obtain significant quantities of gas biogenically.

Fig. 6.1: height against time for cases 1 to 4 and saturated case.

*Also the saturated part for case 3 is shown.*
case 3:

Case 3 allows for compression with a gas void ratio, $e_g^{\text{atm}} = 1.5$ at atmospheric pressure, and no dissolution, i.e. Henry’s coefficient $H = 0.0$.

Case 4:

Case 4 allows for compression, dissolution and advection with $e_g^{\text{atm}} = 1.5$ at atmospheric pressure, and $H = 0.041$ (for methane in tap water at $10 \degree C$).

The temperature is assumed to be constant. The initial mass of gas is approximately the same for in cases 1, 3 and 4. In case 4, parts of the dissolved gas leave the mud layer due to advection.

After deposition, the average gas content in case (1) is 12.6%. At that time, the average gas content in case (3) is 11.5%, which is close to the value for case 1. A maximum local gas content of 18.1% was obtained in case (1), which is low enough to assure that the theoretical assumptions (e.g. stagnant gas) still hold. Due to the presence of the water layer, the gas is compressed and $e_g$ is always well below the stability limit $\gamma_g/\gamma_f - 1 = 1.5$ (see Chapter 3).

Cases 1 to 4 can be compared with the saturated case. The saturated calculation has been performed with the same initial amount of solids and pore water.

In Fig. 6.1 the settlement after the deposition period in cases 1 to 4 is smaller than in the saturated case, which indicates that due to the gas the consolidation is slower. In addition, it was found that the height in the saturated case is smaller than the saturated part of the bed height (i.e. total height minus gas height) in the gassy cases. In case 3 this is visible in Fig. 6.1. The average gas content in cases 1 and 3 is similar, which leads to similar surface settlements. Because of dissolution, case 4 has a lower gas content, which gives settlements that are closer to the saturated case. After the deposition period the retardation due to the gas diminishes (see curve “case 3 saturated part” in Fig. 6.1).

Fig. 6.2 shows the variation of $e_g$ across the height directly at the end of the deposition period of 10 years, and after 22.19 years. As the differences in $e_g$ across the bed height are large, the effect of this on local properties, such as fluid void ratio and excess pore pressure has been investigated. In case 4 the in-situ gas content is much lower, due to dissolution.
Fig. 6.2: profiles of gas void ratio for cases 1 to 4

(a) after 10 years

(b) after 22.18 years

In Fig. 6.3 it can be seen that $e_f$ in cases 1 to 4 is significantly larger than $e_f$ in the saturated case, except in the surface layer in case (2). The differences between cases 1, 3
and 4 are limited. For the top part of the sludge layer, $e_f$ in cases 3 and 4 is larger than in case 1. For the lower part of the sludge layer it is the other way around. Larger $e_f$ values indicate that the consolidation has been slower. This behavior is related to $e_g$ as a function of height (see Fig. 6.2). After 10 years, the $e_g$ values in the top part of the sludge layer are larger in cases 3 and 4 than in case 1. Larger $e_g$ values lead to a slower consolidation, resulting in larger $e_f$ values. After 22.19 years, $e_f$ in the top layer is still larger in cases (3) and (4) than in case (1), whereas $e_g$ in case (4) has dropped below the value for case (1) now. In case 3 swell occurred in the top part of the sludge layer. By simply inhibiting this swell, sensible results were obtained. Case (2) is different from case (1) directly after the deposition period, as the gas is still being produced. As $e_g$ in the surface layer is gradually increasing to the limit value of 0.62, consolidation is faster than in case (1), resulting in smaller $e_f$ values. After 22.19 years both cases give the same results.

Fig. 6.3: profiles of fluid void ratio for cases 1 to 4 and saturated case

(a) after 10 years
In Fig. 6.4 pore water pressure profiles after 10 years and 22.19 years of consolidation are shown in the cases 1 to 4 and the saturated calculation. Initially, the excess pore water pressure is significantly lower as in the saturated case. In addition, the pore water pressures are dissipating slower as compared to the saturated case. This can be seen by comparing the maximum excess pore water pressures after 10 years and 22.19 years. The differences between cases 1 to 4 are limited. It is visible that the cases with the largest $e_g$ values dissipate slowest, i.e. cases 1 and 2 are slowest, next case 3 and finally case 4. This is in agreement with the behavior of the $e_f$ profiles, that has been discussed before.

Other quantities, such as bulk density and operative stress, can be derived from these results. The differences in bulk density between all cases are significant, due to the major differences in $e_g$ (see Fig. 6.2). It was found that the upward and downward flow are affected by the distribution of gas across the bed height, as the local discharge is affected by the local gas content. The discharge decreases when locally more gas is present. Simulations with an undrained bottom boundary and different deposition speed gave similar results.
Fig. 6.4 profiles of excess pore water pressure for cases 1 to 4 and saturated case

(a) after 10 years

(b) after 22.19 years
6.3 variation of $\sigma_{op}(e_f)$ and $k(e_f)$

In order to investigate further the effect of gas on the consolidation behaviour, three different types of sludge behaviour have been investigated. It is expected that the retarding effect of the gas, which is visible from the settlements and flow, is different when another type of mud is used. The mud properties are shown in Table 6.1.

Table 6.1: mud properties.

<table>
<thead>
<tr>
<th>sample</th>
<th>PL (%)</th>
<th>LL(*) (%)</th>
<th>grain sizes (%)</th>
<th>organic content (%)(**)</th>
<th>$\rho_s$ g/cc</th>
<th>$\rho_f$ g/cc</th>
</tr>
</thead>
<tbody>
<tr>
<td>sandy (K16)</td>
<td>32.55</td>
<td>52.60</td>
<td>$&lt;2\mu$m</td>
<td>18.09</td>
<td>36.18</td>
<td>30.24</td>
</tr>
<tr>
<td>mixed (KM)</td>
<td>34.55</td>
<td>70.0</td>
<td>$&lt;16\mu$m</td>
<td>24.39</td>
<td>47.34</td>
<td>20.71</td>
</tr>
<tr>
<td>Slufter south</td>
<td>78.2</td>
<td>115.2</td>
<td>$&gt;63\mu$m</td>
<td>31.91</td>
<td>75.99</td>
<td>5.20</td>
</tr>
</tbody>
</table>

(*) The liquid limit was determined by means of the Casagrande method (ASTM D4318).
(**) determined by Delft Geotechnics with the $H_2O_2$ method

Samples KM and K16 originate from the Ketelmeer. “Slufter south” indicates that this sample originates from the south location at the Slufter disposal site. The $\sigma_{op}(e_f)$ and $k(e_f)$ relations for this mud are clearly different (see Fig. 6.5).

The sandiest sample has the largest permeability and the smallest effective stress level at a given void ratio. For this sample the data from two experiments was combined. The data originate from socalled HYDCON-tests (van Essen & Greeuw 1995).

For the sensitivity analysis the same disposal scenario was used as in section 6.2, i.e. with deposition of 20m of mud in 10 years. For the distribution of the gas across the mud bed case 3 was chosen with $e_{atm} = 1.5$ and $H = 0$. This case was chosen for simplicity. An initial operative stress level of 0.1 kPa was chosen. At this stress the fluid mud flow is expected to have stopped. For K16 an initial stress level of 0.5 kPa was chosen for stability reasons. The void ratio at deposition corresponds with a stress level of 0.1 kPa.
The results are presented in Table 6.2. $\Delta h$ is the difference in height as compared to the saturated case, consisting of $h_g$, which is the height increase due to the gas only, and the
height increase due to retardation and loss of driving force. Due to the presence of the gas, the solids weight is less effective, as the solids are connected to the gas voids. In addition, the drainage path lengths are increased. The first effect gives a retardation, but also an increase in final height. The latter effect gives a retardation, only. \( h_g / \Delta h \times 100\% \) is the percentage of the height difference that is taken by the gas. In case \( h_g / \Delta h \times 100\% \) increases, the effect of the gas on consolidation is relatively less.

The differences in \( \Delta h \) between the subsequent samples are significant (see Table 6.2). When comparing Table 6.2 with Table 6.1 it follows that \( \Delta h \) is not systematically depending on the sand content or clay content after deposition. At the end of consolidation \( \Delta h \) decreases when the clay content increases and the sand content decreases. \( h_g / \Delta h \times 100\% \) is not systematically depending on the clay content after deposition, either. At the end of consolidation it decreases when the clay content increases.

Table 6.2: dependence of height difference on mud type.

\( e_g^{alim} = 1.5 \) and \( H = 0 \)

<table>
<thead>
<tr>
<th>mud type</th>
<th>after deposition:</th>
<th>after 200 years:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>height (m)</td>
<td>( \Delta h ) (m)</td>
</tr>
<tr>
<td>sandy (K16)</td>
<td>19.43</td>
<td>4.39</td>
</tr>
<tr>
<td>mixed (KM)</td>
<td>20.13</td>
<td>4.5</td>
</tr>
<tr>
<td>Slufter south</td>
<td>20.65</td>
<td>3.07</td>
</tr>
<tr>
<td></td>
<td>18.55</td>
<td>4.21</td>
</tr>
<tr>
<td></td>
<td>17.49</td>
<td>3.69</td>
</tr>
<tr>
<td></td>
<td>15.33</td>
<td>2.79</td>
</tr>
</tbody>
</table>

It is visible that \( \Delta h \) at the end of consolidation is smaller than after deposition. Partly this is due to the compression of the gas, partly it can be explained by the fact that at the end of consolidation only the loss of driving force is of importance.

For the Slufter mud it was found that the retardation was largest some time after deposition, i.e. around 50 years. In Fig. 6.6 this is visible from the difference between the saturated part of the mud bed, hsat, and the saturated simulation. The retardation is caused by the inhibition of swell in an earlier stage, i.e. around 10 years. Swell occurs due to large gradients in \( e_g \) (see Chapter 3). Swell is inhibited in the top part of the mud layer, giving a
constant fluid void ratio. This means that this part of the mud layer acts as a drain, i.e. equal amounts of water enter and leave this layer. This means that in fact a thinner layer is consolidating, which is faster. Some time after deposition, the whole layer is consolidating again, which is slower. Similar effects were found for KM. In case the deposition speed is higher the effect is stronger.

6.4 variation of gas content

Next, simulations were made with the same disposal scenario, but with variable gas content. Results for Slufter mud are shown in Fig. 6.6 and Fig. 6.7. Fig. 6.6 shows the saturated part of the mud bed, i.e. hsat, for different values of $e_g^{atm}$. Table 6.3 gives the height, hsat, $\Delta h$ and gas content for different $e_g^{atm}$. In Fig. 6.6 it is visible that hsat is relatively larger at higher gas contents than at lower gas contents, i.e. hsat increases more than proportionally. The discharge is seriously affected by the gas content as well (see Fig. 6.7). The upward discharge decreases at higher gas contents. The downflow decreases to a lesser extend. At higher gas contents the decrease in upflow is less than at lower gas contents. The results for the other mud types are similar.

Fig. 6.6: dependence of saturated bed height on atmospheric gas void ratio

mud type: Slufter south
Table 6.3: dependence of height difference on gas content

*mud type: Slufter south*

<table>
<thead>
<tr>
<th>( e_{atm} )</th>
<th>after deposition</th>
<th>gas content (%)(*)</th>
<th>after 200 years</th>
<th>gas content (%)(*)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>height</td>
<td>hsat</td>
<td>( \Delta h )</td>
<td>height</td>
</tr>
<tr>
<td>0</td>
<td>17.58</td>
<td>17.58</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.75</td>
<td>19.07</td>
<td>17.99</td>
<td>1.49</td>
<td>5.7</td>
</tr>
<tr>
<td>1.5</td>
<td>20.65</td>
<td>18.36</td>
<td>3.07</td>
<td>11.1</td>
</tr>
<tr>
<td>2</td>
<td>21.8</td>
<td>18.6</td>
<td>4.22</td>
<td>14.7</td>
</tr>
</tbody>
</table>

(*) The gas content is an average across the mud bed at in-situ pressure.

Fig. 6.7: dependence of flow on atmospheric gas void ratio

*mud type: Slufter south*
6.5 variation of other input variables

For a calculation with FSCongas also the initial void ratio, $eset$, is needed and a proper value for Henry’s coefficient. A sensitivity analysis concerning these quantities was made by Zwang (1997). Both are of importance, but are not mentioned here.

6.6 conclusions

From the simulation of a typical disposal site it is clear that the presence of large gas bubbles in the mud has a significant effect on consolidation. The consolidation is retarded and the final amount of consolidation is less as compared to the saturated case with the same amounts of solids and water. The retardation is largest during deposition, and diminishes gradually until consolidation is finished. It was possible to include compressibility and dissolution of the gas. The same holds for a typical gas production curve. The total gas content was found to be of main importance for predictions of the surface settlement. For predictions of fluid void ratio, bulk density and excess pore water pressure, the distribution of gas void ratio across the height of the mud bed is of importance.

It was found that the effect the gas has on consolidation is different when an other type of mud is used. The inhibition of swell is affecting the retardation. In case the gas content is increased, the retardation is more than linearly increasing as compared to lower gas contents. This was the case for all three mud types.
Chapter 7 Validation of computer calculations

7.1 general
In this Chapter the practical application of results from this research will be considered. By means of the computer program FSCongas predictions can be made of storage capacity, including effects of gas. In addition, the outflow of contaminated pore water can be predicted. Suitable parameters can be obtained from laboratory tests, such as the GASCON-test. In The Netherlands, several large disposal sites are planned or under construction. The Slufter disposal site, which was put in use in 1987, is mainly used for the storage of contaminated sludge from the port of Rotterdam. It is located at the edge of the coast and has a design capacity of 96.4 million m$^3$ (Gemeentewerken 1993a). As many field data, such as profiles of water content, gas content and pore water pressure, are available, the Slufter site can be used to validate the FSCongas computer program. Parameters were determined for mixed samples from several locations by means of the HYDCON-test and GASCON-test. Conclusions will be drawn about the validity of the parameters and the computer program. It is necessary to understand the main processes in the Slufter depot, such as sedimentation, consolidation and the production and transport of gas. The parameters and the modelling scenario that are thus obtained can be used for predictions of the future disposal capacity.

7.2 the Slufter disposal site
The design of the Slufter consists of a pit with a depth of 29 m below sea level, an area at sea level of 163*10$^4$ m$^2$ and an encircling dyke with a height of 24 m. At sea level the sloped side walls take 45% of the surface area. The bottom consists mainly of sand and is considered to be drained. The bottom is not entirely flat, because of sand production. Two fixed measuring poles, called North and South, are available for monitoring purposes (see Fig. 7.1). In 1994 the sludge level is still below sea level and the water level is approximately equal to the sea level. The mud is pumped to the Slufter site through a long pipeline and is deposited by means of a diffusor. The density inside the diffusor varies between 1.03 and 1.28 g/cc (Deibel et al. 1996). The average density is 1.16 g/cc (Gemeentewerken 1993a). The harbour authorities supplied data on the volume of mud that was stored from September 1987 until December 1994. The main part of the mud surface
consists of mud that is deposited by means of almost horizontal fluid mud flow. As the position of the diffusor is changed regularly, the depot is filled more or less equally.

The geometry of the site and the volume of stored mud can be used to calculate the mud height after deposition. Consolidation is not taken into account yet. In order to do this, it has to be estimated which density the mud has after deposition.

Figure 7.1: view from above of Slufter site

From profiles of water content and gas content from the site it is possible to make an estimate around 1.2 g/cc. It is assumed that the operative stress is of the order of 0.1 kPa after the fluid mud flow has stopped and the vertical consolidation starts. At depths below 1 m a shear strength of the order of 1 kPa was measured (Gemeentewerken 1995), which indicates that the operative stress should have a similar value around 1 kPa.
7.3 monitoring data

The monitoring consists of 2 monthly echo soundings and 4 monthly backscatter measurements for the determination of the mud level. At measuring poles North and South profiles of water content, gas content, shear strength, pore water pressure and temperature are determined. Since 1992, i.e. from 5 years after completion onwards, this is done almost every year. Classification properties are available as well. The Harbour authorities supplied us with data sets up to 1994, without the total depth profiles of shear strength (Deibel et al. 1996). More recent data sets are not complete yet. The samples were taken at 1 m (in 1992) or 1.5 m (in 1994) distance. At several other locations samples were taken from the surface layer, in order to determine the density after deposition and gas content. In addition, measurements of shear strength were performed (Gemeentewerken 1995).

The gas content is determined by means of the so called “sludge sampler”, which is equipped with a membrane that can be shut, without losing too much mud and gas (Opstal & van Tol 1993). On site compression/decompression tests can be performed to determine the gas content. It is assumed that the gas pressure minus atmospheric pressure is equal to the applied pressure, i.e. the in-situ vertical total stress. This assumption was proven to be reasonable (see Chapter 4). From a comparison of gas contents from on-site tests and laboratory tests (Gemeentewerken 1993b) it follows that the effect of solubility is limited. Therefore, solubility was not taken into account in the calculation of the in-situ gas contents. After the compression/decompression testing, the samples were transported to the lab under on-site pressure and extruded for the determination of water content and the classification properties. The average specific weights of the solids and pore water are 2.5 g/cc and 1.02 g/cc respectively.

In order to validate the computer calculations, reliable bulk density profiles are needed. The backscatter apparatus was disturbed by the gas and therefore the data are not used. Therefore, the bulk density was calculated indirectly from the water content and in-situ gas content. In addition, vertical total stress profiles were calculated, which can be compared with the pore water pressures. The difference between them gives an indication of the degree of consolidation (Zwang 1997). Due mainly to differences in mud height (see below), it is difficult to compare the vertical total stress and pore water pressure directly. It follows from Zwang (1997) that the difference between both as a function of height is variable, but is smaller than 10 kPa. Close to the bottom sometimes a drop in pore pressure
was observed, which indicates the position of the drained bottom boundary. It is concluded that the degree of consolidation is still low.

The local bottom and top level of the mud layer can be calculated from the changes in pore water pressure at the boundaries. It follows that the bottom level is likely to be at 29 ± 1 m below sea level. Table 7.1 shows the top levels. In addition, the levels that follow from the top sample are shown. The differences in height are significant. The large difference for location North in 1994 is difficult to explain.

Table 7.1: top level of mud layer

<table>
<thead>
<tr>
<th>determined from:</th>
<th>meters below seallevel</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Nov. 1992</td>
<td>North Nov. 1994</td>
</tr>
<tr>
<td>pore pressure</td>
<td>9.0</td>
</tr>
<tr>
<td></td>
<td>8.7</td>
</tr>
<tr>
<td></td>
<td>11.0</td>
</tr>
<tr>
<td></td>
<td>11.5</td>
</tr>
<tr>
<td></td>
<td>7.2</td>
</tr>
<tr>
<td>sludge sampler</td>
<td>11.0</td>
</tr>
<tr>
<td></td>
<td>4.9</td>
</tr>
<tr>
<td></td>
<td>11.5</td>
</tr>
<tr>
<td></td>
<td>8</td>
</tr>
</tbody>
</table>

In addition, the height was calculated from the nuclear density profiles, backscatter profiles and echo soundings (Elprama et al. 1993). From temperature profiles also an indication of the mud height could be obtained.

7.4 computer calculations with FSCongas: derivation of input data

As FSCongas is a one dimensional finite strain computer program, the geometry of the Slufter site had to be simplified. This was done by superposition of 3 rectangular blocks with height $h_{set1}$ to $h_{set3}$ (see Fig. 7.2). $h_{set1}$ to $h_{set3}$ are the mud heights after deposition of the volumes $V_{set1}$ to $V_{set3}$, at an operative stress level of 0.1 kPa (see Table 7.2). $V_{set1}$ to $V_{set3}$ were calculated from the supplied mud volumes, $V_{sup1}$ to $V_{sup3}$ and the void ratio after deposition, $e_{set}$ as follows:

$$V_{setn} = V_{supn} \cdot \frac{(1 + e_{set})}{(1 + e_{sup})} \quad (1)$$

with $n = 1, 2, 3$ and $e_{sup} = 9.57$

$e_{sup}$ is the void ratio of the supplied mud, corresponding to a density of 1.16 g/cc. For this calculation it was assumed that no gas was present, as the amount is around 4%. A choice for $\sigma_{op}(e_f)$ is needed to calculate $e_{set}$. Using data from GASCON-test SLU2 (see Table
7.3), it follows that \( e_{\text{set}} = 4.843 \) at an operative stress level of 0.1 kPa. \( h_{\text{set1}} \) to \( h_{\text{set3}} \) follow from \( V_{\text{set1}} \) to \( V_{\text{set3}} \) as follows:

\[
h_{\text{setn}} - h_{\text{setn-1}} = \frac{V_{\text{setn}} - V_{\text{setn-1}}}{A_n} \quad \cdots (2) \text{ with } n = 1, 2, 3
\]

\( A_n \) is the surface area at the middle of block \( n \) (see Fig. 7.2). The effect of consolidation on the height of the mud block (containing a constant amount of solids) is small and is neglected. \( V_{\text{set0}} \) and \( h_{\text{set0}} \) are zero.

**Figure 7.2: schematic representation of depot model**

From \( h_{\text{set1}} \) to \( h_{\text{set3}} \), the deposition speeds, \( v_{\text{depn}} \), were calculated as follows:

\[
v_{\text{depn}} = \frac{(h_{\text{setn}} - h_{\text{setn-1}})}{(t_n - t_{n-1})} \cdot (1 + e_{\text{set}}) \quad \cdots (3) \text{ with } n = 1, 2, 3
\]

\( t_n \) is the period in which \( V_{\text{supn}} \) is deposited. \( h_{\text{set0}} \) and \( t_0 \) are zero. The results for parameter set SLU2 are shown in Table 7.2. The deposition speed that is calculated here is a global value for the whole Slufter. It was investigated whether the local deposition speed at locations North and South could be similar (Zwang 1997). The local deposition speed was calculated by means of the data from the sludge sampler. It follows that in 1992 the difference between the local deposition speed and the global value is smaller than 10%. In 1994 the local deposition speed at location North was 6 times larger than the global value.
Table 7.2: calculation of deposition speed

for parameter set SLU2 with \( e_{\text{set}} = 4.843 \)

<table>
<thead>
<tr>
<th>Period no. ( n )</th>
<th>period</th>
<th>( V_{\text{supn}} ) (Mm³)</th>
<th>( V_{\text{setn}} ) (Mm³)</th>
<th>( h_{\text{setn}} ) (m)</th>
<th>( t_{n} ) (years)</th>
<th>( v_{\text{depn}} ) (m/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>sept. 1987- mrt. 1989</td>
<td>22.81</td>
<td>12.61</td>
<td>12.3</td>
<td>1.5</td>
<td>14.834</td>
</tr>
<tr>
<td>2</td>
<td>mrt. 1989- nov. 1992</td>
<td>48.57</td>
<td>26.85</td>
<td>23.5</td>
<td>5.2</td>
<td>5.476</td>
</tr>
<tr>
<td>3</td>
<td>nov. 1992- nov. 1994</td>
<td>54</td>
<td>29.85</td>
<td>25.6</td>
<td>7.2</td>
<td>1.899</td>
</tr>
</tbody>
</table>

The global deposition speed (see Table 7.2) was chosen, as the differences between the local height obtained from the sludge sampler and the local height obtained from the pore water pressures are significant (see Table 7.1 and Figure 7.5). The global value is representative for the Slufter as a whole.

The FSCongas computer program uses the void ratios \( e_{\text{dep}} \) and \( e_{\text{set}} \), being the void ratio before and after deposition, respectively. As mentioned before, the main part of the mud is deposited by means of almost horizontal fluid mud flow. \( e_{\text{dep}} \) is assumed to be equal to the void ratio of the supplied mud, \( e_{\text{sup}} \). In addition, \( v_{\text{depn}} \) is needed, being the deposition speed of the saturated material. The gas is added later, as it compresses, depending on the depth.

Table 7.3: parameter relations for samples from the Slufter

with \( \sigma_{\text{op}}(e_f) = \sigma_0 \exp(m_1 + m_2 * e_f) \) and \( k(e_f) = k_0 \exp(m_3 + m_4 * e_f) \) and

with \( \sigma_0 = 1 \) kPa and \( k_0 = 1 \) m/sec

<table>
<thead>
<tr>
<th>name</th>
<th>( m_1 )</th>
<th>( m_2 )</th>
<th>( m_3 )</th>
<th>( m_4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>GASCON SLU1</td>
<td>7.80</td>
<td>-2.19</td>
<td>-28.62</td>
<td>2.87</td>
</tr>
<tr>
<td>GASCON SLU2</td>
<td>7.77</td>
<td>-2.08</td>
<td>-26.41</td>
<td>2.26</td>
</tr>
</tbody>
</table>

Other input data are parameter relations \( \sigma_{\text{op}}(e_f) \) and \( k(e_f) \). These have been obtained by means of data from laboratory tests on Slufter mud. Figure 7.3 shows all data from HYDCON-tests and GASCON-tests. Tests HYDCON North (SN) and South (SS) were performed on mixed samples, that were sampled over the whole vertical in November 1992.
(van Essen & Greeuw 1993). Test HYDCON SC was performed on a mixed sample from the surface layer (van Essen & Greeuw 1994). GASCON-tests SLU1 and SLU2 were performed on mud, which was sampled from the top layer in November 1996. The final gas contents are 1% and 8% for SLU1 and SLU2 respectively (Greeuw & van Essen 1998). Least squares fits were made for tests SLU1 and SLU2 and are shown in Figure 7.3 and Table 7.3. The classification properties are given in Table 7.4.

Figure 7.3: parameter relations for samples from the Slufter disposal site

(a) fluid void ratio against operative stress

![Graph showing fluid void ratio against operative stress](image)

(b) fluid void ratio against permeability

![Graph showing fluid void ratio against permeability](image)
In Figure 7.3 it is visible that the experimental data are within the same range, which is consistent with the fact that the samples have similar classification properties. The mud sample for test SC has a higher liquid limit, which is reflected in the higher operative stress levels and lower permeabilities. As the least squares fits for SLU1 and SLU2 are within the range of measurements, these were used as input relations.

Table 7.4: properties of Slufter samples

<table>
<thead>
<tr>
<th>sample</th>
<th>PL (%)</th>
<th>LL(*) (%)</th>
<th>grain sizes (%)</th>
<th>organic content (%)(**)</th>
<th>( \rho_s ) g/cc</th>
<th>( \rho_f ) g/cc</th>
</tr>
</thead>
<tbody>
<tr>
<td>South (SS)</td>
<td>37.0</td>
<td>115.2</td>
<td>31.9 &lt;2\mu m</td>
<td>76.0 &lt;16\mu m</td>
<td>5.2 &gt;63\mu m</td>
<td>- -</td>
</tr>
<tr>
<td>North (SN)</td>
<td>33.3</td>
<td>116.3</td>
<td>29.1</td>
<td>77.2</td>
<td>4.7</td>
<td>- -</td>
</tr>
<tr>
<td>SC</td>
<td>39.6</td>
<td>145.1</td>
<td>57.5</td>
<td>79.6</td>
<td>10.9</td>
<td>8.86</td>
</tr>
<tr>
<td>SLU1</td>
<td>29.4</td>
<td>110.1</td>
<td>34.0</td>
<td>66.4</td>
<td>8.4</td>
<td>3.1</td>
</tr>
<tr>
<td>SLU2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(*) The liquid limit was determined by means of the Casagrande method (ASTM D4318).
(**) determined by Delft Geotechnics with the \( \text{H}_2\text{O}_2 \) method.

Next, a gas production curve has to be deduced from the monitoring data. Figure 7.4 shows the gas content at atmospheric pressure as a function of depth for locations North and South in 1992 and 1994. It is visible that the gas content in 1994 has hardly increased. The values vary around 10\% to 11\%. It was observed by the Rotterdam public works that gas bubbles escape from the mud layer. For simplicity, it is assumed that the gas content at atmospheric pressure is constant in time. The initial rise in gas content is assumed to be relatively fast, which is confirmed by the high gas content in samples from the surface layer. Corresponding atmospheric gas void ratios, \( e_{\text{g}}^{\text{atm}} \), were calculated and average values were obtained across the bed height. These average values were used as input for the FSConGas calculation. It is assumed that the gas is produced instantaneously.

Table 7.5: overview of average gas void ratios

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>average ( e_{\text{g}}^{\text{atm}} )</td>
<td>0.57</td>
<td>0.47</td>
<td>0.61</td>
<td>0.57</td>
</tr>
<tr>
<td>standard deviation</td>
<td>0.16</td>
<td>0.12</td>
<td>0.31</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Table 7.5 shows the average \( e_{\text{g}}^{\text{atm}} \) values, with the standard deviations. It is visible that \( e_{\text{g}}^{\text{atm}} \) is
approximately constant in time. In case of location North, \( e_g^{\text{sim}} \) was assumed to be equal to the average in 1992, i.e. 0.57. Table 7.6 gives the input data used for the FSCongas simulation for location North with parameter set SLU2. The newest version of FSCongas has a user friendly input menu.

**Figure 7.4:** gas volume percentages at atmospheric pressure

(a) location North

![Graph showing gas volume percentages for North location with data points for 1992 and 1994.](image)

(b) location South

![Graph showing gas volume percentages for South location with data points for 1992 and 1994.](image)
Table 7.6: overview of input data for a FSCongas run for location North
with parameter set SLU2

<table>
<thead>
<tr>
<th>name:</th>
<th>value:</th>
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<tr>
<td>number of layers</td>
<td>1</td>
</tr>
<tr>
<td>number of periods</td>
<td>3</td>
</tr>
<tr>
<td>***deposition period 1: $t_{\text{begin}}$; $t_{\text{end}}$ (years)</td>
<td>0 1.5</td>
</tr>
<tr>
<td>bottom condition; $d$ = drained</td>
<td>$d$</td>
</tr>
<tr>
<td>top condition; $a$ = add</td>
<td>$a$</td>
</tr>
<tr>
<td>$e_{\text{dep}}$; $v_{\text{dep}}$ (m/year); $e_{\text{set}}$</td>
<td>9.57 14.834 4.843</td>
</tr>
<tr>
<td>division time step</td>
<td>4</td>
</tr>
<tr>
<td>***deposition period 2: $t_{\text{begin}}$; $t_{\text{end}}$ (years)</td>
<td>1.5 5.2</td>
</tr>
<tr>
<td>bottom condition</td>
<td>$d$</td>
</tr>
<tr>
<td>top condition</td>
<td>$a$</td>
</tr>
<tr>
<td>$e_{\text{dep}}$; $v_{\text{dep}}$ (m/year); $e_{\text{set}}$</td>
<td>9.57 5.476 4.843</td>
</tr>
<tr>
<td>division time step</td>
<td>4</td>
</tr>
<tr>
<td>***deposition period 3: $t_{\text{begin}}$; $t_{\text{end}}$ (years)</td>
<td>5.2 7.2</td>
</tr>
<tr>
<td>bottom condition</td>
<td>$d$</td>
</tr>
<tr>
<td>top condition</td>
<td>$a$</td>
</tr>
<tr>
<td>$e_{\text{dep}}$; $v_{\text{dep}}$ (m/year); $e_{\text{set}}$</td>
<td>9.57 1.899 4.843</td>
</tr>
<tr>
<td>division time step</td>
<td>4</td>
</tr>
<tr>
<td>height of water layer (m)</td>
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<tr>
<td>$\sigma_{\text{op}}$: $m_1$ and $m_2$</td>
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</tr>
<tr>
<td>$k$: $m_3$ and $m_4$</td>
<td>-26.41 2.26</td>
</tr>
<tr>
<td>specific weights $\gamma_s$; $\gamma_f$; $e_{\text{atm}}$; Henry's coefficient $H$</td>
<td>25 10.2 0.57 0.0</td>
</tr>
<tr>
<td>number of nodes</td>
<td>100</td>
</tr>
<tr>
<td>grid refinement</td>
<td>0.0 1.49 0.0 -0.49 0.0</td>
</tr>
<tr>
<td>time factor; number of time steps; skipout</td>
<td>1.05 100 5</td>
</tr>
</tbody>
</table>

For location South the same input parameters were used, except $e_{\text{atm}}$ being equal to 0.61, i.e. the average in 1992. FSCongas calculates the in-situ gas void ratio by means of Boyle’s and Henry’s Law. The effect of solubility is neglected, i.e. $H=0$, as this was done in the calculation of the experimental values as well.

The parameters “division time step”, “grid refinement”, “time factor” and “skipout” are similar to those in the computer program FSConbag (Greeuw et al. 1992). As they are not of direct relevance, the explanation is omitted here. Also simulations without gas were made for comparison.
7.5 computer calculations with FSCongas: results

Figure 7.5 shows height against time for location North and South.

Figure 7.5: comparison of measured and simulated height

(a) location North

(b) location South
Time $t=0$ corresponds to September 1987. It is visible in Fig. 7.5 that the simulations with SLU1 and SLU2 are reasonably close to the measurements. At location North, the differences between the measurements in 1994, i.e. after 7.2 years, are large (see also Table 7.1). Possibly, more mud was deposited locally than the global deposition indicates. The saturated part of the mud height from the gassy simulation with SLU2 and the saturated simulation with SLU2 are shown as well in Fig. 7.5. As all lines are relatively close, it follows that the effect of the gas on the mud height is limited. The simulation with parameter set SLU1 is close to the simulation with set SLU2.

Figure 7.6 shows the profiles of in-situ gas void ratio for locations North and South. Simulations with SLU1 and SLU2 are shown. Globally, the simulations are in reasonable agreement with the measurements. This means that it is possible to approximate the in-situ gas content by means of a constant gas void ratio at atmospheric pressure, i.e. each part of the layer has the same amount of gas. In 1992, the gas content in the surface layer is higher than average (see Figure 7.4), which is reflected in the differences between the simulations and the experimental gas void ratios in Fig. 7.6. It is visible that for location North in 1994 the difference in height between the top values of the simulation and measurement is large. This is consistent with Fig. 7.5a.
Figure 7.6: in-situ gas void ratios

(a) location North

in 1992

and in 1994
Figure 7.7 shows the profiles of fluid void ratio for locations North and South. Simulations with SLU1 and SLU2 are shown, as well as the saturated simulation with SLU2.
locations North and South the difference between the simulations as a group and the measurements is larger than the difference between the simulations. For location South all simulations are globally in agreement with the measurements. Local variations in fluid void ratio are due to variations in composition, such as sand content (see Fig. 7.8). The bottom layer has a lower fluid void ratio and a higher sand content than the mud layer above. In this layer consolidation is faster than the simulation, which uses average mud properties. The top layer for location South in 1992 has a high fluid void ratio, which might be due to the high gas content. In the surface layer, escaping gas bubbles cause opened channels and weaken the mud structure. At greater depth, the gas is fixed inside the soil skeleton and retards the consolidation. The agreement between the simulations and the measurements for location North is less as compared to location South. In 1994, the bottom layer has a much lower fluid void ratio than simulated. This is caused by the high sand content in this layer (see Fig. 7.8). The top layer in 1992 has a much higher fluid void ratio than simulated. This is probably caused by the high gas content (see Fig. 7.6).
Figure 7.7: in-situ fluid void ratios

(a) location North
in 1992

and in 1994
(b) location South

in 1992

and in 1994
Figure 7.8: height against sand content

(a) location North

(b) location South

Figure 7.9 shows the bulk density profiles for locations North and South.
Figure 7.9: in-situ bulk density

(a) location North

in 1992

and in 1994
(b) location South

in 1992

and in 1994
For location South (see Fig. 7.9b) the simulations with SLU1 and SLU2, including gas, are in reasonable agreement with the measurements. In the bottom region at location South, the measured bulk density is larger than simulated. This is due to the lower fluid void ratios (see Fig. 7.7). The saturated simulation is clearly out of the range of the gassy simulations. The difference between the gassy and the saturated simulation increases as a function of height, as the gas content increases. For location North (see Fig. 7.9a) the agreement between the simulations with SLU1 and SLU2 and the measurements is well in 1992. In 1994, the measured bulk density in the bottom region is much larger than simulated. This is caused by the lower fluid void ratios (see Fig. 7.7). The saturated simulation is clearly out of the range of the gassy simulations. It can be concluded that the gassy simulations with SLU1 and SLU2 are clearly better than the saturated simulation.

Figure 7.10 shows profiles of excess pore water pressure for locations North and South. In 1992, the difference between the gassy simulations with parameter sets SLU1 and SLU2 and the measurements is smaller than 15 kPa. At location North the measurements are larger, whereas at location South it is the other way around. The differences are partly caused by the differences between the simulated mud height and the height that follows from the deviation of the excess pore water pressure from zero. In 1994 this is also the case for location South. In 1994, the agreement at location North is quite good, apart from the bottom layer. It is not clear why the excess pore pressure suddenly increases. In 1994, the measurements show a large spread.

Simulations with SLU1 and SLU2 and the saturated simulation with SLU2 are clearly different. On the basis of the excess pore water pressures alone it is difficult to decide which simulation is the best.

7.6 conclusions

The aim was to validate the computer simulations by means of field measurements from the Slufter disposal site. This was done by means of profiles of water content, gas content, pore water pressures, etc. from the locations North and South. Mixed samples were taken from several locations for parameter determination. It follows that the parameters that were determined by means of the GASCON set-up were appropriate to model the consolidation behaviour in the field. The simulations with both parameter sets SLU1 and SLU2 are in reasonable agreement with the measurements.
Figure 7.10: excess pore water pressures

(a) location North:

in 1992

and in 1994
(b) location South:

In 1992

And in 1994
It was assumed that the consolidation starts at an operative stress level of 0.1 kPa. The gas could be implemented in the model as an average over the height of the measured gas contents at atmospheric pressure. The effect of solubility was systematically neglected, as it is partly included in the measurement of the gas content. The in-situ gas content was calculated by means of Boyle's Law. The deposition speed was obtained from the storage curve and the depot geometry, as given by the harbour authorities. Local differences in grain size and gas content are the main causes for differences between the simulation and the measurements. It was found that the bulk density is very sensitive to the amount of gas present. The scenario and the range of parameters that were thus obtained might be considered as representative for the Slufter site. By means of these data the future disposal capacity can be predicted, assuming that the accumulation of gas remains at the current level. The escape of gas from the disposal site needs further investigation.

7.7 recommendations

The measurement of bulk density and pore water pressure needs improvement. Possibly, both can be combined in one measuring device, in order to save time and to avoid inaccuracies in height. In order to determine the initial conditions for consolidation, additional field measurements of the shear strength and shear stiffness (alike McDermott 1996) are desirable. For the interpretation of these measurements correlations between shear strength and operative stress from the laboratory (Greeuw & van Essen 1998) can be used. The accumulation and escape of gas over longer periods needs further investigation, in order to make long term predictions. The application of a multi-layer consolidation model, including gas, is desirable, as the inhomogenities are large. A difficulty is that consolidation parameters have to be obtained for the subsequent layers. In addition, the sand content has to be limited, estimated below 50%, in order to assure that the gas voids are much larger than the pore sizes.
Chapter 8 Conclusions

The achievements of this research will be discussed in the light of the ultimate aim to make a more accurate prediction of the storage capacity of disposal sites with gassy mud as compared to the past in which an estimate of the gas content was added to a saturated calculation of surface settlement. In addition, the prediction of the outflow of contaminated pore water at the boundaries of the mud layer should be predicted more accurately. For these purposes a finite strain computer program for gassy soil, called FSCongas, has been developed.

8.1 validation and verification

By means of suitable laboratory tests, that cover the relevant stress range inside a deep disposal site, the FSCongas computer program has been validated (see Chapter 4). The tests consisted of column tests with an X-ray facility for density measurement and constant rate of loading oedometer tests. During the column tests, the mud height, water height and profiles of density and excess pore water pressure were measured at suitable intervals. During the oedometer tests the sample height, gas volume and the pore water pressure drop across the sample were measured. The gas pressure was calculated from changes in gas volume. The gassy mud samples were prepared artificially. Also one column test with biogenic gas production was included. These laboratory tests were simulated successfully with input parameters within the experimental range, including self weight consolidation. Creep was not included in the simulation. It was found that the basic assumptions that were made in the finite strain theory (see Chapter 2) for gassy mud are right. This means that the gas voids are much larger than the surrounding void spaces and are fixed inside the soil skeleton. In addition, the consolidation behaviour of the surrounding soil matrix can be described in terms of $\sigma_{op}(e_f)$ and $k(e_f)$, analogous to a saturated soil. No systematic dependence of $\sigma_{op}(e_f)$ and $k(e_f)$ on gas content was found. It was assumed that the gas pressure is approximately equal to the vertical total stress, which is confirmed by results from constant rate of loading oedometer tests. In case of the column test with biogenic gas production, at some stage the gas bubbles were escaping. Gas filled fissures were visible at the side walls and they cause noisy X-ray profiles. It was possible to simulate these conditions successfully too.
The numerical implementation has been verified by comparing different type of discretisations (see Chapter 3). A finite difference method has been compared with a finite element method. Stable and equivalent solutions were found in all cases.

8.2 parameter determination
Chapter 5 deals with the determination of accurate parameter relations $\sigma_{op}(e_F)$ and $k(e_F)$ for mud with a natural gas production. The laboratory device, the so called GASCON-cell can cope with effective stress levels starting from 0.1 kPa up to 15 kPa. In case of a saturated sample, parts of the mud layer can be tested in an oedometer or a triaxial device at higher stress levels. After consolidation under self weight, a hydraulic pressure difference is applied step by step. It was found that the gas content and gas production rate could be determined quite accurately. From 4 tests on Ketelmeer mud with gas contents ranging from 0% to 20% it followed that the presence of gas has no effect on the finite strain parameter relations as functions of fluid void ratio. This implies that parameter relations from saturated tests can be used. The same followed from the special oedometer tests (constant rate of loading tests) in Chapter 4. By means of the GASCON-cell it was possible to make a distinction between the amount of gas inside the mud sample and the amount that escaped. In addition, the distribution of the gas content across the bed height can be determined. This gives insight in the critical gas content that can be achieved in the field. At the side walls fissures were visible that play an important role during the escape of gas. It was found that artificially prepared gassy samples have no fissures, whereas the samples with a natural gas production have.

8.3 sensitivity analysis
Input data to the computer program FSCongas are properties concerning the material, such as the initial void ratio of the supplied mud, the initial void ratio of the settled mud, the gas void ratio distribution at atmospheric pressure (as a function of time), Henry's coefficient and the finite strain parameter relations: $\sigma_{op}(e_F)$ and $k(e_F)$. Other input data concerning the disposal scenario are: deposition rate, boundary conditions, deposition time, water level. A typical input file is given in Chapter 7, Table 7.6. Uncertainties in these input characteristics lead to variation of the output quantities, which can be compared with uncertainties in field measurements.
In order to investigate the sensitivity of the computer calculations to changes in input characteristics, several distributions of gas across the bed height have been used, consisting of $e_g = \text{constant}$, $e_g$ increasing linearly up to a certain maximum, or with $e_g$ calculated from an initial value by means of Boyle's and Henry's Law. In addition, 3 different type of material have been used (see Chapter 6). It was found that the distribution of the gas across the mud bed has a major influence on the bulk density profile and to some extent also on the profiles of fluid void ratio and excess pore water pressure. When the gas content is increased as compared to the saturated case (with the same amount of solids and water) a significant increase in height occurs. At higher gas contents the increase in height is relatively larger. It followed from the simulations that the gas significantly retards the consolidation speed as compared to the saturated case. Also at the end of consolidation the saturated part of the bed height is still larger in the gassy case, which is due to the decrease of the weight of the soil skeleton with gas bubbles as compared to the saturated case. The differences in height depend on the type of mud that was used (see Chapter 6).

8.4 comparison with field measurements

The accuracy of the prediction using parameters from GASCON-tests has been investigated by making a comparison with field measurements from the Slufter disposal site (see Chapter 7). Two parameter sets, i.e. $\sigma_{op}(e_f)$ and $l(e_f)$, were used from GASCON-tests that were performed on mixed samples of Slufter mud with final gas contents of 1% and 8%. It was investigated whether the difference between these parameter sets gives a relevant difference in output as compared to the field measurements. Due to the large depth of the site (29 m), field measurements are difficult to perform and are rather inaccurate. In addition, local inhomogenities occur, which are difficult to deal with in a one dimensional computer program. The disposal site is filled more or less equally, with height differences amounting to a few meters. The field measurements consist of e.g. profiles of water content, gas content and excess pore water pressure from two locations, North and South. Also classification properties have been determined. The bulk density was calculated from the water content and gas content. It was found in Chapter 7 that the agreement between the computer simulations and the field measurements is reasonably good for both parameter sets. It is concluded that accurate predictions should be possible during the life time of this depot. As the amount of gas inside the mud layer stays more or less constant, an
extrapolation can be made. More accurate predictions can probably be made using a simulation for a non-homogeneous deposit, but this will require a large amount of additional input data, which are not available at this moment.

For other, not yet existing, depots it is difficult to predict how much gas stays in the mud layer. From GASCON-tests and column tests on Slufter mud it follows that a volume percentage around 10% of gas stays in Slufter mud (Greeuw & van Essen 1998), whereas 20% stays in Ketelmeer mud (see Chapter 5). The reason for this difference is not clear. In addition, the gas production rates are highly variable (factor 100) for different batches of mud.

From these findings it is concluded that accurate predictions of the storage capacity of disposal sites require sufficient knowledge about the accumulation and escape of gas from the mud that is to be stored. In addition, the initial density at which the consolidation starts has to be estimated and the consolidation properties have to be determined. In case of the Ketelmeer depot, experiences with the filling of the temporary depot are very useful. The FSCongas computer program is a suitable monitoring device, as demonstrated for the Slufter disposal site, by means of which the initial predictions of storage capacity can be adjusted. The time scales in the field are much longer than in the laboratory, which gives a need for good field measurements over a long period.

8.5 future research

Although it is believed that the present prediction is reasonable, future research is desirable to optimise the field measurements. The prognoses is highly dependent on the (local) deposition speed. In order to avoid differences in the local mud height, the field measurements may consist of a direct measurement of bulk density by means of a nuclear transmission probe and an accurate measurement of excess pore water pressure at one time. In addition, measurements of shear strength and shear stiffness are useful for predictions of the bearing capacity and accessibility of the mud layer. Correlations between operative stress and shear strength from laboratory tests, can be used to predict the operative stress values in the field.

In The Slufter site sandy layers were found locally, which can be simulated as the FSCongas computer program can cope with multi-layer calculations. However, the parameter sets and the gas contents ought to be quite similar for the subsequent layers, in order to have a
stable calculation. This limits the applicability. By choosing suitable interface layers, the problem can probably be surmounted. A difficulty is that the parameter sets have to be determined for all subsequent layers. In addition, the sand content has to be limited, estimated below 50%, in order to assure that the gas voids are much larger than the surrounding pore sizes.

In case the field measurements have become more accurate, it makes sense to improve the assumptions that were made in the simulation. For example, the assumption that the gas pressure is equal to the vertical total stress plus atmospheric pressure can be refined at higher operative stress levels. At higher operative stress levels, the strength of the saturated soil matrix that is surrounding the gas voids is larger and therefore, part of the applied stress is carried by the soil matrix.

In addition, the differences between the parameter relations at different gas contents, might be understood by means of Scanning Electron Microscope images. Possibly, differences in void structure can be visible. The application of a backpressure allows for more realistic stress conditions. This can be done in the GASCON-cell, for example.

In addition, swell was inhibited as the computer program uses the same \( \sigma_{\text{op}}(e_f) \) relation during consolidation and swelling. The difference between the both \( \sigma_{\text{op}}(e_f) \) relations may be a factor ten. The computer program can be adapted to include swelling. This swelling is considered to be a real effect (see Chapter 3).

The simulations that were performed were without creep. From column tests and oedometer tests it followed, however, that significant creep may occur. Further research would be needed to include an accurate creep module.

### 8.6 final conclusion

It is believed that the consolidation of gassy mud in large disposal sites can been modelled quite accurately, by taking into account large strains, non-linear permeability, non-linear compressibility and the production and compression of gas.
List of Symbols:

$Cu$  
undrained shear strength

$\Delta_{gas}$  
$-\frac{RT}{V_s} \int_{t_0}^{t} dN(z, t') dt'$

$\Delta z$  
node distance

e  
total void ratio $= e_f + e_g$

c$_f$  
fluid void ratio $= \frac{S_f n}{(1 - n)}$

e$_g$  
gas void ratio $= \frac{(1 - S_f)n}{(1 - n)}$

e$_{g, atm}$  
gas void ratio at atmospheric pressure

e$_{g, max}$  
maximum gas void ratio

$\gamma_f$  
specific weight of fluid

$\gamma_s$  
specific weight of solids

$h_{water}$  
height of free water layer

$H$  
Henry's coefficient

$j$  
time step number

$k$  
permeability

$n$  
porosity $= \frac{e}{1 + e}$ and node number

$N$  
number of moles of gas

$p$  
pore water pressure

$p_g$  
gas pressure (absolute)

$q$  
specific discharge of fluid (excluding gas flow)

$r$  
radius of curvature of gas-water interface and inhomogeneous right hand side term

$R$  
gas constant

$\rho_f$  
specific density of fluid
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
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<tr>
<td>$\rho_s$</td>
<td>specific density of solids</td>
</tr>
<tr>
<td>$S_r$</td>
<td>degree of saturation</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>total vertical stress</td>
</tr>
<tr>
<td>$\sigma_{op}$</td>
<td>operative stress = total vertical stress - pore water pressure</td>
</tr>
<tr>
<td>$t_0$</td>
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<tr>
<td>$t_{in}^n$</td>
<td>time at which node $n$ is deposited</td>
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<td>$t_{prod}$</td>
<td>gas production time</td>
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<td>absolute temperature</td>
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<td>$V_f$</td>
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</tr>
<tr>
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</tr>
<tr>
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<tr>
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<td>height of sludge layer</td>
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<tr>
<td>$z$</td>
<td>material (Lagrangian) coordinate</td>
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<tr>
<td>$z_{max}$</td>
<td>total solids height</td>
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</table>
References:


Ministry of Transport, Public Works and Water Management.


Contract report for the Rijkswaterstaat, The Netherlands, C-CORE Publication 
number 96-C2.


Monte, L.J. & Krizek, R.J. (1976). One dimensional mathematical model for large-strain 

CO-354690/12; in assignment of the Dutch Ministry of Transport, Public Works and 
Water Management.

characterisation and treatment of contaminated dredged material at Antwerpen, 
2.15-2.19.

Ketelmeer. Rotterdam Public Works report No. 95-041/B, in assignment of the 
Dutch Ministry of Transport, Public Works and Water Management.


material disposal site capacity. Dissertation submitted to the Graduate College of 
Texas A&M University.

SE-50766/361/2.

consolidation of saturated clays IV. An overview of nonlinear finite strain 
sedimentation and consolidation. Sedimentation/Consolidation Models: predictions 
and validation (Edited by R.N. Yong & F.C. Townsend). Proc. ASCE Symposium 
San Francisco, American Society of Civil Engineering, 1-29.

Schuurman, E. (1966). The compressibility of an air/water interface mixture and a 
thoretical relation between the air and water pressures. Géotechnique 16, 269-281.


Summary

Consolidation behaviour of gassy mud: theory and experimental validation

In The Netherlands large amounts of polluted sediments have to be stored in deep disposal sites for environmental and nautical reasons. Environmental impact assessment studies are essential to obtain the necessary permits. An important aspect is minimising the release of contaminants to the subsoil. The mud is deposited at a relatively low density, and consolidates under its own weight, starting from the bottom. In this way an isolating layer is formed at the bottom. The storage capacity is determined by the way the mud consolidates. In order to predict the release of contaminated water to the subsoil and the storage capacity of these disposal sites, a proper consolidation program has to be used. As significant quantities of gas were observed to be present in the sediments, the effect of this on the consolidation process has to be taken into account.

This research consists of: the development of a finite strain theory for gassy mud and numerical implementation in an existing saturated finite strain consolidation program. The numerical implementation has to be verified by using different discretisations. Special laboratory tests that were performed at the University of Oxford were used to validate the computer calculations. These tests consist of self weight column tests and oedometer tests on samples with an artificial gas production. During the column tests the density was measured by means of a X-ray system. Column tests were performed on samples with a natural gas production as well. In addition, a practical parameter test, the so called GASCON-test has been developed for samples with a natural gas production. During this test the sample consolidated under the action of a hydraulic gradient, after a short period of self weight consolidation. A sensitivity analysis was performed in order to investigate the interaction between the presence of gas and other soil properties. Several distributions of gas content across the mud height were used. Finally, field measurements from the Slufter disposal site were used to validate the practical applicability of the computer program.

It has been observed that the gas voids are much larger than the void spaces of the surrounding soil skeleton. Except for very soft soils, these voids can be supposed to be fixed inside the soil skeleton. Small minisci bridge the gaps between the surrounding soil
particles. It has been assumed that the gas pressure is equal to the total vertical stress plus atmospheric pressure. This assumption has been confirmed by means of oedometer tests. The finite strain parameter relations, that were obtained from the oedometer tests and GASCON-tests at varying gas content, tend to reduce to a single line, when plotted as functions of fluid void ratio. This implies that parameter relations from saturated tests can be used.

The numerical implementation uses a Finite Difference Method, which gave almost the same results as a Finite Element Method.

Successful simulations were made of self weight column tests, indicating that the self weight solution is reliable. It is visible that the presence of gas retards the consolidation and also the final settlement is less, as compared to the saturated case with the same amount of solids and water. At higher stress levels, the simulations of the oedometer tests were in good agreement with the measurements.

GASCON-tests on Ketelmeer mud with varying gas content, up to 20%, were successful because the gas content could be measured accurately and accurate parameter relations could be obtained.

From a sensitivity analysis of a typical disposal site it follows that the total average gas content is of main importance for predictions of surface settlement. The distribution of the gas across the bed height is of importance for predictions of local properties, such as fluid void ratio and bulk density.

Finally, simulations of the Slufter disposal site were in reasonable agreement with the field data, consisting of e.g. profiles of gas content, water content and pore water pressure. The simulation of the bulk density significantly improved as compared to the saturated simulation. A representative set of parameters and initial conditions have been obtained, in order to make future predictions.

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Samenvatting

Consolidatie gedrag van gashoudend slib:
theorie en experimentele validatie

In ons land is het om nautische en milieuhygiënische redenen noodzakelijk dat er grote hoeveelheden baggerspecie worden geborgen in diepe depots. Milieu-effect-rapportages zijn onmisbaar om de benodigde vergunningen te verkrijgen. Een belangrijk aspect is minimaliseren van het indringen van verontreinigingen in de ondergrond. Het slib wordt met een relatief lage dichtheid gestort, waarna het consolideert onder invloed van zijn eigen gewicht, beginnend op de bodem. Op deze wijze wordt er een isolerende laag op de bodem gevormd. De bergingscapaciteit wordt bepaald door de wijze waarop het slib consolideert. Om het indringen van verontreinigingen in de ondergrond en de bergingscapaciteit van deze depots te voorspellen moet er een geschikt consolidatie-programma worden gebruikt. Aangezien er significante hoeveelheden gas zijn aangetroffen in het slib, moet rekening worden gehouden met het effect dat dit heeft op het consolidatie-proces.

Dit onderzoek bestaat uit: het ontwikkelen van een ‘finite strain’ theorie voor gashoudend slib en de numerieke implementatie in een bestaand verzadigd ‘finite strain’ consolidatie-programma. De numerieke implementatie moet worden geverifieerd door verschillende discretisaties te gebruiken. De computerberekeningen werden gevalideerd m.b.v. speciale laboratoriumproeven, die zijn uitgevoerd aan de Universiteit van Oxford. Deze proeven bestaan uit kolomproeven en oedometer-proeven op monsters met een kunstmatige gasproductie. Tijdens de kolomproeven werd de dichtheid gemeten m.b.v. een röntgenopstelling. Er zijn ook kolomproeven uitgevoerd op monsters met een natuurlijke gasproductie. Daarnaast is er een praktische parameterproef, de zogenaamde GASCON-test, ontwikkeld voor monsters met een natuurlijke gasproductie. Tijdens deze proef consolideerde het monster onder invloed van een hydraulisch drukverschil, na een periode van consolidatie onder eigen gewicht. Er is een gevoeligheidsanalyse uitgevoerd om de interactie van de aanwezigheid van gas en andere bodemeigenschappen te onderzoeken. Er zijn verschillende distributies van het gas als functie van de hoogte gebruikt. Tot slot zijn veldmetingen uit het Slufter-depot gebruikt om de praktische toepasbaarheid van het computerprogramma te valideren.
Er is geobserveerd dat de gasholten veel groter zijn dan de poriën in het omringende bodemskelet. Behalve voor erg slappe bodems, is er verondersteld dat deze gasholten vast zitten in het korrelskelet. Kleine menisci overbruggen de openingen tussen de omringende slibdeeltjes. Er is verondersteld dat de gasdruk gelijk is aan de verticale totaaldruk plus de atmosferische druk. Deze aanname is bevestigd d.m.v. oedometer proeven. De ‘finite strain’ parameter relaties die volgen uit oedometerproeven en GASCON-testen bij verschillende gasgehalten vormen bij benadering één enkele lijn als deze worden uitgezet als functie van het vloeistof-porie-getal. Dit betekent dat parameterrelaties uit verzadigde proeven kunnen worden gebruikt.

T.b.v. de numerieke implementatie is een Eindige-Differentie-Methode gebruikt, die vrijwel dezelfde resultaten gaf als een Eindige-Elementen-Methode.

Uit succesvolle simulaties van de consolidatie onder eigengewicht in kolomproeven volgt dat de eigen-gewichtsoplossing betrouwbaar is. Er volgt dat de aanwezigheid van gas de consolidatie vertraagt en ook is de eindzetting kleiner, in vergelijking met het verzadigde geval met dezelfde hoeveelheden droge stof en water. Bij hogere spanningsniveaus waren de simulaties van oedometer proeven in goede overeenstemming met de metingen. GASCON-testen op Ketelmeer-slib met verschillende gasgehalten, met als maximum 20%, waren succesvol omdat het gasgehalte nauwkeurig kon worden bepaald en nauwkeurige parameterrelaties konden worden verkregen.

Uit de gevoeligheidsanalyse voor een typische depot volgt dat het totale gemiddelde gasgehalte het meest van belang is bij het voorspellen van de zetting. De distributie van het gas als functie van de hoogte is van belang voor lokale eigenschappen, zoals vloeistof-porie-getal en bulkdichtheid.

Tot slot komen de simulaties van het Slufter-depot redelijk overeen met de veldgegevens, bestaande uit o.m. gasgehalte, watergehalte en poriewaterdruk. De simulatie van met name de bulkdichtheid was veel beter dan voor het verzadigde geval. Een representatieve set van parameters en begincondities is verkregen, zodat toekomstige voorspellingen mogelijk zijn.

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