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# Deepwater sample disturbance due to stress relief
# 由于应力释放引起的深水土样扰动性研究

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**Abstract:** Samples taken from seabed soils in deep water are subjected to a large stress relief. This paper presents the comprehensive study results of laboratory tests where deepwater sampling of clay with various amounts of gas dissolved in the pore water has been simulated. Measurements in triaxial and oedometer tests on Lierstranda clays show that the change in void ratio increases linearly with degree of gas saturation $\eta$, when reconsolidated to in-situ stresses. Other measured parameters, like undrained shear strength, strain under peak shear stress, dilatancy parameter and preconsolidation stress, also vary systematically with $\eta$, showing that disturbance increases with $\eta$. The results obtained from the tests have been used to develop recommendations for optimal procedures to store and handle samples containing gas.
**Key words:** deepwater sampling; stress relief; sample disturbances; gas exsolution; laboratory test
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**摘 要:** 从深水海底取得的土样要经受很大的应力释放。模拟孔隙水中溶解有不同含量气体的深水黏土取样过程,对 Lierstranda 黏土进行了一系列三轴和高压固结试验。试验结果表明,自重应力下的孔隙比变化与孔隙水中的气体饱和度 $\eta$ 成线性增长关系。其它测得的土性参数,如不排水强度、峰值应力下的应变、剪胀系数和先期固结压力等均随着 $\eta$ 有规律地变化,显示土样的扰动性也随着 $\eta$ 的增加而增加。据此,本文提出了对可能含有气体的深水土样的最佳贮藏与处置方案。
**关键词:** 深水取样; 应力释放; 土样扰动; 气体逸出; 实验室测试

## 0 Introduction

An increasing tendency for oil and gas exploration and field development in deep waters (e.g. > 500 m) has been seen for the last few years. As a result, there is a need to characterize sea bottom soils for foundation design of anchors for floating structures and to evaluate interaction of pipelines with the seabed. In deepwater field developments there is also an increasing need for geohazard evaluations, including submarine slides, requiring reliable soil parameters. The issue of sample disturbance of soft deepwater soils has thus become very important.

For deepwater soil investigations, it is highly likely that collected samples will be more disturbed than those obtained in shallow water or onshore. The main reasons are that:

(1) Control of the sampling process will be reduced due to large water depth.

(2) The samples may be obtained using simple sampling equipment (e.g. long gravity cores) from general survey vessels.

(3) Stress relief during recovery of the sample causes expansion and disturbance.

(4) Possible gas hydrates can melt, expand and cause disturbance to the soil structure.

These potential disturbances may have a serious influence on the quality of the soil parameters obtained from laboratory test on deepwater samples. This paper reports the study results related to the effects of gas exsolution on soil parameters as measured in the triaxial (Anisotropically Consolidated Undrained Triaxial Compression, CAUC) and odeometer (Constant Rate of Strain Compression, CRSC) tests.

## 1 Basic appoach of study[y]

The term $\eta$ is the degree of gas saturation and it indicates how saturated the in situ pore water is with gas. Detailed definition of $\eta$ was given by Rad et al (Rad and Lunne, 1994).

Gas that is completely dissolved in the pore water of soft clays has normally no effect on its geotechnical parameters. Thus, deepwater soils with moderate amount of gas dissolved in the pore water are expected to behave in situ as if no gas is present. However, when soil samples are taken from seabed up to a ship, a large total stress relief occurs. This stress release can cause gas to come out of solution, expand, and damage the structure of the soil sample.

In order to quantify the effects of sample disturbance due to stress relief and gas coming out of solution, the following approach was used in this study:

(1) Due to the important effect of soil structure, high quality block samples of clay from a well investigated onshore site were used, rather than artificial clay manufactured in the laboratory.

(2) In situ deepwater conditions (corresponding to 1500 m water depth) was simulated by applying a back pressure of 15 MPa to the samples. The pore water that initially had no gas was replaced with pore water with various amounts of dissolved gas by percolating the samples by water with dissolved gas.

(3) Stress relief from bringing the samples to the sea surface was then simulated by releasing the high back pressure.

(4) Triaxial and odeometer tests were carried out on the simulated deepwater samples.

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Table 1 Summary of soil parameters of Lierstranda clay

| Clay | $H$ /m | $w$ /% | $w_L$ /% | $w_P$ /% | $I_P$ /% | $\gamma$/(kN·m$^{-3}$) | OCR* | $s_u/\sigma_{v0}'$ | $K_0$** |
|---|---|---|---|---|---|---|---|---|---|
| Lier-stranda | 12.3 – 16.4 | 34 – 38 | 34 – 40 | 20 – 21 | 16 – 18 | 18.3 – 18.9 | 1.8 – 1.4 | 0.46 – 0.32 | 0.54 – 0.67 |

①* based on CRSC (rapid) tests on block samples; ②** values measured in situ. ③Some tests at 6.1 m and 22.4 m( $I_P$ = 20% and 14%)

(5) Results of triaxial and odeometer tests on samples with 0% gas were assumed to represent undisturbed "in situ" soil behavior.

(6) The effect of sample disturbance due to stress relief of samples containing various amounts of gas in situ could then be found by comparing with results to tests on samples with 0% gas.

## 2 Description of clay tested

One onshore marine soft clay from the site Lierstranda that was well investigated in previous projects was selected. The Lierstranda test site is located just outside the city of Drammen, 35 km south-west of Oslo, Norway. Table 1 summarizes a range of soil parameters for Lierstranda clay tested in this study.

## 3 Critaria to evaluate sample disturbance

Based on previous study of Norwegian Geotechnical Institute (NGI), the measured volume change in CAUC triaxial or CRSC odeometer tests when consolidated back to the in situ stresses, is still the best and most practical parameter for evaluation of sample disturbance. Previously NGI used the volumetric strain (Andresen and Kolstad, 1979)

$$\varepsilon_{vol} = \frac{\Delta V}{V_{TOT}}$$

where $\Delta V$ = change in pore volume when consolidated back to the in situ stresses; $V_{TOT}$ = initial total volume

Later NGI argued that the normalized change in void ratio, $\Delta e/e_0$, should be used. $\Delta e/e_0$ presents the change in pore volume relative to the initial pore volume when consolidated back to the in situ stresses. It is reasonable to assume that a certain change in pore volume will be more detrimental to the particle skeleton as the initial pore volume decreases. It is therefore suggested to use $\Delta e/e_0$ rather than $\varepsilon_{vol}$ when quantifying sample disturbance. Table 2 presents the criteria to evaluate sample disturbance when using $\Delta e/e_0$.

**Table 2 Criteria to evaluate sample disturbance**

| Over consolidation ratio | $\Delta e/e_o$ | | | |
|---|---|---|---|---|
| | Very good to excellent | Good to fair | Poor | Very poor |
| 1– 2 | < 0.04 | 0.04– 0.07 | 0.07– 0.14 | > 0.14 |
| 2– 4 | < 0.03 | 0.03– 0.05 | 0.05– 0.10 | > 0.10 |

It must be mentioned that the sample disturbance criteria proposed above is mainly based on tests on marine clays with plasticity index in the range 10% ~ 55%, water content 30% ~ 90%, OCR = 1~ 4 and depth 0~ 25 m below ground level. For soils with properties outside this range the criteria in Table 2 should be used with caution.

## 4 Test results and evaluations

### 4.1 Effects of sample size and sample height to diameter ratio

The CAUC tests performed on block samples to study the effect of tube sample disturbance were initially carried out on specimens with diameter of 71.4 mm and height to diameter ratio of about $h/D$ = 1.96 (referred to as large specimen in the following). Smaller specimens were used in the present test series in order to reduce the time needed to percolate water with gas through the samples. The small specimens had a diameter of 35.7 mm and a height to diameter ratio of 1.53.

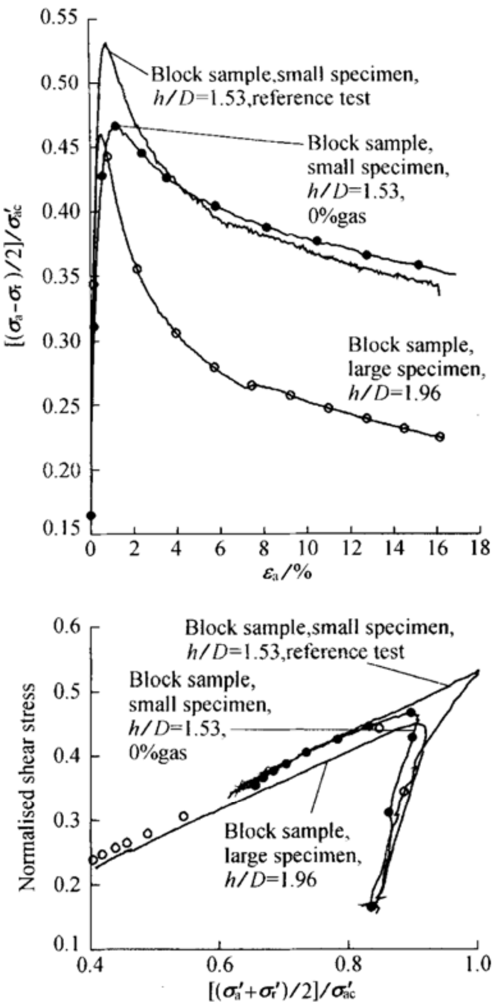


**Fig. 1 Effects of sample diameter, height to diameter ration and percolation of water for CAUC tests on block samples at 13.3 m depth**

Fig. 1 shows the stress strain curves and the stress paths for three triaxial CAUC tests carried out on specimens prepared from a block sample taken at 13.3 m depth. Disregarding the test with percolation of water (with 0%

gas), it can be observed that the peak shear stress for the small specimen is significantly (15%) larger than for the corresponding test on the large specimen. This may be due to the smaller sample (scale effect) and/or the smaller height to diameter ratio in the small specimen.

### 4.2 Effect of pore water percolation

Percolation of a large volume of water through clay specimens may disturb the clay. In order to separate the effect of percolation from the effect of gas exsolution, one test was performed on a small specimen with percolation of water with 0% gas. The result is included in Fig. 1. Comparison with the small specimens without percolation shows that percolation causes some disturbance and reduces the peak shear stress up to 13%.

In order to check the uniformity of the samples after percolation of water with dissolved gas, two sets of CRSC odeometer tests were carried out (one on a specimen prepared from the top of the sample and one from the bottom. The results of all the odeometer tests with $\eta$ = 0, 6, 20, 67 and 100% (at 15 MPa) are shown in Fig. 2. The dashed curves are from the top of the sample and the full lines from the bottom. It can be observed that the top specimens are consistently more disturbed than the bottom ones.

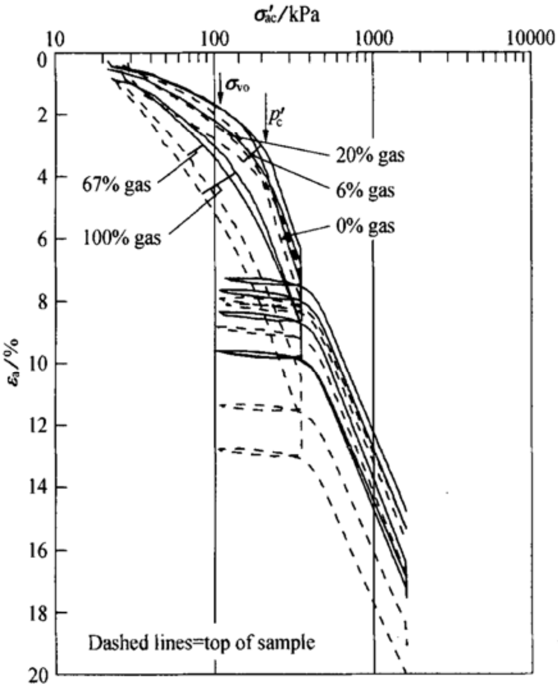


**Fig. 2 CRSC tests at 13.3 m depth on top and bottom specimens with various degrees of gas saturation**

In conclusion, the results referred to above seem to indicate that the results of the CAUC tests are influenced by the height to diameter ratio and/or the size of specimens used for the testing. Further, the effect of percolation of pore water makes some changes to the properties of the clays and also induces some inhomogeneity in the samples. The tests on specimens percolated with water 0% gas will therefore be used as reference for comparison with the tests on specimens with various amounts of gas dissolved in the pore water.

### 4.3 Effects of gas exsolution in triaxial tests

The stress strain curves and the stress paths from triaxial CAUC tests with gas saturation of $\eta$ = 0, 6, 20, 67 and 100% are presented in Fig. 3. The data show a clear effect of the degree of gas saturation, both on the stress strain curve and the stress path. The data in Fig. 3 are from the tests with shortest rest period after the total stress release.

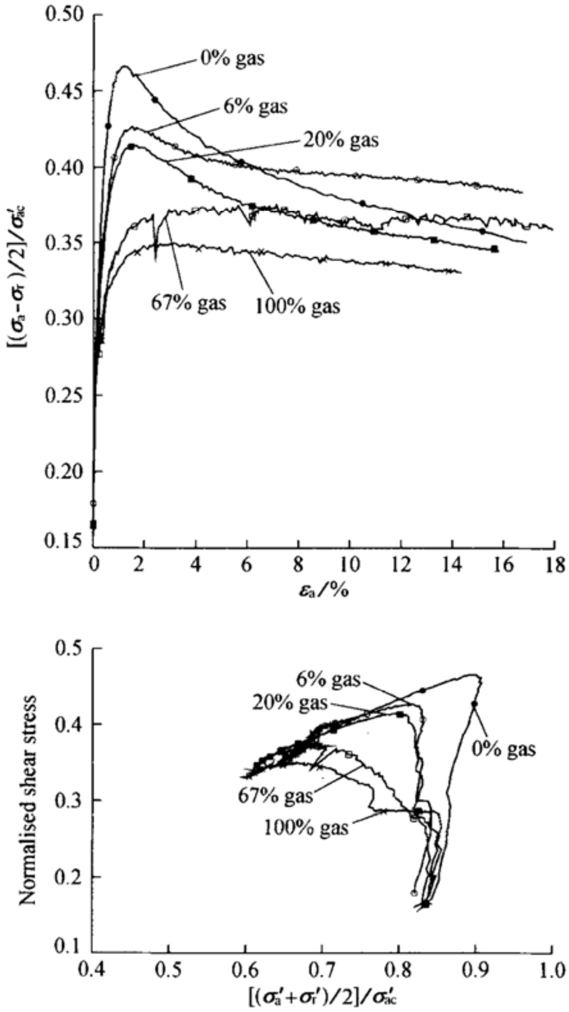


**Fig. 3 CAUC tests on block samples after gas exsolution**

The effect of gas in the pore water is also illustrated in Fig. 4, which shows various measured parameters as functions of the degree of gas saturation. The data points labelled with the duration of the rest period between the total stress release and the mounting in the triaxial testing device. Fig. 4 includes data for tests with various rest periods in addition to the tests presented in Fig. 3.

The results in Fig. 4 show that:

(1) The normalized change in void ratio, $\Delta e/e_0$, when the clay is consolidated back to the in situ stresses, increases linearly with increasing degree of gas saturation.

(2) The normalized shear strength decreases significantly with increasing degree of gas saturation.

(3) The axial strain at peak shear stress increases with increasing degree of gas saturation.

(4) The dilatancy parameter of pore water pressure,

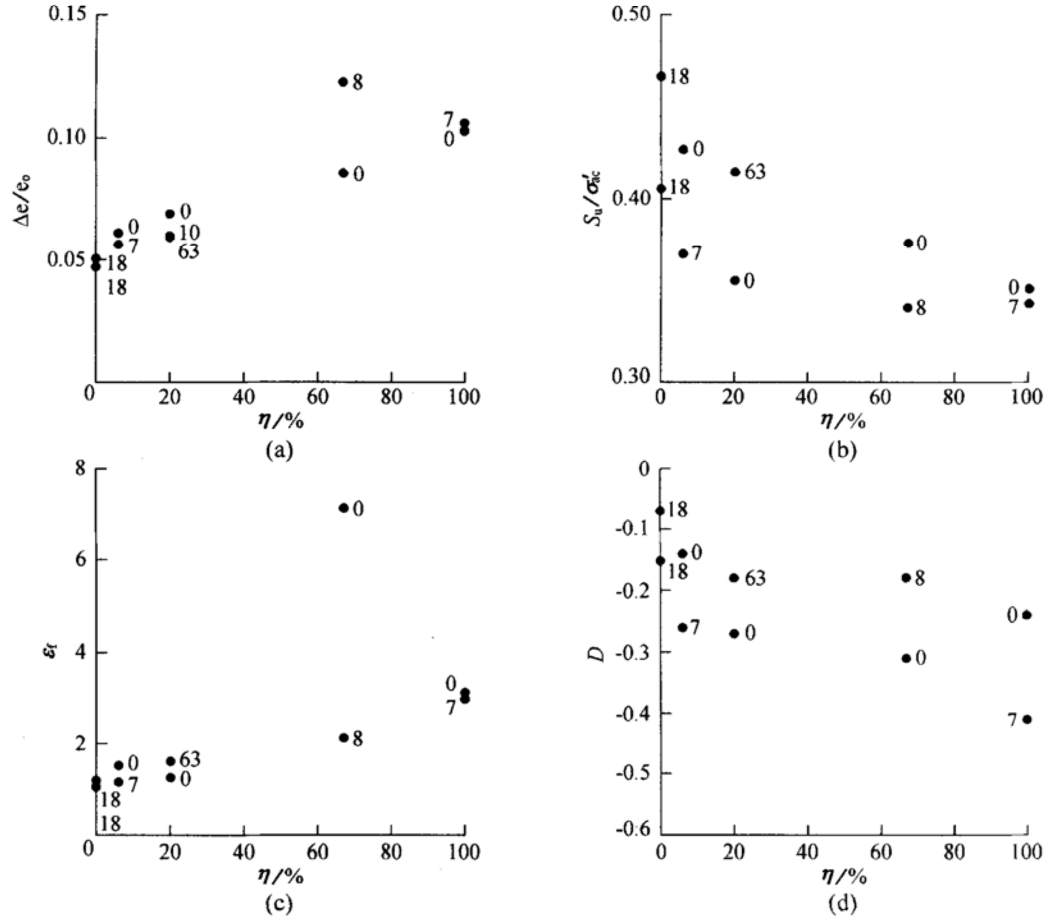


**Fig. 4** $\Delta e/e_0$, $\varepsilon_f$, $s_u/\sigma_{ac}'$ **and D vs degree of gas saturation for CAUC tests**

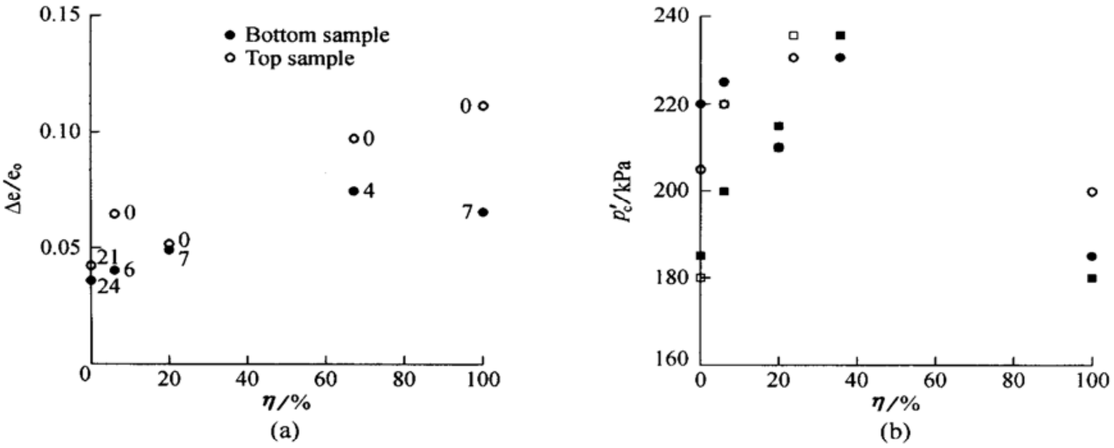


**Fig. 5** $\Delta e/e_0$ **and** $p_c'$ **vs degree of gas saturation for CRSC tests**

$D = (\Delta u - \Delta\sigma_m)/(\Delta\sigma_1 - \Delta\sigma_3)$, decreases with increasing degree of gas saturation, indicating that the clay become more contractive with increasing degree of gas saturation. The plot shows the secant value of $D$ from the initial stress to 2/3 of the peak shear stress.

(5) Most of the test results show that the effect of gas exsolution increases with increasing rest period after stress relief. However, this increase is relatively small, and for some of the tests, the effect of rest period does not have effect on the measured parameters. In some cases, the test with longest rest period even show less disturbance. This indicates that most of the gas exsolution occurs within a few hours after stress relief.

These observations clearly show that sample disturbance will be greater if there is gas dissolved in the pore water, and that the sample disturbance increases with increasing degree of gas saturation.

## 4.4 Effects of gas exsolution in oedometer tests

The results of the odeometer tests on samples with various degree of gas saturation were presented in Fig. 2. The effect of gas in the pore water is also illustrated in Fig. 5, which shows the measured values of $\Delta e/e_0$ and preconsolidation stress, $p_c'$, as functions of the degree of gas saturation.

The results in Fig. 5 show that:

(1) The normalized change in void ratio, $\Delta e/e_0$, when clay is consolidated back to the in situ stresses, is very similar to the results from the triaxial tests. $\Delta e/e_0$ increases linearly with increasing degree of gas saturation.

(2) Tests on clay from the top of sample that was percolated suffer more disturbance than tests from the lower part, as discussed previously.

(3) The preconsolidation stress, $p_c'$, shows some tendency for reduction with increasing degree of gas saturation, but the effect is much smaller than for the triaxial shear strength. This may partly be because $p_c'$ is difficult to determine in tests with significant disturbance, and partly because determination of $p_c'$ is somewhat subjective. Two different methods were used to determine $p_c'$ in this case; the Casagrande method (Casagrande, 1936) and the Janbu method (Janbu, 1969).

## 5 Recommendations on sample handling and storing

Based on the work in this study and also in several consulting projects involving advanced laboratory testing of deep water clay samples, the following recommendations can be made on sample handing and testing procedures:

(1) If it is expected that a deepwater sediment contains gas dissolved in the pore water, it is possible to get an indication of this by doing in situ measurements with DGP (Deepwater Gas Probe), as described by Mokkelbost and Strandvik (1999).

(2) Gas hydrates are very unstable, and soil samples extruded in the laboratory may no longer contain gas hydrates even if they existed in situ. This is because bring samples from seabed to deck means both reduction in pressure and increase in temperature. Therefore samples should be very carefully studied in the offshore laboratory for any signs of gas coming out of solution; including, but not limited to expansion of sample, gas bubbles on sample surface and smell.

(3) An early quantification of sample disturbance can be obtained by doing CRSC tests in the offshore laboratory so that the parameter $\Delta e/e_0$ can be determined.

(4) X- raying of sample tubes or samples waxed in cardboard containers is strongly recommended. Expansion of sample parts can be observed, and the parts of the sample that are least disturbed may be identified for more important laboratory tests.

## 6 Summary and conclusions

Measurements in triaxial and oedometer tests on Lierstranda clays show that the change in void ratio when consolidating back to in situ stresses increases linearly with degree of gas saturation, $\eta$. Other measured parameters, like undrained shear strength, strain to peak shear stress, dilatancy parameter and preconsolidaiton stress, also vary systematically with $\eta$, showing that disturbance increases with $\eta$. Indications are that the disturbance caused by gas exsolution depends on the state of structure prior to gas exsolution. An intact structure can resist the effects of gas exsolution better than an initially disturbed structure. The results also give some indications that the effects of sample disturbance may not be uniquely defined by the normalized change in void ratio, $\Delta e/e_0$, the criteria for sample disturbance. Nevertheless, it is still believed that $\Delta e/e_0$ is a practical and useful parameter to quantify sample disturbance.

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