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# SARDINIA 91

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## PROCEEDINGS

## VOLUME I

DELFT GEOTECHNICS, (1989) " Vergelijkende doorlatendheidsmetingen zandbentoniet." Kenmerk CO-305340/12. Grondmechanica Delft, 1989.

OUSAMA AL-AKHRASS, M. (1990) " A low gradient permeability test for fine grained soils." M.Sc. Thesis H.H. 50, IHE-Delft, Delft Geotechnics, 1990.

# HYDRAULIC CONDUCTIVITY TESTS ON COHESIVE SOILS

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SUMMARY: The paper deals with the evaluation of vertical and horizontal permeabilities of a kaolin by using triaxial apparatus. Influence of various variables such as gradient, consolidation pressure, particle migration, permeant nature, and anisotropy on the coefficient of permeability were investigated.

## 1. INTRODUCTION

The need for hydraulic conductivity determination in fine-grained soils seems to be increasing, as a result of recent developments. One such trend is greater concern over the long-term enviromental effects associated with burial of toxic wastes. When consideration is given to water and pollutant movements over periods of up to hundreds of thousands of years, cohesive soils can no longer be treated as impervious and their hydraulic conductivity must be determined.

Laboratory tests are generally used to determine the hydraulic conductivity of clays. They may be performed with either fixed- or flexible-wall permeameters using constant or falling head methods. Fixed-wall devices have the advantage of low cost and convenience for testing compacted soils; however, they have several disadvantages, such as incomplete control over the stress state of the sample, difficulty in trimming and inserting natural soil into the test ring, potential leakage along the sample permeameter wall interface, and possible effects of untrapped air inside samples. Sidewall leakage may be particularly important with a concentrated organic chemical, because the chemical may cause the soil to shrink and pull away from the permeameter wall. The main advantages and disadvantages of the various fixed-wall permeameters are summarized in table 1.

Hydraulic conductivity may also be determined using triaxial apparatus. Flexible-wall devices minimize sidewall leakage and are suitable for testing by using back-pressure, measuring specimen volume changes and controlling both horizontal and vertical effective stresses. There are several factors that may be investigated separately to determine their influence on the measurement of hydraulic conductivity coefficient in long- and short-term test conditions performed with triaxial apparatus. The impact of these factors on test results and alternative equipment and

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procedures are reported in table 2.
This paper examines the suitability of triaxial equipment for determining the hydraulic conductivity of cohesive soils. All tests were carried out either in a triaxial cell, according to the constant head method, or in an oedometric cell, according to the falling head method, and their experimental results were partially compared. During the investigation several factors influencing hydraulic conductivity, such as gradient, test duration, effective stress, anisotropy, particle migration, diffusion through the membrane, and nature of the permeant fluid, were evaluated.

## 2. EXPERIMENTAL PROGRAM

A kaolin of medium plasticity was used in the investigation. Its main index properties and chemical compounds are summarized in table 3.
The tested samples were prepared in the laboratory. Kaolin was pulverized by using a pestle until its particles were less than 0.425 mm. It was mixed by hand with natural water; the resulting moisture content of the mix was twice its liquid limit (≈120%). After mixing the slurry was covered and allowed to hydrate for a week. Natural water was used for both mixing and initial permeation. Two pore fluids were used as permeants to investigate their effects on hydraulic conductivity of kaolin:
1. deaired distilled water, DDW;
2. an inorganic leachate, IS, (composition in table 4).
The fully hydrated kaolin-water slurry, consisting of nearly 45% kaolin and 55% water by weight, was placed in a cylindrical Rowe consolidation cell 250 mm wide and 140 mm high.

table 1: Advantages and disadvantages of different fixed-wall permeameters.

| PERMEAMETER TYPE | ADVANTAGES | DISADVANTAGES |
|---|---|---|
| Compaction Mold | *Simple and economical for testing compacted clay | *Sample may be unsaturated *Lack of capability to measure amount of shrinkage or swelling *Incomplete control over stress acting on the soil *Sidewall leakage |
| Double-Ring Compaction Mold | *Sidewall leakage may be controlled | *See above |
| Consolidation Cell | *Undisturbed samples may be tested *Different vertical stresses may be applied *Axial deformations may be measured | *Sidewall leakage *Difficulty of performing test at low effective stresses *Difficulty of trimming some soils *Thinness of specimens |
| Fixed-Cylinder | *No particular advantages | *Difficulty of trimming soil into containing ring *Sidewall leakage *Vertical stresses cannot be applied |



Care was taken to remove as much air as possible, placing small amounts of soil at a time and vibrating it. Consolidation was allowed either vertically or horizontally by placing a porous strip along the lateral surface and two porous disks at both bases.

table 2: Short- and Long- terms permeability testing variables (adapted from Evans-Fang, 1988).

| VARIABLE | TYPICAL CAUSE | ERRORS | SOLUTIONS |
|---|---|---|---|
| GRADIENT | High for sufficient pore volume displacement in a short time | *Not representative of field conditions *Migration of fines | *Conduct further tests to determine k at low gradients and compatibility at high gradients |
| EFFECTIVE STRESS | High to maintain positive effective stress at influent end | *Differential consolidation *Not representative of field conditions *Underestimation of k | *see above |
| PARTICLE MIGRATION AND ORIENTATION | High gradient | *Underestimation of k | *see above *Perform grain size distribution analysis after testing to check for migration |
| DIFFERENTIAL CONSOLIDATION | See above | *Reduced cross-sectional area | *See above *Use shorter samples |
| MAINTAINING SATURATION | Pressures generated by compressed air may cause air in solution | *Decrease of k due to entrapped air | *Refresh permeant frequently *Eliminate air/permeant interface *Other equipment modifications |
| DIFFUSION THROUGH MEMBRANE | Molecular diffusion of contaminants under chemical diffusion gradient | *Permeant chemistry not representative of field conditions | *Eliminate diffusion gradient by using contaminated cell water *Use alternative membrane system *Use silicon oil as cell fluid |
| BOUNDARY INFLUENCE | High cell pressure | *Reduced cross-sectional area *Underestimation of k | *Use $\phi$ > 35 mm |
| LENGTH/DIAMETER ($L/\phi$) RATIO | Dimension of sample | *k decreases with increasing $L/\phi$ ratio | *Standardization necessary |
| TEST DURATION | Generally too short | *Overestimation of k | *Measuring in steady state condition |

| $w_l$= 60% | $w_p$= 35% | $I_p$= 25% | G= 2.63 | %<2μ= 55 |
|---|---|---|---|---|

| CHEMICAL COMPOUNDS | PERCENTAGES |
|---|---|
| $SiO_2$ | 48.0 |
| $Al_2O_3$ | 37.0 |
| $Fe_2O_3$ | 0.9 |
| TiO | 0.1 |
| CaO | 0.1 |
| $Na_2O$ | 0.1 |

table 3: Kaolin chemical compounds.

| CHEMICAL COMPOUNDS | WEIGHT (mg/liter) |
|---|---|
| $NH_3$ | 1200 |
| $Na_2SO_2$ | 3000 |
| $MgSO_4$ | 1500 |
| $FeCl_2$ | 100 |
| $ZnCl_2$ | 10 |
| KCl | 1200 |

table 4: IS chemical compounds.

The slurry was thus consolidated at a vertical pressure of 100 kPa. A stress of 100 kPa was selected as consolidation pressure, resulting in a sample with relatively high void ratio, yet stiff enough to be trimmed without much sample disturbance. The average water content and wet unit weight were 52% and 16.55 kN/m$^3$ respectively.
Hydraulic conductivity determinations are carried out either on triaxial equipment used as a flexible-wall permeameter, or an oedometric cell used as a fixed-wall permeameter.

2.1. Triaxial Permeability Tests

Twelve cylindrical samples of 38 mm diameter and 55 mm length were obtained from three water-kaolin slurries consolidated in the Rowe cell at 100 kPa. Six had axes in the vertical direction, and six in the horizontal one.
Four (two vertical and two horizontal) were consolidated with an isotropic effective pressure of 100 kPa, four of 200 kPa, and four of 300 kPa. Six (three vertical consolidated at a pressure of 100, 200, and 300 kPa respectively, and three horizontal consolidated in the same manner) were filtered with DDW, and six with IS. Flow was always in the axial direction, but, as different samples were trimmed with their axes in the consolidation direction (or perpendicular to it), both vertical and horizontal permeabilities for the material were obtained.
Details of the triaxial equipment are shown in fig.1. Air over water interface cells were used to apply inflow and outflow and cell pressures; each pressure was checked by two regulators and monitored with two pore pressure transducers. Plexiglass cylindrical standtubes were used for back-pressure saturation and for reading inflow and outflow from samples. Samples were placed in the cell and mounted between porous disks with a permeability of about $10^{-6}$ m/s. Although organic compounds were not used and molecular diffusion of contaminants could not occur through the membrane, all samples were trapped with teflon and then wrapped in a lattice membrane. Cell were filled with water,



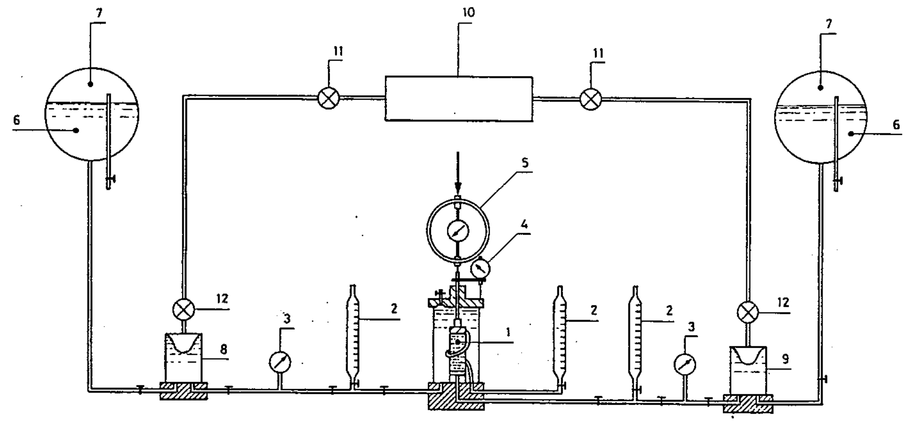

Fig.1 Triaxial permeability apparatus.
1.sample; 2.burette; 3.pore pressure transducers; 4.micrometer; 5.dinamometer; 6.water reservoir; 7.vacuum; 8.air-water cell pressure generator; 9.air-water inflow pressure generator; 10.air compressor; 11. and 12. air pressure regulator.

while inflow and outflow standpipes were charged with permeant. The system was deaired using flushing techniques. A back pressure of 300 kPa, applied to both ends of the samples, was maintained constant throughout the saturation and consolidation phases. Cell pressure was then increased to its test value and samples allowed to consolidate.
At the end of consolidation, inflow and outflow readings were recorded and the sample volume change calculated. Seepage was induced by increasing only the bottom inflow air-pressure while maintaining the outflow line pressure at the initial back-pressure value. Acquisition of flow data was begun immediately after application of the seepage gradient. Once an equilibrium hydraulic conductivity had been reached with natural water, this fluid was removed from the influent reservoir and replaced with the tested permeant.
Triaxial specimens were free to deform both axially and radially in response to the seepage force imposed for permeability measurements. Gradients ranging from 20 to 170 were used to evaluate their effect on the hydraulic conductivity of kaolin. Each sample was tested first with the lower of the four gradients, which was then gradually increased. The successive gradient was applied after two pore volumes of permeant fluid had been filtered through the sample in steady state condition. This condition was considered to have been achieved when influent flow was equal to effluent flow.
Coefficient of permeability k (hereafter only called permeability) was computed by means of coefficient of hydraulic conductivity, obtained with the constant head equation, and correcting it using the relative viscosity and density of permeant:

$$k = \beta\ q/(i \times A \times \delta t) \qquad (1)$$

where q is the effluent fluid volume, i the test gradient, A the cross-sectional area of sample, $\delta t$ the elapsed time, and $\beta$ the ratio between relative viscosity and relative density computed by dividing the absolute viscosity and density of the permeant by those of distilled water at 25°C.
A rotational viscometer was used to evaluate permeant viscosity with temperature ranging from 10 and 30°C and shear rate from 0 to 300 $s^{-1}$. Scattering was less than 6%.
At the end of the permeability tests, each sample was cut into three different parts, one at the top, one in the middle and one at the bottom of the specimen, and aerometric tests were then carried out. The results were compared each other to evaluate possible migration of finer particles due to hydrodynamic force.

## 2.2. Oedometric Permeability Tests

Two samples of 70 mm diameter and 20 mm height were vertically trimmed from a water-kaolin slurry consolidated in a Rowe cell at 100 kPa. One was filtered with DDW, and one with IS. Each sample was inserted into the test ring between two porous disks. A conventional step-loaded oedometer test was carried out; after 24 hours' consolidation stage a head difference of 3 m was applied between the two ends of the sample, connecting its bottom to a 5 mm diameter burette filled with the test permeant and then performing a falling head permeability test. During the test, readings of the decrease in hydraulic head in time were recorded over a period of 24-48 hours. In order to compare permeabilities obtained with constant and falling head tests, oedometric vertical pressures of 100, 200 and 300 kPa were particularly investigated. Vertical permeability was calculated from the falling head equation and by using the correction factor $\beta$:

$$k = \beta \times \ln(h_0/h_t)\ (a \times L)/(A \times \delta t) \qquad (2)$$

where a and A are the cross-sectional areas of the burette and sample respectively, L is sample height, $h_0$ and $h_t$ excesses of hydraulic head at time t=0 and after time $\delta t$ respectively. It was assumed that flow is governed by Darcy's law, the steady state condition is established immediately and permeability is uniform and remains constant throughout the test.

## 2.3. Test Results

Permeability is primarly dependent on the void ratio. Kaolin was prepared as a slurry at a void ratio of about 3.1. In that condition the orientation of clay particles should be completely random and permeability the same in all directions. As kaolin was anisotropically consolidated in the Rowe cell some preferential particle orientation orthogonal to the direction of major vertical effective stress was expected to develop and $k_v$ became less than $k_h$.
The ratio $R_k$ between horizontal and vertical permeabilities for the range of void ratio reported here was of 1.8 for IS samples and of 3.7 for DDW ones (Fig. 2). Scattering was limited and anisotropy was completely preserved even after



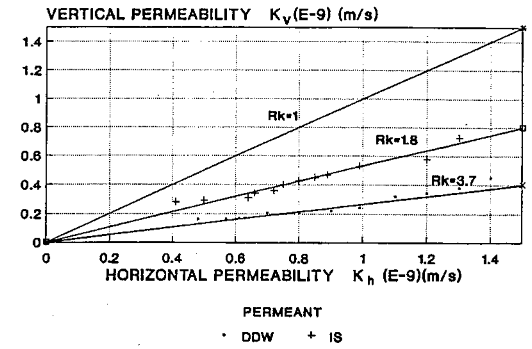


Fig.2 Comparison of $k_v$ and $k_h$ obtained with triaxial tests

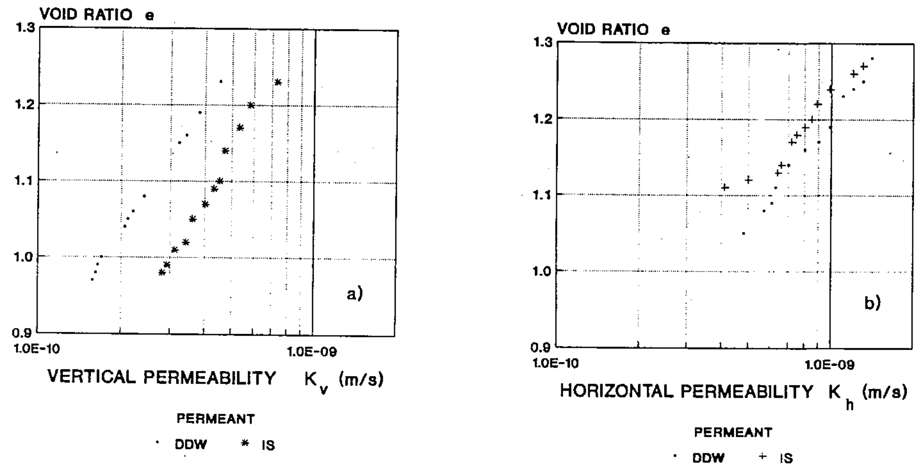


Fig.3 a,b e-log $k_v$ and e-log $k_h$ relationships for both DDW and IS permeants from triaxial tests.

isotropically consolidation of sample in triaxial cell.
Vertical and horizontal permeabilities of the kaolin filtered with DDW and IS during triaxial permeability tests are summarized in Figg. 3 a,b with permeability plotted on a logarithmic axis. Although with different amounts both permeabilities decreased when kaolin was compressed from a void ratio of 1.3 to 0.9, following a linear trend with little scatter. When kaolin was vertically filtered with IS its permeability $k_v$ showed greater values than those with DDW, whereas $k_h$ was not influenced by the nature of permeants when seepage was horizontal. Coefficent $C_k$, defined as the slope of e-log k linear trend, assumed similar values (≈0.55 for $k_v$ and ≈0.45 for $k_h$) not dependent on the used permeant.
For Darcy's law to be considered valid, permeability does not change with gradient. Figg. 4 a,b and 5 a,b represent the measured values of vertical and horizontal permeabilities as a function of the gradient and isotropic consolidation pressure used during testing, for DDW and IS respec-

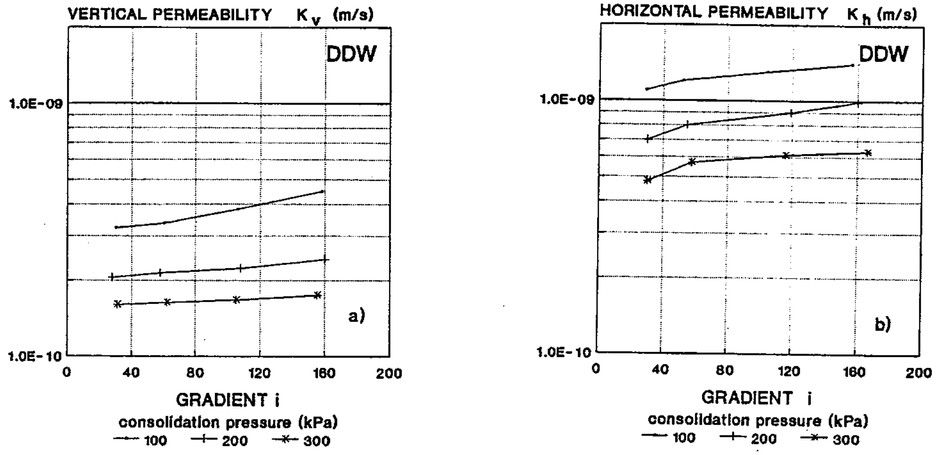


Fig.4 a,b Permeant DDW. i-log $k_v$ and i-log $k_h$ relationships from triaxial permeability tests.

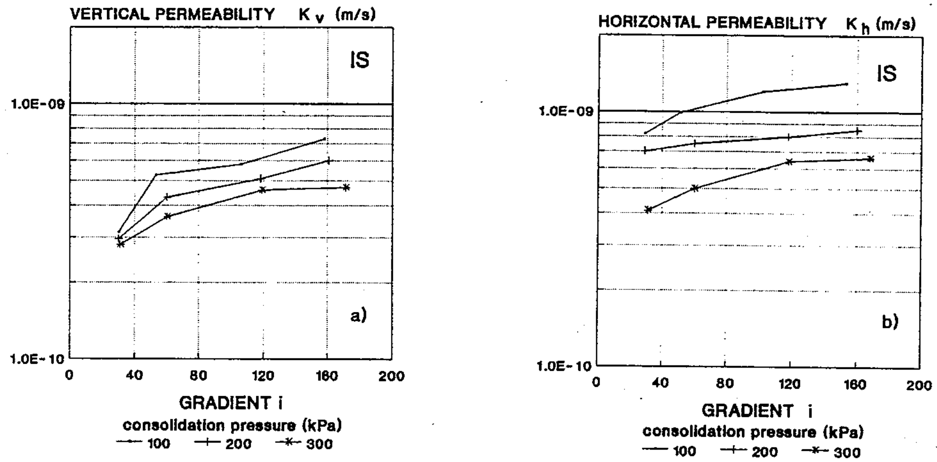


Fig.5 a,b Permeant IS. i-log $k_v$ and i-log $k_h$ relationships from triaxial permeability tests.

tively. Horizontal permeability always exhibited values greater than vertical one. Permeability generally decreased as consolidation pressure was increased, whereas $k_v$ seemed to be much less sensitive to gradient variations than $k_h$. This observed slight increase of permeability with the applied gradient could be attributed to the inability to maintain constant the sample void ratio throughout the test and in particular along the sample length.
Kaolin-water slurry was initially homogeneous and isotropic. During the test the finer particles likely moved due to hydrodynamic forces. Grain size distribution analyses were conducted on various parts of specimen after completion of the test. Although grain size distributions were initially uniform part of fines migrated from the lower and the middle thirds to the top part of sample (fig. 6), according



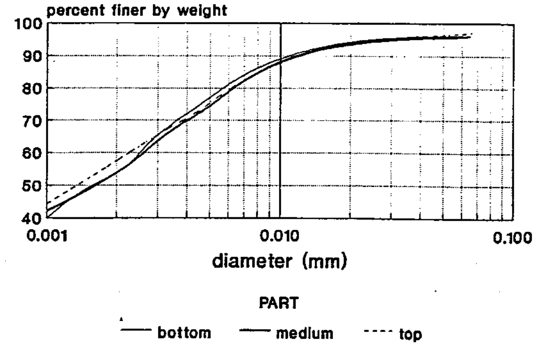


Fig.6 Grain size distribution curves relative to three different parts of a tested sample.

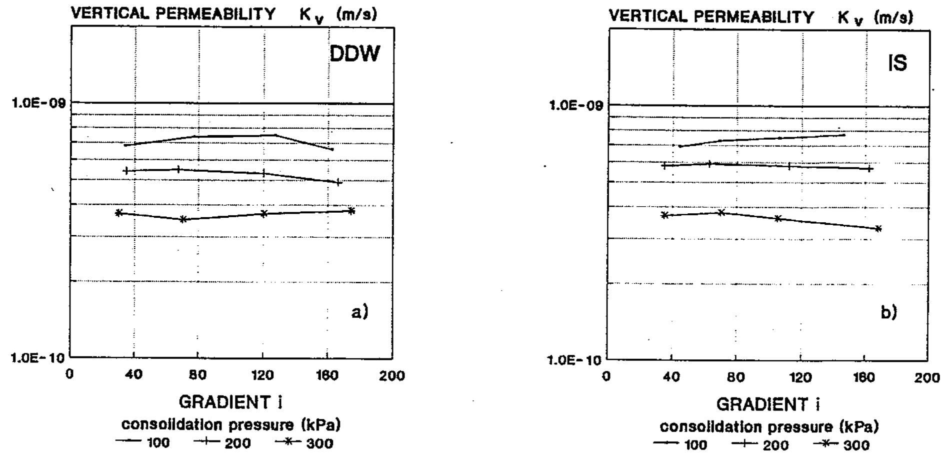


Fig.7 i-log $k_v$ relationships for both DDW and IS permeants from oedometric tests.

to Evans-Fang (1988).
At last, vertical permeabilities determined using an oedometric device, as a fixed-wall permeameter, and the DDW and IS permeants were reported in fig. 7 a,b. Vertical permeabilities obtained with oedometric falling-head tests generally were higher (1.5÷2.0) than those determined with triaxial tests, for both permeants. Such a difference could be attributed to the sidewall leakage effect, which is one of the main disadvantages of the oedometric procedure, in particular at low vertical pressure. Permeability decreased as vertical consolidation pressure was increased, whereas it seemed to be not dependent on the applied gradient and the filtered permeant.

## 3. CONCLUSIONS

The main features of the study can be summarized as follow:
1. Kaolin exhibited an anisotropy permeability with ratios $R_k$ ranging from 1.8 (for IS samples) to 3.7 (for DDW samples).

2. Both vertical and horizontal permeabilities decreased as consolidation pressure was increased.
3. e-logk relationships showed nearly linear trends with slopes $C_k$ ranging from 0.45 ($k_h$) to 0.55 ($k_v$).
4. Permeability generally seemed to be not much sensitive to gradient variations, according to the Darcy's law.
5. IS samples showed vertical permeabilities greater than those of DDW samples, whereas their horizontal permeabilities seemed to be not too dependent on the used permeants.
6. $k_v$ determined using an oedometric device generally was higher than those obtained with triaxial tests, for possible sidewall leakage effects.

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# STABILITY OF LINING SYSTEMS ON SLOPES

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SUMMARY : Authors describe in a first step the tests performed with shear boxes and inclined planes to characterize the soil-geomembrane interaction in order to define a test method.In a second step they present a computer program to study the stability of complex lining systems on slopes with the determined parameters and one example of the parametric studies which can be achieved.

## 1 - INTRODUCTION

World is more and more conscious of the necessity to preserve his environment. A consequence is the development of environmental structures as lagoons, ponds or waste disposals. Geosynthetics (geotextile,geogrid,geonet and geomembrane) are now often used in complex lining systems for the imperviousness of such structures. The security and the good behaviour of these structures is first conditionned by a proper design and a proper building of the lining systems.

Some french laboratories (Laboratoires des Ponts et Chaussées, Centre National du Machinisme Agricole, du Génie Rural,des Eaux et Forêts) have developed researches on one part of the design : the stability of lining systems on slopes.Systems are submitted to specific conditions as loading by a protection structure, large displacements and specific hydraulic conditions.

This paper describes results of the investigations concentrated in a first approach on the problem of the stability of lining systems on slopes with low normal stresses which can be repesentative of structures as lagoons, facing of dams,caps or building of waste disposals.

The french approach for the stability design of lining systems in the previous described conditions is based on three steps:

1 determination of the interaction parameters (soil-geomembrane, geotextile-geomembrane...) with laboratory tests

2 development of a stability computer program

3 studies and graphs

## 2 - LABORATORY TESTS

### 2.1 - State of the art :

Bibliography shows off in most of the cases a classical approach with shear tests to characterize the soil-geosynthetic interaction. For some particular applications inclined plane tests

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