BESTEMMELSE AV HVILETRYKK (K_0) I NORSKE LEIRER – ANBEFALINGER BASERT PÅ EN SAMMENSTILLING AV LAB-, FELT- OG ERFARINGSDATA.

A revised look at the coefficient of earth pressure at rest for Norwegian Clays

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SAMMENDRAG
Artikkelen presenterer retningslinjer og korrelasjoner for å bestemme hviletrykk (K_0) i norske leire i fravær av stedsspesifikke data. For å evaluere K_0 er det etablert en database med K_0-målinger fra avanserte laboratorieforsøk og fra feltforsøk. Ved hjelp av en rekke regresjonsanalyser ble det utviklet empiriske korrelasjoner mellom K_0, OCR (overkonsolideringsgrad) og I_P (plastisitetsindeks). Resultatene fra regresjonsanalyser gir høy regresjonskoeffisient (dvs. R^2> 0.99). Resultatene viser også at effekten av I_P på K_0 er av mindre betydning enn tidligere antatt. Sammenlignet med de nye resultater i denne studien, synes K_0-diagrammet fra Brooker og Ireland (1965) å gi et mindre pålitelig estimat på K_0.

ABSTRACT
The purpose of this study is to present guidelines and correlations to estimate the coefficient of earth pressure at rest (K_0) in Norwegian clays in absence of site-specific data. A database of K_0-measurements from advanced laboratory tests and *in situ* tests was established. From a series of multivariate regression analyses, it was possible to develop empirical correlations between K_0, overconsolidation ratio (OCR) and plasticity index (I_P). The results of the statistical analyses showed high regression coefficients (i.e. R^2>0.99) and suggest that the plasticity index, has little influence on K_0, at least for Norwegian clays. Compared to the recommended relationships in this study, the well-known K_0 chart from Brooker and Ireland (1965) shows greater variability about the correlation curves and seem to provide less reliable estimate of K_0.

1 INTRODUCTION
The coefficient of earth pressure at rest, K_0, is defined as the ratio of the effective horizontal stress to the effective vertical stress. The K_0-parameter is used in the design of, for example, retaining walls, basement walls, pile foundations, pipelines and tunnels. It is also used for generating initial stresses when using advanced numerical methods to solve complex geo-engineering problems. The results of many types of laboratory tests also strongly depend on the estimate of K_0 (e.g. small strain shear modulus, G_{max}, from resonant column tests, strength and moduli from static and cyclic triaxial tests). Although K_0 can have a significant impact on inputs and calculation results, the reliability in the estimates of K_0 is still uncertain.

Factors potentially affecting the development of the effective horizontal stress (σ'_h) *in situ* may include, for example, earlier stress and strain history, mineralogy, cementation, aging, weathering, pore water fluid, temperature and cementation (Mayne and Kulhawy 1990). The determination of σ'_h is time-consuming and difficult to achieve, both in the lab and in the field. Therefore, over the years geotechnical engineers have relied mostly on empirical relationships to assess K_0. Example of relationships and charts for the evaluation of K_0 include those of e.g.

Jaky (1944), Kenney (1959), Brooker and Ireland (1965), Massarsch (1979) and Mayne and Kulhawy (1990). However, most of these relationships were developed for clay types and soil history which are not necessarily representative of Norwegian conditions. The question is how well do these relationships apply to Norwegian soil conditions.

This paper presents a database of K_0-measurements from laboratory and *in situ* tests collating the results for eight Norwegian clays. A series of multivariable regression analyses were performed on the data in the K_0 database to establish guidelines for a reliable estimation of K_0 in Norwegian clays in the absence of site-specific K_0-data. The available Norwegian K_0-data are also compared to the previously published data from Brooker and Ireland (1965) and the differences are discussed.

2 LITERATURE REVIEW

The coefficient of earth pressure at rest was first introduced by Donath (1891) as the ratio of the horizontal stress to the vertical stress under a condition of zero lateral strain. After the principle of effective stress was introduced, the coefficient of earth pressure at rest, K_0, was defined as:

$$K_0 = \frac{\sigma_h'}{\sigma_v'} = \frac{\sigma_h - u}{\sigma_v - u} \quad [1]$$

where σ_v and σ_h are the total vertical and horizontal stress, u is the *in situ* pore water pressure and σ'_v and σ'_h are the vertical and horizontal effective stress. The next significant work on K_0 was performed by Terzaghi (1920) and Terzaghi (1925) at Robert College in Turkey. In 1925 he reported values of K_0 for yellow residual clay and a blue marine clay of 0.7 from test results with modified equipment.

Kjellman (1936) used a triaxial device to perform one-dimensional compression tests on sand. He found that K_0 was a function of the stress history of the soil. Binnie and Price (1941) developed an apparatus which was intended to measure the variation of lateral pressure over the full range of consolidation for a clay sample subjected to a given vertical load.

Jaky (1944) established a theoretical solution where K_0 was presented as a function of the effective friction angle (φ') of the soil:

$$K_0 = 1 - sin\varphi' \left(\frac{1 + \frac{2}{3} sin\varphi'}{1 + sin\varphi'} \right) \quad [2]$$

A simplified version of Eq. [2] was also presented in presented by Jaky (1944):

$$K_0 = 1 - sin\varphi' \quad [3]$$

The differences between Eq. [2] and [3] are around 8% at low friction angles and 16 % at high friction angles. However, considering the difficulty of making an appropriate choice for the friction angle φ' for a given soil, this approximation was suggested as sufficiently accurate for most engineering purposes (Wroth, 1972).

Brooker and Ireland (1965) performed a comprehensive series of laboratory K_0-tests on five clay soils with well-documented properties (Table 1). In their study, all soils were air-dried and passed through a number 40 sieve before testing on specimens reconstituted at a water content corresponding to a liquidity index of about 0.5. In the oedometer cell, loads were thereafter applied to the sample in increments up to a maximum pressure of 15 MPa. An examination of the Brooker and Ireland (1965) test results showed a form of equation similar to that proposed by Jaky (1944):

$$K_0 = 0.95 - sin\varphi' \quad [4]$$

The results obtained by Brooker and Ireland (1965) also showed that K_0 in clay soils was strongly dependent on the overconsolidation ratio (OCR) and the plasticity index (Fig. 1).

The Brooker and Ireland (1965) plasticity chart for estimating K_0 has been used extensively over the years and is still one of the main reference for the evaluation of K_0 in Norwegian practice. However, it is important to understand that this chart has not been developed for marine clays nor for natural soils. The stresses at which the samples were subjected in the Brooker and Ireland (1965) study were very high and outside the range normally encountered in geotechnical applications. It is therefore of great interest to compare the results obtained by Brooker and Ireland (1965) with K_0 data for clays typically found in Norway.

Table 1: Properties of clay soils used in the Brooker and Ireland (1965) study.

Soil	Test Type	Specific Gravity	Liquid Limit (%)	Plasticity Index (%)	Clay Content (%)
London Clay	K_0 oedometer	2.83	65	38	64
Weald Clay	K_0 oedometer	2.76	41	21	39
Bearpaw Clay	K_0 oedometer	2.76	101	78	59
Chicago Clay	K_0 oedometer	2.80	28	10	36
Goose Lake Flour	K_0 oedometer	2.72	32	16	31

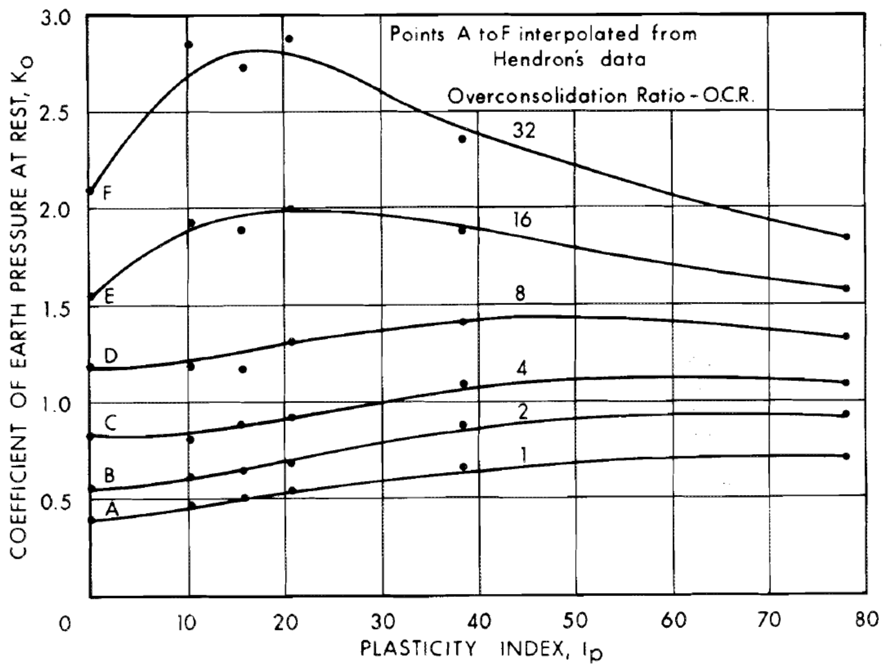

Figure 1: Relationship between K_0, plasticity index (I_p) and overconsolidation ratio (OCR) by Brooker and Ireland (1965).

3 DATA INCLUDED IN THE PRESENT STUDY

A database of K_0, OCR and soil index properties for Norwegian clay soils was compiled in the present study. Both laboratory and *in situ* test results were included in the database. Laboratory results include data from instrumented oedometers and K_0-triaxial test devices with radial strain sensors for the determination of K_0 for zero lateral strain. Field data from Self Boring Pressuremeter (SBPM), Hydraulic Fracture (HF) testing, and Dilatometer (DMT) tests were also added to the database. It is important to realize that neither laboratory nor *in situ* tests are easy to carry out or interpret when assessing K_0. All methods mentioned above have uncertainties. For example, Dyvik et al. (1985) discussed some of the difficulties in assessing K_0 from oedometer cell. Therefore only best estimates from the available test results are used in this study.

An overview of the data and properties available for the eight Norwegian clays included in the present study is given in Table 2.

Table 2: Properties of Norwegian soils used in this study.

Soil	Test Type	Total unit weight (kN/m³)	Liquid Limit (%)	Plasticity Index (%)	Clay Content (%)
Drammen	K_0 oedometer, K_0 triaxial test DMT, HF, SBPM	18.6	54	26	47
Haga	K_0 oedometer, DMT, SBPM	19.0	43	21	45
Troll Plastic	K_0 oedometer	—	62	40	45
Troll Lean	K_0 oedometer	—	32	18	27
Koa	K_0 triaxial test	19.3	30	13	53.3
Onsøy	K_0 triaxial test, DMT, HF, SBPM	16.0	74	41	57.3
Peon	K_0 triaxial test	20.3	41	30	40
Aasgard	K_0 triaxial test	21.8	—	15	—

4 RESULTS FROM REGRESSION ANALYSIS

4.1 Brooker and Ireland (1965) data

The K_0-plasticity index-OCR chart proposed by Brooker and Ireland (1965) from Figure 1, as well as the data sets they used to derive it, are reproduced in Figure 2. The original chart has been developed for soils with plasticity indices ranging from 0 to 78% and OCR values ranging from 1 to 32. Not surprisingly, the proposed boundaries (shown as grey lines) correspond closely to the five sets of experimental data used. Note that the K_0-values used for a plasticity index of zero in the Brooker and Ireland (1965) data (Fig. 1), are those that correspond to a clean sand. These values for sand were excluded from the regression analyses for clay soils presented herein.

The multiple regression analyses performed herein assumed an exponential form equation linking the coefficient of earth pressure at rest with the plasticity index and OCR. The general form of the equation was:

$$K_0 = a\, I_p^b\, OCR^c \qquad [5]$$

where K_0 is the coefficient of earth pressure at rest, I_P is the plasticity index of the clay and OCR is the overconsolidation ratio. The *a, b* and *c* parameters in Eq. [5] are empirical factors describing the best fit from the regression analyses.

The left diagram on Figure 2 present the results of a multivariable regression analysis conducted on the Brooker and Ireland (1965) data set (with the exception of the data points for I_P =0). The best fit regression equation derived from this analysis is shown as well as the lines corresponding to different values of OCR (i.e. the thick colored lines). Although the regression coefficient (R^2) is rather high (i.e. 0.94), it is clear from the figure that the regression curve cannot properly capture the trend of the data points. This is true especially at OCR of 16 and 32, where the fit is clearly poor. There is also an undue influence of the K_0-values at a plasticity index of 0 on the curves drawn by Brooker and Ireland (1965).

Given that OCR values commonly encountered in engineering practice in Norway are less than 8 or 10, it seemed appropriate to rerun the regression analysis without the data corresponding to OCR values of 16 and 32. Limiting the scope in this manner is not believe to constrict design application. The revised regression equation and corresponding curves are shown in the right diagram of Figure 2. In this case, the R^2-value is higher (i.e. 0.97), as evidenced visually by the better fit of the regression curves to the Brooker and Ireland data.

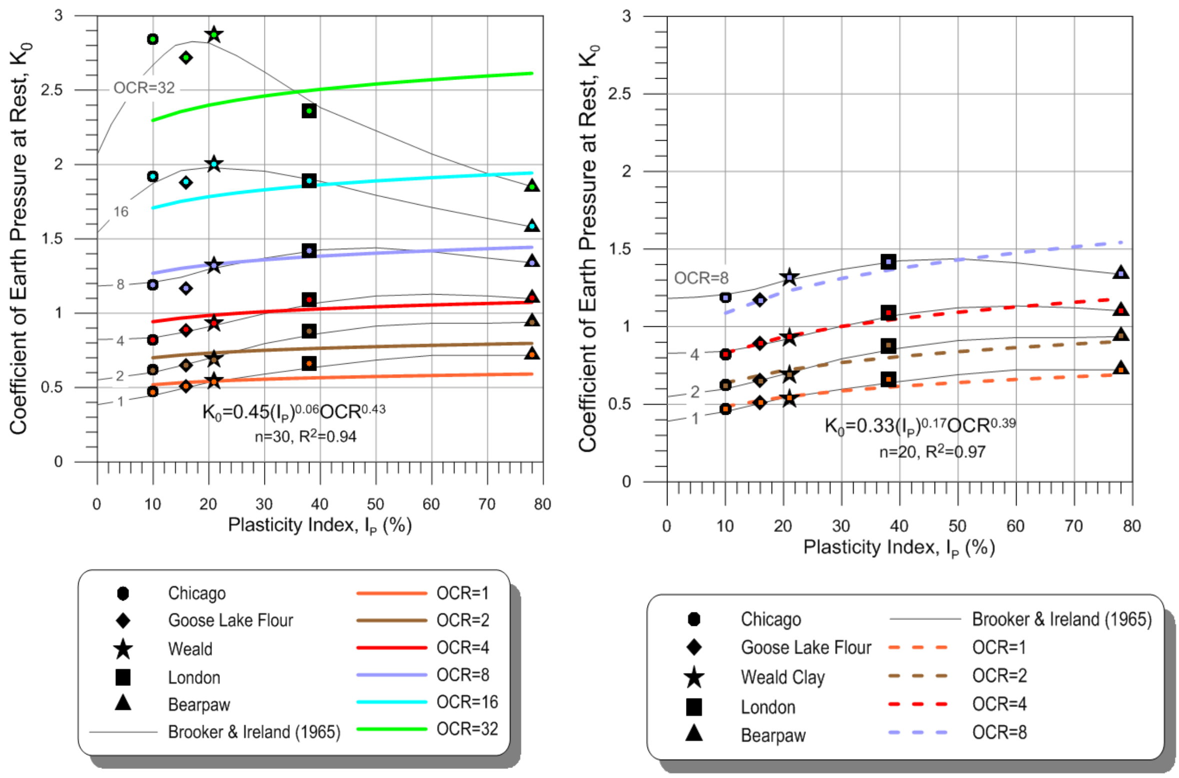

Figure 2: Results from regression analysis on the Brooker and Ireland (1965) data for clays. Left: for OCR = 1-32; Right: for OCR = 1-8.

4.2 Norwegian clays

The database of Norwegian clays includes the results obtained by Dyvik et al. (1985) where K_0-oedometer tests were performed on specimens of Drammen clay, Haga clay and Troll clays (i.e. Offshore clays: Troll lean clay and Troll plastic clay). In addition, more recent data from tests performed at NGI on clays from Koa, Peon, Onsøy and Aasgård were added to the database.

The data collected on Norwegian clays were analyzed statistically in a similar manner as for the Brooker and Ireland (1965) data with the help of multivariable regression analysis. As for the Brooker and Ireland data, Figure 3 shows the data and regression curves for the results of the K_0-oedometer tests reported by Dyvik et al. (1985): the left diagram for OCR-values from 1 to 32, and the right diagram for OCR-values from 1 to 8. The resulting equation and curves from the multivariable regression analysis are also shown on the figures. The R^2-values are very high in both cases ($R^2 > 0.996$), and is significantly higher than those obtained for the Brooker and Ireland (1965) data. Similar to the Brooker and Ireland (1965) data, the goodness of fit seems to degrade with the two highest OCR-values, although to a smaller degree than in Figure 2.

The regressions in Figure 3 show that (i) the exponent on the plasticity index is close to zero, and (ii) the exponent on the OCR is nearly constant at about 0.47, which was not the case for the data in Figure 1.

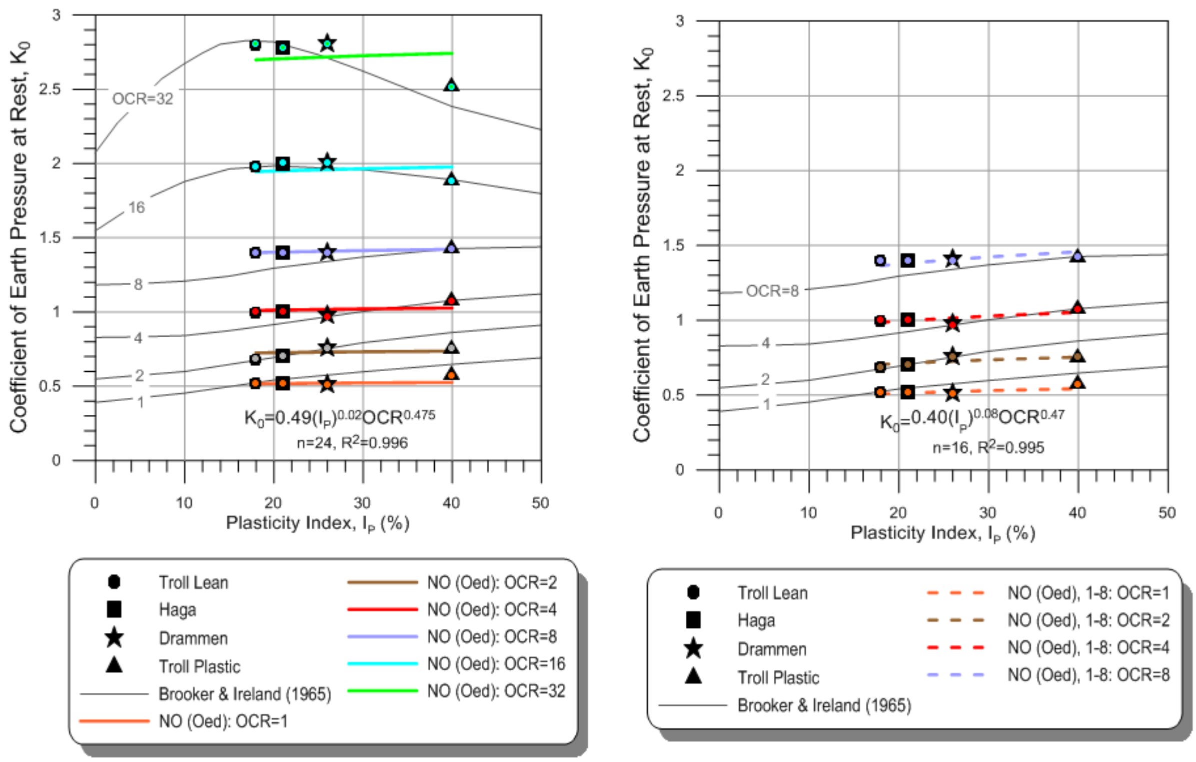

Figure 3: Results from regression analysis on the Norwegian data where K_0 is interpreted from K_0-oedometer tests for clays. Left: for OCR = 1-32; Right: for OCR = 1-8.

The results shown in Figure 3 are promising, but are limited by the fact that they are based on instrumented oedometers alone, and to plasticity indices between 18 and 40%.

Data from K_0-triaxial tests (CK_0UC)[1] on five Norwegian clays (Table 1) were also included and the regression analysis was repeated. The results are shown in Figure 4, in the same manner as Figure 3. Two of the data points were at OCR values of 3 and 4.9. Short regression curves for

[1] CK_0UC = K_0-consolidated undrained triaxial compression tests.

these two intermediate OCR values are included in Figure 4. The resulting regression equation for the combined K_0-triaxial tests and K_0-oedometer tests, for OCR between 1 and 8 was:

$$K_0 = 0.48\, I_p^{0.03}\, OCR^{0.47} \qquad [6]$$

where the R^2-coefficient is still high and equal to 0.976. There are some minor differences in the coefficients and exponents in Figure 3 and the left diagram of Figure 4. However, the overall trend is unchanged. Once again the exponent on the plasticity index is very close to zero, indicating little influence of the plasticity index on the K_0-value.

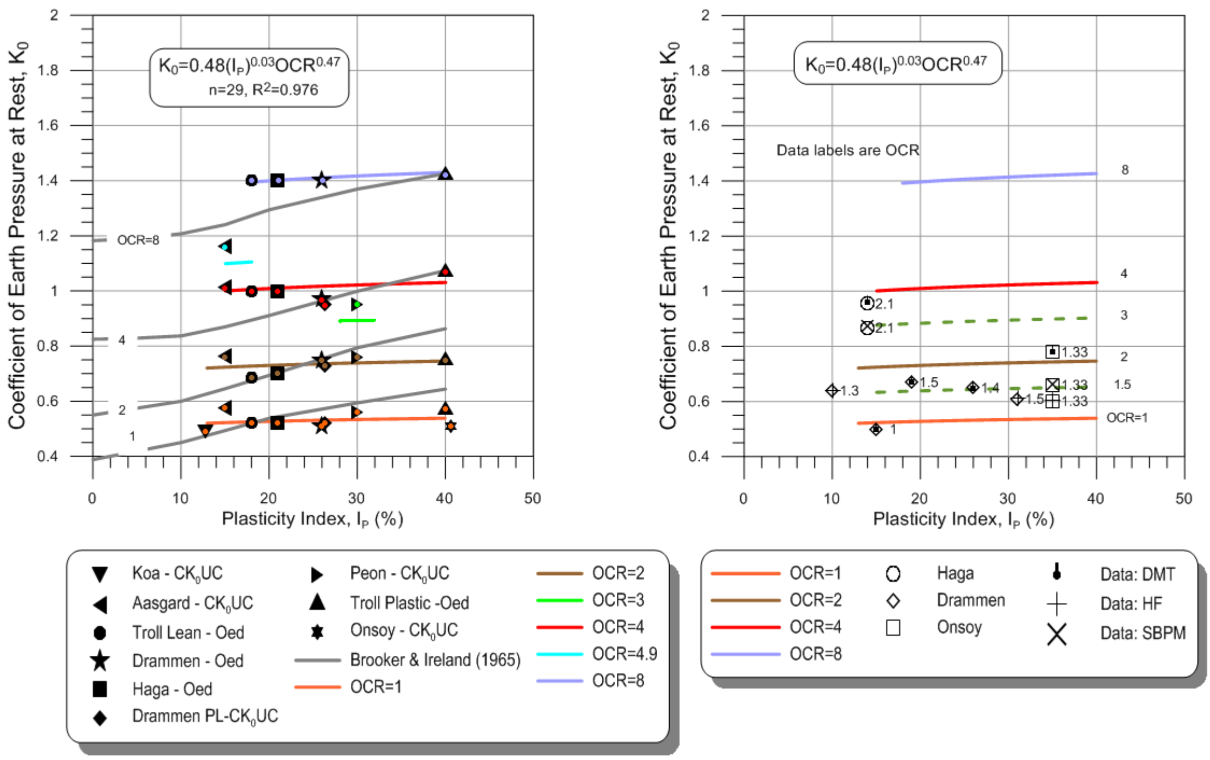

Figure 4: Left: Results from regression analysis on Norwegian clays where K_0 is interpreted from K_0-oedometer tests and CK_0UC triaxial tests; Right: Comparison of laboratory regression lines with K_0 from in situ tests in three Norwegian clays.

Due to the difficulties associated with retrieving high quality undisturbed soil samples and the time and cost constraints associated with running advanced K_0-laboratory tests, researchers have over the years looked into *in situ* methods for estimating K_0. Example of methods for estimating K_0 *in situ* are the self-boring pressuremeter test (SBPM) (Ghionna et al., 1983), the hydraulic fracturing test (HF) (Bjerrum and Andersen, 1972) and the dilatometer test (DMT) (Marchetti 1980).

Interpreted *in situ* values from DMT, HF and SBPM tests at the Haga site (Dyvik et al. 1985), Drammen site (Lacasse and Lunne 1979) and Onsøy site (Lunne et al., 2003) are shown on the right diagram of Figure 4. The *in situ* test results on this figure are overlain with the regression curves in the left diagram of Figure 4. Additionally, regression curves for OCR of 1.5 and 3 were included. The agreement is generally good for sites that are normally to slightly overconsolidated (i.e. Onsoy and Drammen).

The K_0 *in situ* data for the Haga site, which consists of a highly overconsolidated clay, is larger than values determined in the laboratory. The reasons for this are difficult to pinpoint but could be related to i) uncertainties in the *in situ* measurements; ii) the interpretation of the *in situ* tests, and/or iii) K_0 *in situ* is for a reloading phase of the soil whereas the K_0-measurements in the laboratory were for 1st unloading after reaching a maximum loading stress. Also, the Haga tests were run at relatively shallow depth, possibly in the top dry crust, where the material may be unsaturated.

5 DISCUSSION

Results from multivariable regression analyses on eight Norwegian clays with plasticity index between 13 and 41% suggest a simpler and more reliable relationship than the Brooker and Ireland (1965) data for the evaluation of K_0 based on OCR and I_P. A discrepancy can be observed between the best statistical fit of the Norwegian data and the previous results published by Brooker and Ireland (1965) (Figure 4). For low plasticity clays (I_p = 15%), the Brooker and Ireland (1965) relationship seems to underestimate K_0 by as much as 17% (when the regression curves are used as reference). For plastic clays (I_p = 35-40%), the inverse occurs and the Brooker and Ireland (1965) relationship can overestimate K_0 of Norwegian clays also by a factor of up to 17%, at low overconsolidation ratios. The reasons for the observed discrepancy may be in part attributed to e.g.:

- The Brooker and Ireland (1965) K_0 charts were developed for a wide range of clay types and soil history which are not necessarily representative of Norwegian conditions.
- The Brooker and Ireland (1965) relationships were influenced by data for sands (data at I_p = 0%).
- The stresses at which the samples were subjected in the Brooker and Ireland (1965) study were very high and outside the range normally encountered in geotechnical applications.
- The test results reported in Brooker and Ireland (1965) were performed in the 50's and 60's on instruments with limited possibilities compared to present day technology.

The results by Brooker and Ireland (1965) showed that the K_0 depended on OCR and I_P of a given clay (Fig. 1). Others, such as Kenney (1959) and Massarsch (1979), also presented relationships between K_0 and I_P for Canadian and Swedish clays, respectively.

The regression analyses for eight Norwegian clays in this study show much less influence of plasticity index, I_P, on K_0. For all practical purposes, the regression lines shown in Figures 3 and 4 are nearly flat showing little influence of I_P, and the I_P exponent from the regression analyses is close to zero. Regression analyses were also performed on the Norwegian clay database between K_0 and OCR only. The best fit was given by the following equation:

$$K_0 = 0.53OCR^{0.47} \quad [7]$$

The results of this regression analysis, shown on the left diagram in Figure 5, show that all of the K_0-laboratory data on the eight Norwegian clays fall within ±5% of Eq. [7]. A similar analysis was performed on the Brooker and Ireland (1965) data and the results are presented on the right diagram in Figure 5. In this case the difference in measured and estimated K_0 are larger than for the Norwegian clays and falls within a ±15% interval.

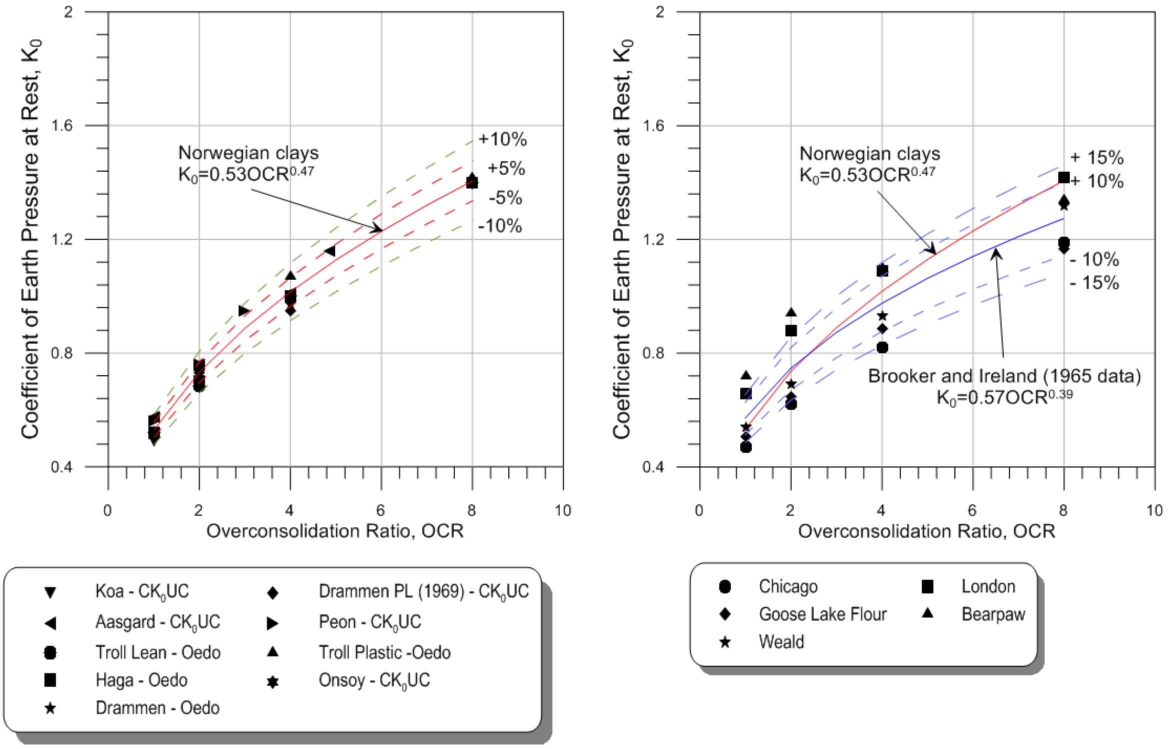

Figure 5: Results from regression analysis between K_0 and OCR only. Left: Norwegian clays data with OCR value from 1-8; Right: Brooker and Ireland (1965) data also with OCR value from 1-8.

6 CONCLUSIONS AND RECOMMENDATIONS

The purpose of this study was to present guidelines and correlations to assist geotechnical engineers in estimating the coefficient of earth pressures at rest (K_0) for Norwegian clays. For this, a database of K_0 measurements from advanced oedometer and triaxial tests and standard geotechnical engineering properties was established. The database allowed a comparison of K_0 data with the charts proposed by Brooker and Ireland (1965). The main findings and recommendations of this study are:

- The results from multivariable regression analyses on the Norwegian clay database suggest simple relationships for the evaluation of K_0 based on OCR and I_P. The results of the regression analyses show a very high regression coefficient.
- The Brooker and Ireland (1965) charts were developed for a wide range of clay types and soil history which are not representative of conditions in Norway. In low plasticity clays, the Brooker and Ireland (1965) charts underestimate K_0, while they overestimate K_0 in highly plastic clays.
- Results from K_0-tests in the laboratory and *in situ* have been compared and seem to match well for normally to slightly overconsolidated clays. However, large differences are observed for the highly over consolidated clays such as Haga.
- The Norwegian clays show a generally flat relationship between K_0-OCR and I_P. The influence of I_P on K_0 seems to be negligible and much less than previously anticipated.
- Based on the results from multivariate regression analyses, it is recommended to use equations [6] and [7] for the estimation of K_0 in Norwegian clays.

In general, it is also recommended that engineers consider all available data when estimating the value of K_0, including available relationships and site-specific geotechnical data. The use of correlations in geotechnical engineering should be limited to the conditions for which they were developed and calibrated. The recommendations presented in this paper should be used in conjunction with the engineer's own experience and engineering judgment. The conclusions drawn apply to Norwegian clays with plasticity index up to 45%. One should verify the regression curves for clays with higher plasticity. For this purpose, the database also contains datasets for high quality K_0-values reported in the literature. This will be the next step in the investigation.

In the near future it is recommended to assess the impact of K_0 on, for example, the behavior of clay material in the triaxial tests and on the assessment of small strain stiffness in the laboratory. Results from such study will contribute to an improved understanding of the impact of the coefficient of earth pressure at rest on specific geotechnical problems.

7 ACKNOWLEDGEMENTS

This work was part of the strategic research project SP8-GEODIP at NGI with fuding from The Research Council of Norway. The authors would like to thank the many colleagues at NGI who helped assembling the large dataset in the laboratory and in the field, and those who helped with discussion of the data.

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