Study of the permeability of clay soils measured by detecting the swelling and its kinetics

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Abstract:
In this study a new method to measure the permeability of clay soils by laser interferometry was invented by Hassan Asselman in the Optics and Photonics team is used. Our research mainly based on experiments designed to study the variation of permeability (m / s) measured by the new method based on the porosity (\%) of clay soils. The latter was measured by the following methods: by means of a chemical and pycnometer dry impregnation. results allowed us to determine a new experimental law connecting the two aforementioned experimental parameters and a comparison with other empirical formulas (Kozeny-Carman, Terzaghi, Hazen, ...). This study also allowed us to measure: the evolution of the speed of the swelling potential as a function of time at each interval corresponding to a displacement of the mirror \( \lambda / 2 \), never explored, to our knowledge so far on clays and the kinetics of the swelling that has been performed on said clay "Téffaline" (clay fraction which is illite) area Tetouan used in the manufacture of pottery.

Mots clefs:
Permeability, interferometry-laser, clay soils, cinétique du gonflement.....

1 Introduction

We use the prototype [1], [2] invented by Hassan ASSELMAN [3], [4] to measure the permeability of clay soils by detecting swelling using laser interferometry. This device has qualities, strengths and broad scope that make it very attractive and easy to implement and there is a plan for its commercialization in the near future. The RROB (Research Report with Comments on the patent) developed by OMPIC (Moroccan Office of Industrial and Commercial Property) indicates that the patent No. 1.586.243 of French Bernard CORVAISIER filed on October 1, 1968 under the entitled "Apparatus for studying the swelling of a soil sample" (odometer), Filer: French State, represented by the Minister of Equipment and Housing and the Central Laboratory of Bridges and Roads, resident in France (Paris) and is used by the World of Design Offices for the analysis of clay soils, is very tedious and slow, and since that time (1968) there has been no change! Hence, the enormous importance of the
Hassan ASSELMAN prototype [2], [3] with its incredible gain of time (a few hours instead of a few months) and accuracy. The conclusion of the pre-feasibility report No LLRA077-12 Moubtakir [5], directed by CERIMME (Center of Study and Research of Metallurgical Industries, Mechanical, Electrical and Electronic and funded by OMPIC), points out that this new prototype is technically easy to implement and its profitability will depend on its cost price and on the marketing approach that will accompany its release.

As part of our research, we will proceed to the measurement of permeability by the method of Hassan Asselman [3], [4] which is the fruit of many years of research. In this study we will make a comparative study of our measurements with permeability values calculated from the empirical formula of Kozeny-Carman [6].

It is noted that permeability also called the infiltration rate is the movement of water from the surface to the depth of soil. It is considered one of the most important properties for the ground engineer. In fact it must be taken into account in the design of geotechnical projects, in agricultural activities and in the underground storage of waste. Indeed if the permeability is perceived by the agricultural engineer as a beneficial and profitable source, it is however seen by the ground engineer as an element that is the cause of the damage. Moreover, it is of great help when it comes to the underground storage of waste that actually raises many complex and varied problems. This leads researchers to think about the different ways to get a lower permeability of clay soils. Darcy in 1856 established the law governing this phenomenon.

Permeability in situ measurement techniques developed in the literature are mainly, variable level measurement system, constant level measuring system, Slug Test, pumping wells ... [7]

The empirical methods are:
- The Poiseuille law [8]
- The Empirical formulas [8], [9]: Allen Hazen (correction due to the temperature), Schlichter, Terzaghi and Loudon ..

Note that a well-known relationship between permeability and pore properties was proposed by Kozeny and later modified by Carman. The resulting equation is widely known as the Kozeny-Carman equation (KC) [10], although both authors have never published together.

2 Experimental device

2.1-device for measuring the permeability of clayey soils by Hassan ASSELMAN method

The experimental device we developed is an adaptation of the Michelson interferometer. It has been used previously by our laboratory for measuring the thermal expansion of solids [11].

The path difference between two consecutive dark-bright fringes varies corresponding to a variation in the thickness of the air layer, less than micrometer (about 0.2μm for λ = 632.8 nm). Hence, the high sensitivity of our method and its importance are to be noticed.

The original application of this device to study the clays swelling phenomenon was presented for the first time in [12].
The experimental setup for measuring the velocity in depth of infiltration of water in clay soils is shown in Figure 1. This comprises the following elements:
- A He-Ne laser of wavelength 632.8 nm and power of 1 mW
- A short focal length lens (2cm) to observe the interference
- A Michelson interferometer comprising a beam splitter for transmitting 50%, two perpendicular mirrors: one is fixed, adjustable in the horizontal and vertical planes. The other is movable.
- The movable mirror is in the clay sample in the form of a parallelepiped, dried, incorporated into the interferometer and shaped at its upper longitudinal surface shape centered canal, smaller than the length for retaining the parallelepiped drops of water on the surface and thereby controlling the water content.

When injecting a volume of distilled water (a few drops) to the sample surface, it swells and the mirror moves. It notes the time when the $\Delta T$ swelling deformation begins at $\Delta Z$ depth (indicating the arrival of the water at that depth [3]). In other words, in this case we measure the permeability of clay soils by detecting swelling using laser interferometry.

Permeability is given by the following relationship:

$$v(m/s) = \frac{\Delta Z}{\Delta T} \quad (1)$$

The swelling potential (%) is given by:

$$g(h) = \frac{dV}{V} = \frac{3N\lambda}{2L} \quad (\%) \quad (2)$$

N: number of scrolled interference fringes and L: sample length.

Since the permeability depends on the water content, we wanted a first time set this parameter, and our choice is to work on a sample passed through the oven at 105 °C.

**2.1- Device for measuring the porosity by the chemical method**

The porosity of the soil ($\eta$) is defined as the ability in its solid state to be penetrated by a fluid. It helps to know the importance of void that is to say whether the soil is in a loose or tight condition. It is defined as the ratio of the void volume ($V_v$) accessible to water and air apparent total volume ($V$) of sol. The porosity is always less than 1, it may also be expressed in (%).

$$\eta = \frac{V_v}{V} \quad en \ (%).$$
For measurements of porosity and void ratio (e), we operated by the chemical method using a pycnometer to calculate the volume of the solid \( V_s \) and a dry impregnation to calculate the volume of the void \( V_v \).

- The volume of the solid is measured with a pycnometer, it is obtained by the following equation [13]:

\[
V_s = \frac{m_1 + m_2 - m_3}{\rho_w}
\]

With:
- \( m_1 \): mass of the pycnometer containing distilled water and magnetic rod
- \( m_2 \): mass of the pycnometer containing soil, distilled water and magnetic rod
- \( m_3 \): volume of the solid particles
- \( \rho_w \): density of distilled water

- The volume of the void is measured by dry impregnation; it is given by the following equation:

\[
V_v = \frac{V_{\text{moy}}}{m_3}
\]

With:
- \( V_{\text{moy}} \): the average volume of water impregnated in the dry sample.
- \( m_3 \): volume of the solid particles.

### 3 Results and Discussions

#### 3.1- Results related to the porosity

We selected samples of clay soils and got the following results (Table 1):

<table>
<thead>
<tr>
<th>Sample clay</th>
<th>Sampling location</th>
<th>Porosity ( \eta ) in (%)</th>
<th>Void ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yellow marne</td>
<td>Faculty of science Tetouan-Morocco</td>
<td>35</td>
<td>0.53</td>
</tr>
<tr>
<td>Illite</td>
<td>Region téffaline to Tetouan-Morocco</td>
<td>40</td>
<td>0.66</td>
</tr>
<tr>
<td>Clay Fraction ghassoul (smectites category)</td>
<td>Green ghassoul Fez-Morocco</td>
<td>44</td>
<td>0.78</td>
</tr>
<tr>
<td>bentonite</td>
<td>Region Nador-Morocco</td>
<td>50</td>
<td>1</td>
</tr>
<tr>
<td>Montmorillonite</td>
<td>Commercial clay</td>
<td>63</td>
<td>1.7</td>
</tr>
</tbody>
</table>

**Table 1:** results for the porosity for each type of

The experimental results obtained about the void ratio will be used in the empirical formula of Kozeny Carman (Equation 8), to calculate the permeability to be compared with those obtained by our experimental method.
In fact, as indicated by Carrier [13], there is about half a century Kozeny and Carman proposed the following expression to predict the permeability of porous media [14]:

$$K = \left(\frac{\mu}{\gamma}\right) \left(\frac{1}{C_{K-C}}\right) \left(\frac{1}{S_o^2}\right) \cdot \frac{e^3}{(1+e)}$$  \hspace{1cm} (7)

Where $\gamma$ = unit weight of permeant , $\mu$ = viscosity of permeant; $C_{K-C}$ = Kozeny-Carman empirical coefficient; $S_o$= specific surface area per unit volume of particles (1/cm); and $e$ = void ratio.

 Kozeny-Carman however, gives the following more empirical formula used [6]:

$$k = \frac{P_w g e^3}{C_2 \eta_w S^2 (1+e)}$$  \hspace{1cm} (8)

Where
- $k$: permeability coefficient (m/s)
- $P_w$: density of water (1.00 g/cm$^3$)
- $g$: acceleration due to gravity (9.81m/s$^2$)
- $e$: void ratio (%)
- $\eta_w$: dynamic viscosity of water at 20°C ($\eta_w$=10.3kg/(m .s))
- $S$: specific surface of the grains (m$^2$ / m$^3$
- $C_2$: form factor, changing according to the shape of the particle and ranges between 5 and 7 (5 for spherical and 7 for angular grains) [in our case we chose $C_2= 6$].

The empirical formula of Taylor which is in fact a simplification of the Kozeny-Carman formula is written [6]:

$$K = \frac{D_s^2 \gamma^2}{\mu} \frac{e^3}{1+e} C_3$$  \hspace{1cm} (9)

Where
- $k$: permeability coefficient (m/s)
- $D_s$: Diameter of solid grains
- $e$: void ratio
- $\mu$: dynamic viscosity of water at 20°C
- $\gamma$: unit weight of permeant
- $C_3 = 3$

Results for the permeability calculated by the empirical formula of Kozeny-Carman for each type of clay are given in Table 2.

We will be limited to compare the experimental results with the empirical formula of Kozeny-Carman because it gives all the constants involved in the formula.

### 3.2- Permeability of the clay samples obtained by laser interferometry
For each type of clay we obtained the following results (Table 2):

<table>
<thead>
<tr>
<th>Sample clay</th>
<th>Measured by the method of Hassan Asselman</th>
<th>Calculated by the empirical formula of kozeny-carman</th>
<th>According to the literature [16]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yellow marne</td>
<td>3.75</td>
<td>$1.3410^{-7} - 1.3410^{-5}$</td>
<td>-</td>
</tr>
<tr>
<td>Illite</td>
<td>3.00</td>
<td>$2.0810^{-7} - 2.0810^{-5}$</td>
<td>2.8 - 13.9 [16]</td>
</tr>
<tr>
<td>Clay Fraction ghassoul(smectites category)</td>
<td>66.00</td>
<td>$3.1810^{-7} - 3.1810^{-5}$</td>
<td>-</td>
</tr>
<tr>
<td>Bentonite</td>
<td>150</td>
<td>$5.8610^{-7} - 5.8610^{-5}$</td>
<td>-</td>
</tr>
<tr>
<td>Montmorillonite</td>
<td>333</td>
<td>$2.1410^{-6} - 2.1410^{-4}$</td>
<td>-</td>
</tr>
</tbody>
</table>

| Clay Fraction ghassoul (smectites category) | 66.00 | $3.1810^{-7} - 3.1810^{-5}$ | - |

**Table 2: Permeability values for each type of clay.**

In our case the overall accuracy of the permeability measurement does not exceed 3%.

La perméabilité des argiles mesurée par notre dispositif expérimental est donnée par la courbe suivante (figure2):

![Figure 2: Permeability in μm/s according to the void ratio.](image)

Some of our determinations are close to values calculated by Taylor’s empirical formula which is in fact a simplification of the empirical formula of Kozeny-Carman. For others, the difference can be explained by the influence of the water content. Indeed Taylor formula is validated in a saturated porous medium, while our values on the contrary are measured in a non-saturated porous medium (sample dried at 105 °C). Consequently additional experiments are required. Moreover our value to téffaline clay (illite clay fraction) is in good agreement with literature values estimated by the method variable level [16], which are between 2.8 and 13.9 μm/s in clay loams (table 2).
3.4- Velocity of the swelling potential as a function of time.

By measuring the time between two consecutive orders of scrolling of the interference fringes we can determine the average speed of the relative movement of the mirror. This corresponds to a displacement of the mirror $\lambda/2$ (never explored so far on clay soils, indeed odoemètre would be unable to explore the details presented on this curve pace, because it is limited to displacements intervals of the order of 0.01 mm, and the same curve would be reduced to 3 points, hence; the importance of our new experimental method). The change in speed over time is shown in Figure 3 for Téffaline clay (clay fraction: illite) Gross Tetouan used for pottery manufacturing.

![Figure 3: velocity potential of the swelling as a function of time at a depth $\Delta Z = 6.5$mm.](image)

The swelling has a first rapid phase and ends with a constant evolution until the final stopping of swelling that occurs in about one hour to a water content of about 6%.

To explain this variation, it is believed that for a given degree of hydration, the velocity of variation of the length $\Delta L$, the sample humidified at depth $z$ where it detects the swelling, increases with the same pace during the time Figure 3. Knowing that the swelling by strain rate is:

$$V_g = \frac{\Delta L}{\Delta t}$$  \hspace{1cm} (9)

Therefore the speed $V_g$ should follow the same variation, for the same time interval $\Delta t$. 

3.4 kinetics of the swelling ($\mu$m/s) versus time

The evolution of swelling over time is related to the distribution of swelling inter-particle and interfolaire on the one hand and the evolution of hydration in the clay structure on the other hand. The curve obtained shows the deformation of the soil due to its contact with water and it is divided into two phases: primary swelling phase and secondary swelling phase. Numerous experimental studies show this type of kinetics, such as: Seed & al. (1962); Pacher & Liu (1965); Serratrice (1996)…[17].
The pace of change obtained by our experimental method is in good agreement with that found in the literature [17].

4 Conclusion

In this work, we have performed original experimental measurements of clay soils by Hassan ASSELMAN’s method that is based on the detection of swelling using laser interferometry. This method is characterized by a very high accuracy (about 3%), sensitivity and speed of obtaining results (about an hour).

Our permeability results are in good agreement with the literature obtained by the variable load method and are close to those calculated with the simplified empirical formula of Kozeny-Carman. This study also allowed us to study the kinetics of swelling and changes in the speed of the swelling potential versus time for a swelling movement of $\lambda / 2$, to our best knowledge, this has been never achieved so far.

This method could be used in the near future to determine the specific surface of the grains in soil in a fast and accurate manner by simply measuring the permeability and void ratio.

5 Acknowledgements

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Références


16. Elena Laoura, Maderey Rascóncon, collaboration Arturo Jiménez Román Principles hidrogeografia. Study of the hydrological cycle University Texts Series, Institute of Geography National University of Autonoma México Texts University, N°.1, 2005