

INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING



This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:

<https://www.issmge.org/publications/online-library>

This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.

In-situ stresses in overconsolidated clays relative to depth

Contraintes 'in-situ' en argiles sur-consolidées (en fonction de profondeur)

K. SCHETELIG, Darmstadt, FRG

E. FRANKE, Darmstadt, FRG

SYNOPSIS In a 300 m thick Tertiary sequence of clays at Frankfurt the horizontal in situ stresses were investigated in function of depth by pressuremeter and laboratory tests. The earth pressure was directly measured by a MENARD probe. K_0 -values determined by these tests complied at least approximately with overconsolidation ratios OCR obtained by oedometric tests with samples from corresponding depths of 5-40 m. The results indicate K_0 -values dependent on depth as expected, reaching 1-2 at the surface and decreasing to $(1 - \sin \varphi) = 0,6$ at 40-50 m depth. The soil mechanical and geological conditions at Frankfurt are compared with the London clay. At Frankfurt a maximum overburden of 120 m in the average can be re-constructed by stratigraphical methods; in London a higher overburden has to be assumed on account of jointing and random fissures.

AIM

At Frankfurt numerous high-rise buildings and tunnels were constructed which affect the sub-grade up to depths of 40 m. For computations of the deformation behaviour the development of appropriate models is necessary which describe the subsoil by a reasonable system of parameters, one of which is K_0 dependent on depth.

In the London basin under similar geological conditions K_0 -values of 3-4 were measured close to the surface which decrease with depth (SKEMPTON 1961, BURLAND 1982). Corresponding investigations were performed at Frankfurt, too. The relation between K_0 , OCR and depth is shown schematically on Fig. 1. Close to the surface K_0 may exceed 1 due to the reduced vertical load relative to the maximum overburden and K_0 may reach a maximum value K_p . With increasing depth K_0 decreases in dependence on OCR (therefore named $K_{0(oc)}$) finally approaching $K_{0(nc)} = 1 - \sin \varphi$ remaining constant for depths being great in comparison with the overburden eroded in the geological past.

The aim of the investigation was to study in the Frankfurt subsoil the dependence of K_0 on depth approximated by

$$K_{0(oc)} = K_{0(nc)} \sqrt{OCR} = f(z) \quad (1)$$

following e.g. SCHMIDT (1966), ALPAN (1967). Geological and soil mechanical methods were used for this investigation independently in order to compare the results of both. The Frankfurt area yielded favourable conditions for this program, because the maximum height

z of the overburden in the geological past could be evaluated by means of a stratigraphic, paleogeographic and tectonic analysis. The 300 m thick formation is well known and scarcely faulted. Orogenesis or any folding has never taken place, an ice cover never existed and any other disturbances, e.g. dissolution of salt or gypsum in the deeper subsoil do not occur.

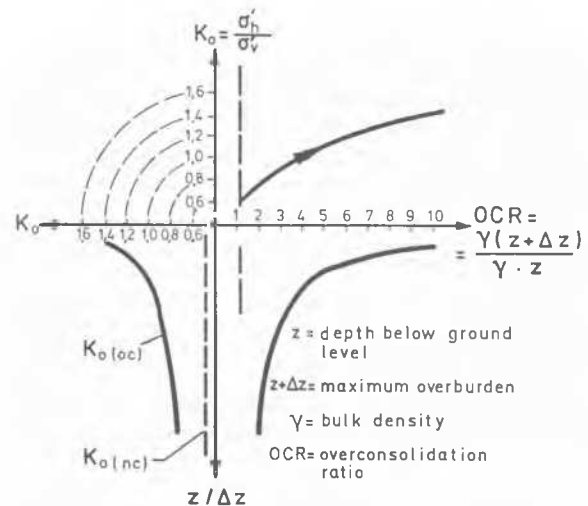


Fig. 1: Relation between K_0 , OCR and Depth

DETERMINATION OF $K_0 \left(\frac{1}{OCR} \right)$ BY PRESSUREMETER TESTS

The horizontal in-situ stress σ_h' shown on Fig. 3a could be directly measured and using the known vertical component $\sigma_v' = \gamma z$

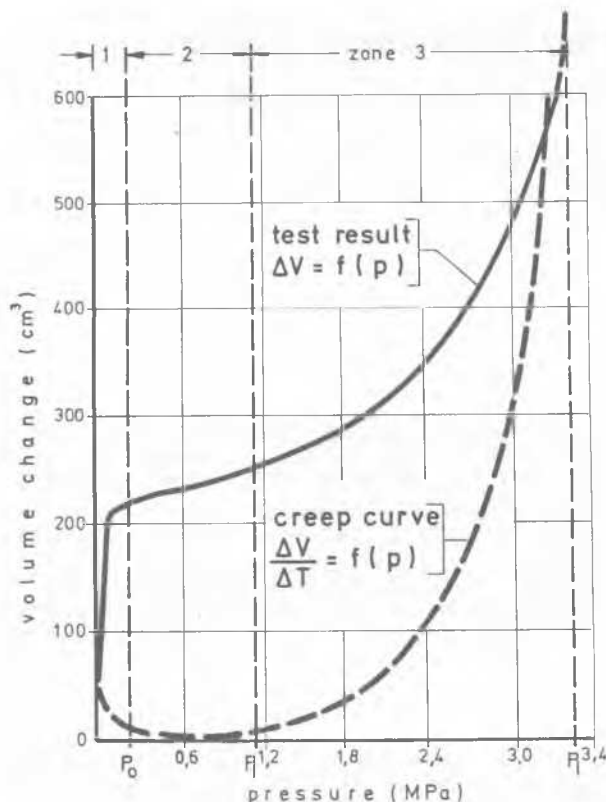


Fig. 2: Typical Test Result of Pressuremeter Tests

$$K_o^{(1)} = \frac{\sigma_h'}{\sigma_v'}$$

was derived (see Fig. 3b). Point p_o of Fig. 2 can be identified as horizontal stress σ_h' (after MENARD 1957, BAGUELIN et al (1978)). At p_o a sharp bend indicates that the stress release of the borehole wall is "repaired". Therefore, further displacements meet with considerably increasing resistance ($p > p_o$).

This procedure yields realistic results in stiff clays (WROTH 1976). The point p_o in question (Fig. 2) can be controlled by drawing the creep velocity in relation to each load increment Δp . At that point where the creep velocity reaches its minimum, $p = p_o$ is indicated too. K_o -values increased towards the surface and exceeded 1 up to maxima of about 2.

DETERMINATION OF $K_o^{(2)}$ USING OCR FROM OEDOMETRIC TESTS

It is well-known that the determination of the maximum geological overburden by the load-settlement-curve of compression tests is difficult and uncertain. Mostly a distinct break between first- and re-loading cannot be recognized. The maximum overburden can be more precisely determined by the relation of the creep

velocity in secondary compression (see Fig. 4). Of course in the zone of $\sigma_{v, max}$ extremely small and uniform load increments are to be used.

In this way the observed (obs OCR)-values were determined for samples of the same depths, for which $K_o^{(1)}$ was measured by pressuremeter tests.

COMPARISON OF THE RESULTS OF PRESSUREMETER AND OEDOMETRIC TESTS

From the $K_o^{(1)}$ -values of Fig. 3b the (cal¹ OCR)-values of Fig. 3c and from the (obs OCR)-values of Fig. 3c the $K_o^{(2)}$ -values of Fig. 3b were calculated using equ. (1). In addition (cal² OCR)-values were calculated by

$$\text{cal}^2 \text{ OCR} = \frac{(z + \Delta z) \gamma}{z \gamma'} \quad (2).$$

The corresponding curves were drawn in Fig. 3c, assuming tentatively different values for the height of the geological overburden Δz .

From Fig. 3c it can be seen that max. $\gamma \Delta z$ must have been between 0.5 and 1.2 MPa, i.e. for $\gamma = 20 \text{ kN/m}^3$ the maximum overburden comes to 25-60 m and for $\gamma' = 10 \text{ kN/m}^3$ to 50-120 m. But it has to be mentioned that the piezometric water level and its variation in the geological past is not known. Additionally, it has to be reported that σ_v' -values in equation (2) were calculated on account of $\gamma = 20 \text{ kN/m}^3$ and that the pressuremeter tests were done in a dry borehole. More information and more research are necessary concerning these questions.

Deviations between $K_o^{(1)}$ and $K_o^{(2)}$ in Fig. 3b and between the (obs OCR)- and the (cal¹ OCR)-values in Fig. 3c, respectively, characterize the accuracy previously reached. This accuracy may be improved by a greater number of tests. However, the results previously obtained already allow the conclusion that K_o at about 40 m depth approaches 1 - $\sin \varphi$ and increases towards the surface up to 1-2. In the following these soil mechanical test results are compared with geological investigations.

COMPARISON OF GEOLOGY BETWEEN THE FRANKFURT AND LONDON BASIN

At Frankfurt the Permian bedrock is overlain by a 300 m thick sequence of clays, silts, sands and limestone intercalations, deposited under marine, brackish and freshwater conditions. The general geological conditions and the tectonic setting are to be seen from Fig. 5-8. The paleogeography and the earth history could be well re-constructed because of local tilting, some flexures, various horst and graben structures and a permanent erosion during Upper Tertiary and Quaternary so that formations of different ages are exposed close together.

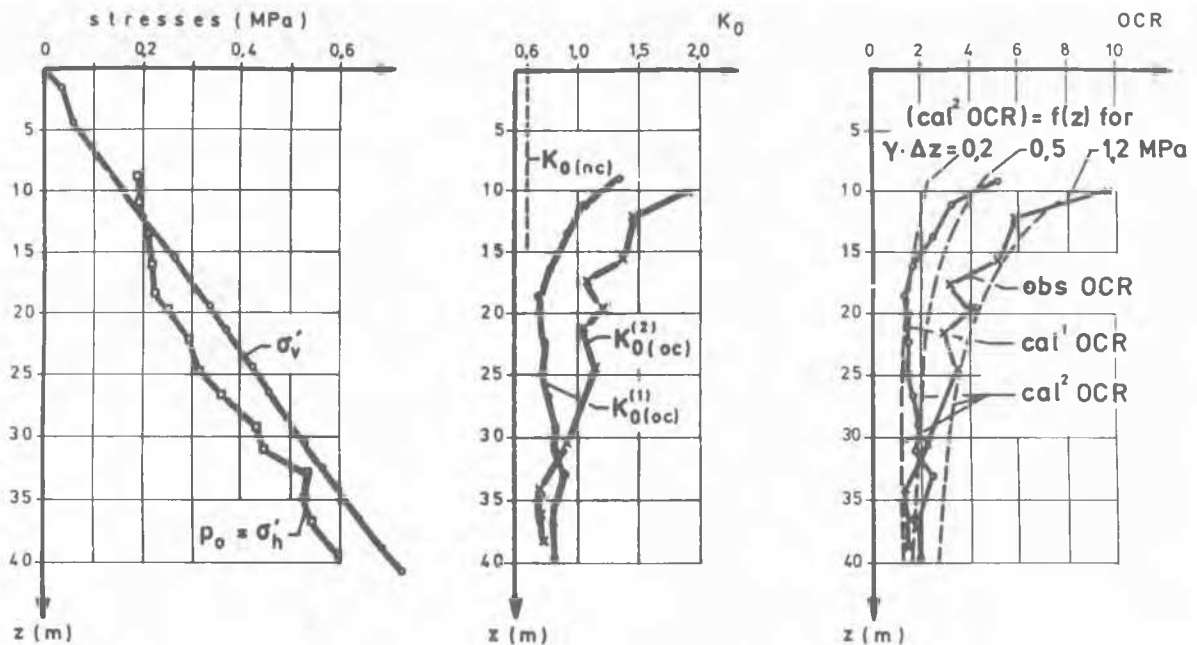
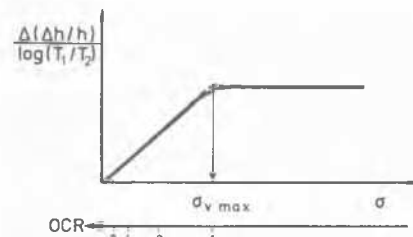


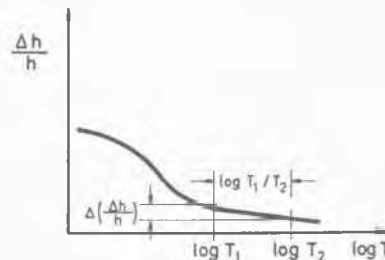
Fig. 3: Comparison of Results of Pressuremeter and Oedometric Tests Dependent on Depth.

Reference to Fig. 3:

- a) calculated $\sigma_v' = \gamma z$ and σ_h' from pressuremeter test
- b) $K_{0(nc)} = 1 \sin \varphi$
 $K_{0(oc)}^{(1)}$ using σ_h' from pressuremeter test
 $K_{0(oc)}^{(2)}$ calculated with equ. (1) using (obs OCR)-values of oedometric tests
- c) (obs OCR) from oedometric test
(cal¹ OCR) calculated with equ. (1) using $K_{0(oc)}^{(1)}$ -values
(cal² OCR) calculated with equ. (2) using assumed values of $\gamma \Delta z = 0,2 \dots 0,5 \dots 1,2$ MPa for comparison



a) Creep Velocity in Secondary Compression Related to Effective Vertical Stress.



b) Example of the Time-Settlement Curve of one Load Increment

Fig. 4: Determination of the Maximum Geological Overburden after MURAYAMA/SHIBATA (1958)

Tectonically, Frankfurt is located at a crossing of a SW-NE striking Paleozoic depression south of the Taunus and the N-S striking Rhine graben, widening since Oligocene with an average velocity of 1 mm/a. The graben depth is about 2000 m. In the N-S direction additional shear stresses were encountered. Due to the Horloff-Dieburg graben in the east (see Fig. 5) Frankfurt represents a horst structure dipping 30° NW towards the Rhine graben and the northern depression. Generally, the subsoil can be characterized as tectonically weakly stressed. It may be assumed that the vertical and horizontal in-situ stresses

maintained permanently principal stresses. A temporary inclined state of the stress ellipsoide would have resulted in more frequent and stronger tilting, flexures or folds. The ero-

sion of the original overburden did not change this state of stress except the fact that today close to the surface the horizontal component is greater than the vertical one, i.e. $K_0 > 1$.

On account of a stratigraphic, paleogeographic and tectonic analysis the maximum geological overburden of 50-200 m (Fig. 8) increases from west to east, i.e. from younger to older formations. The results of this geological evaluation correspond satisfactorily to the soil mechanical investigations. The comparison indicates that the assumption of a permanent piezometric water level close to the surface and therefore $\sigma'_v = \gamma \Delta z$ yields more conforming results. But, considering this comparison it has to be mentioned that certain differences between soil mechanical and geological investigations on in-situ stresses may originate from the relaxation of clays under stress resulting in a permanent adaptation of the fabric to the corresponding state of stress. Therefore from the highest values of maximum overburden are to be expected from geological investigations. All samples of soil mechanical tests were subjected to the relaxation during the geological past. With oedometric tests this affect is increased by additional relaxation during the test period. From pressuremeter tests medium values are to be expected (see Fig. 3c).

At Frankfurt deviations from the general stress distribution occur in areas of karstification of limestone interbeds and presumably also above recently developing faults in strain and shear zones. Geological indications on such zones are open joints even in stiff clays or open bedding planes. In such areas increased settlements above tunnels and greater displacements of the tunnel roof indicate reduced K_0 -values up to figures < 1 .

The soil mechanical investigations were directed on the clays, their fraction of fines $< 2\mu$ comes mostly to 35-75%. Minimum contents of $< 2\mu$ up to 0 were found in the marine Oligocene clay. In the brackish and limnic Miocene clays the fraction $< 2\mu$ exceeded throughout 50%. The average mineralogical composition can be seen from Table I.

TABLE I MINERALOGICAL COMPOSITION OF THE TERTIARY CLAYS AT FRANKFURT		
Mineral (%)	Oligocene marine	Miocene brackish
lime	15-32	0-5
quartz	10-30	20 (max. 40)
kaolinite	10-30	0-10
montmorillonite and mixed layers	0-15	50-70
chlorite	10-20	10-15
mica	10	2-5
gypsum	-	mostly 0 (max. 20)
feldspar, pyrite, organic matters	5	0-10

The different content of swelling clay minerals in Oligocene and Miocene is caused by a different composition of the source area and

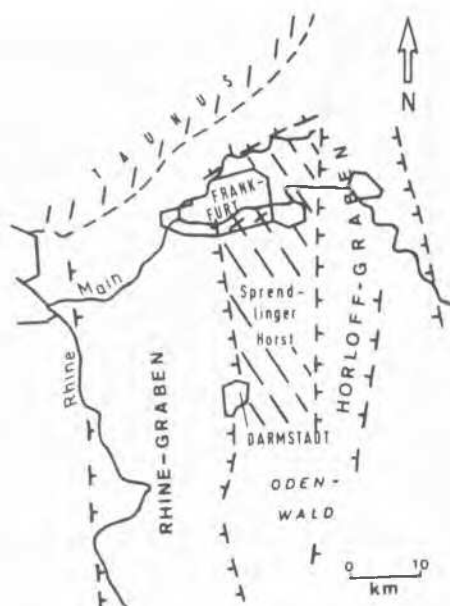


Fig. 5: Tectonic Situation around Frankfurt

an occasional hypersaline facies in the Oligocene. Thereby, montmorillonite is altered into chlorite. The extreme content of montmorillonite in the Miocene results from large volcanic effusions in the eastern surroundings.

The quantitative analysis is based on 5 selected samples which were tested by a differential-thermo-analysis and a subsequent mass spectrographic analysis (ETH Zürich) as well as about 20 half-quantitative analysis (on account of height and width of the X-ray peak) with consideration to the grain size distribution of the silt and clay.

The cation-exchange-capacity comes to 11-45 meq/100 g dry sample, the lower figures were determined in the Oligocene clay, the values in the Miocene vary from 23-45 meq. 90% of the cations are Ca^{++} and Mg^{++} .

A cation loading of -0,23 and 0,35 per half element was determined which explains the tendency of swelling and shrinkage.

The London clay was deposited in a widely extended and very uniform marine basin. Therefore also the sedimentation and the mineralogical composition of the London clay does not show any specific differences along the geological profile. Also diagenesis and tectonics are uniform in the whole London basin.

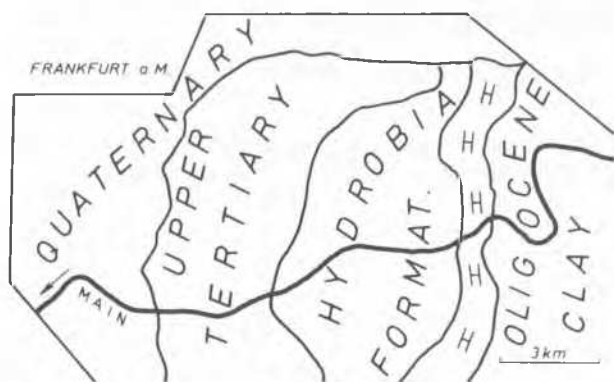


Fig. 6: Geological Map of Frankfurt (Schematic)

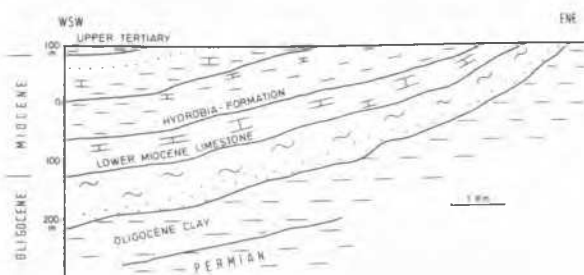


Fig. 7: Geological Cross Section (W-E) (Schematic)

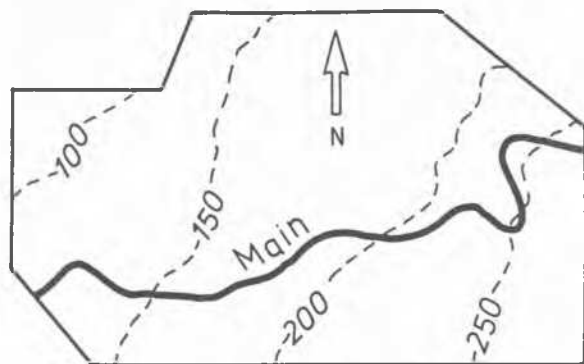


Fig. 8: Geological Maximum Overburden

The composition of the marine Eocene London clay corresponds to the brackish Miocene Hydrobia formation at Frankfurt. But it has to be mentioned that in the London clay about 10% montmorillonite or mixed layers, respectively, are uniformly found whereas at Frankfurt the content of swelling minerals may change every meter, an effect of the rapidly changing sedimentological conditions in the smaller and rather isolated basin. Nevertheless, these different geological and mineralogical conditions do not affect the in-situ-stresses, as pressuremeter tests have demonstrated. Also, the cation exchange capacity and cation loading do not indicate specific differences between the London and the Frankfurt clay.

The decisive difference is of course the earth history. At Frankfurt a maximum geological overburden of 50-200 m was encountered. In London this figure cannot be directly determined by geological investigation. But on account of soil mechanical tests an overburden in the order of magnitude of 300 m is estimated (SKEMPTON 1961).

At Frankfurt jointing is mostly not developed and the clay appears as a homogeneous soil. Contrary in London major joints, several meters long and wavy random fissures of 10-40 cm length and dipping 0-30° occur. From comparison with highly overconsolidated Mesozoic mudstones in Germany it may be derived that such random fissures originate from the de-consolidation of highly over-consolidated clays or mudstones because of exceeding the strength close to the surface. The major joints and the random fissures are geological indications on the considerable overburden of the London clay and the high in-situ-stress resulting therefrom.

CONCLUSIONS

The results presented herein illustrate that a combination of adequate soil mechanical and geological investigations enables a determination of the in-situ-stresses being satisfactory in view of practical engineering purposes. Provision may be a more or less constant in-situ-stress field during the whole geological past, producing permanently $\pm$ horizontal and vertical principal stresses and corresponding homogeneous petrographic fabric of the soil.

In view of pressuremeter tests the soil must be so stiff, that at the borehole wall no irreversible failures take place during the drilling. Only in soft clays a self-boring-pressuremeter can be used.

At Frankfurt the interstratification of clays, silts, sands and even hard and jointed limestone interbeds and the diagenesis of these rocks do not have affected the K_0 -values in a recognizable manner. Also the influence of the relaxation of the clays is slightly considering the high overburden during the geological past of about 10 Mio. years.

According to several observations in tunnels at Frankfurt in-situ-stress measurements may be an adequate method to obtain early information on recently developing faults or any atectonic displacements below the foundations. This agrees with indications from seismically active areas. Such observations are of interest for soil mechanics and geology as well.

ACKNOWLEDGEMENT

We appreciate the collaboration of Dipl.-Ing. H. Mader, who carried out the pressuremeter and oedometric tests and designed most of the figures.

REFERENCES

- Alpan, I (1967). The empirical evaluation of the coefficients K_0 and K_{OR} , soils and foundations, Vol.7, Nr. 1, pp 31-40
- Baguelin, F., Jezequel, I.F., Shields, D.M. (1978). The pressuremeter and foundation engineering. Trans. Tech. Publ., Clausthal/Germany
- Burland, I.B., Maswoswe, I. (1982). Discussion to TEDD/CHARLES (1981): In-situ measurements of horizontal stress in overconsolidated clays using push-in-spade shaped pressure cells. Géotechnique 32, No. 3, Sept. 1982, pp 285-286
- Menard, L. (1957). An apparatus for measuring the strength of soils in place. Thesis Urban/Illinois/USA
- Murayama, S., Shibata, T. (1958). On the secondary consolidation of clay. Proc. 2nd Japan Congr. Test. Mat. Non Metallic Materials, Kyoto, pp 178-181
- Schmidt, B. (1966). Discussion of "Earth pressure at rest related to stress history". Can. Geotechn. Inst., Vol. II, pp 57-138
- Skempton, A.W. (1961). Horizontal stresses in overconsolidated Eocene clay. Proc. 5th ISCM, Paris, Vol. 1, pp 351-357
- Wroth, C.P. (1976). General Report "In situ measurement of initial stresses and deformation characteristics." Proc. ASCE Conf. on in situ measurement of soil properties, Raleigh, NC. Vol.2