Thermo-osmosis
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Publisher's version / Version de l'éditeur:
https://doi.org/10.4224/20331418
Technical Translation (National Research Council of Canada), 1957

NATIONAL RESEARCH COUNCIL OF CANADA

Technical Translation TT-708

Title: Thermo-osmosis

(Thermo-osmose)

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References: Annales de l'Institut Technique du Bâtiment et des Travaux Publics, (110): 130-136, 1957

Translator: D.A. Sinclair, Translations Section, N.R.C. Library

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Preface

The Division of Building Research is studying many aspects of moisture flow in porous materials; thermally induced moisture flow is of special significance in building research. The Division is therefore pleased to include this paper in its series of Technical Translations with the permission of the author and gratefully acknowledges the work of Mr. D.A. Sinclair in preparing this translation.

Ottawa,
November 1957

Robert F. Legget,
Director

THERMO-OSMOSIS

It is my somewhat perilous privilege to deal with a difficult subject - thermo-osmosis. We shall see in the course of this paper that the phenomenon of thermo-osmosis has not, perhaps, as great an importance in practice as might have been thought at one time. However, in connection with this study, certain extremely important side issues have become apparent, and these may possibly shed a rather new light on the inter-relationships between soil and water. Therefore, I shall not hesitate, even before such a specialized audience as this, to return to the fundamentals and from time to time to give a somewhat theoretical turn to my discussion.

We have studied thermo-osmosis in connection with certain practical problems.

These problems involve cases of destructive action which have occurred in building or road foundations. The destruction resulted from the expansion of the soil beneath the foundation accompanying an increase of water content below the construction. In such cases it was thought that the water migration might be due to differences in the soil temperature produced by the presence of the construction and in accordance with the mechanism of thermo-osmosis. We therefore thought that it might be useful to see what part this phenomenon could play, so as to be able to furnish a remedy should the case arise.

There is a considerable amount of literature on destruction of this kind. It has occurred primarily in countries with large amounts of solar radiation during the greater part of the year, e.g. South Africa, Texas, and, of special interest to ourselves, North Africa and more particularly Morocco.

Now let us consider the phenomenon briefly.

The migrations of water in a soil under the influence of the temperature have been observed for some time, since Bouyoucos pointed them out in 1915. The phenomenon manifests itself as an increase of water content on the cooler side. In some earlier papers together with M.F. Soeiro[1,2] we showed that this accumulation of water at the cold end corresponded to a dynamic equilibrium: a transfer of water in the vapour phase from the warm side to the cold side is associated with an opposite movement in the liquid phase. During the period necessary for the establishment of equilibrium the transfer of water in the vapour phase is greater than that in the liquid phase and the balance of the two movements favours an accumulation of water on the cold side. At equilibrium the ratio of movement in both phases are obviously equal.

An extremely simple experimental set-up is used for studying these phenomena. It is represented in Fig. 2 . Two isothermic tanks controlled to a tenth of a degree constitute the sources of heat and cold, respectively. A cylindrical sample is placed in contact with the tanks. It is carefully insulated in order to avoid heat losses. Finally, thermocouples are placed so as to determine whether good thermal contact is obtained and to measure the temperature gradient in the sample. When the test is concluded the sample is cut into slices of equal thickness and the water content of each slice is measured. In this way the distribution of the water is obtained as a function of the difference of temperature. Fig. 2 shows a few typical distributions obtained with plateau loams. The initial water content, measured from direct samplings taken at the time of preparation of the sample, is constant. This is represented by the straight horizontal lines in Fig. 2. The ascending curves represent the water contents at the conclusion of the test. The thermal gradient if measured systematically, for the temperature drop on contact with the tank is not an apparatus constant but depends on the placing. On the other hand, the decrease in temperature towards the cold side is approximately linear and this makes it possible to discover any large error such as the presence of a fissure in the interior of the sample.

It is evident from Fig. 2 that the water content increases more or less appreciably on the cold side, depending on the initial conditions of the soil and the temperatures of the tanks. Numerous parameters can be chosen to define the initial conditions of the soil. The two essential conditions among all the possible ones are firstly the initial water content which is clearly essential to the very existence of the movement, and secondly the air content, which presents the possibility of movements in the vapour phase. The temperature enters the picture in the form of the thermal gradient and also as the mean temperature, although the latter is less important. Fig. 3 indicates the results obtained during a series of tests with a loam having the Atterberg limits LL = 34%; LP = 18%; IP = 16. These results deserve some comment. The water migration is established from water content distribution diagrams like those of Fig. 3. The graph of the mean distribution curve shows a maximum water content α_f and minimum water content α_c at the cold and warm ends respectively of the sample of length L. The water content gradient is defined by the expression $\frac{\alpha_f - \alpha_c}{L}$. The temperature gradient is expressed by $\frac{\Delta\theta}{L}$. Note that in Fig. 3.2 the water content gradient is an increasing function of the temperature which approaches a linear function. Thus, without incurring too great an error one variable may be omitted in expressing the results of tests as a function of the ratio $\frac{\text{gradient of water content}}{\text{temperature gradient}}$. Fig. 3.1 for example, indicates the variation of this ratio as a function of the initial water content. The tests were carried out on samples of constant density but varying air content. The working conditions are thus not wholly comparable and this is a second parameter which is neglected. These two simplifications in the presentation of the tests explains the scatter in the results of Fig. 3. Two systematic errors are superimposed on the experimental scatter. This could only be remedied by increasing the number of tests to an extent which seemed to us prohibitive. Nevertheless, Fig. 3 clearly shows that the transfer of water is a maximum for a water content in the vicinity of 8%. This is the initial water content which has been chosen in order to get a maximum effect.

The test results show that the movements of water cease when the initial water content tends towards zero, a result which appears obvious, and also as the soil approaches saturation. This result also appears obvious, since the gaseous phase is suppressed when part of the movement of water takes place in the form of water vapour, as we have pointed out above.

Actually, in a saturated system the phenomenon is entirely different. In such a case, if a movement could occur the water would move from the hot side to the cold side, i.e., in the opposite direction to the liquid movement of the phenomenon observed in an unsaturated medium. Thus two cases must be distinguished:

(1) The open system, where water may enter or leave the sample, in which case there is a flow through the soil;

(2) The closed system in which the water is forced to

remain in the material. When the soil is not compressible, the water cannot be displaced, but the appearance of interstitial pressure difference between the warm and cold ends is observed.

Fig. 4 shows the setup used for studying saturated media. It is entirely analagous to that of Fig. 1 except that two reservoirs are supplied in order to place the ends of the sample in contact with water. The upper diagram shows the principle of measuring the interstitial pressure, (closed system), while the lower one shows that of measuring a flow (open system). It is clear that there must be some correspondence, owing to the permeability of the soil, between the interstitial pressure difference and the flow produced by a thermal gradient. This is precisely what is found experimentally in a very satisfactory way.

Fig. 5 represents the observed interstitial pressure variation between the two ends of the sample as a function of the thermal gradient and for various temperatures. It is seen that there, too, the migration of the water is an increasing function of the thermal gradient.

Generally speaking the observed pressures are rather small, of the order of 50 gm. per sq. cm. for temperature differences up to 30°C. It is important to note, however, that the pressure differences (closed system) and the flows (open system) are multiplied by three or four when the interstitial water contains an ionizable salt. Thus, for example, pressures of the order of 200 to 300 gm. per sq. cm. are obtained.

This has been a brief summary of the fundamental phenomena which govern the movements of water in the soil under the effect of a thermal gradient.

For application to foundation practice the two phenomena must be separated. The water migrations due to a difference of temperature in a saturated soil do not appear to play a very important role. In fact, interstitial pressures of the order of 50 gm. per sq. cm. are not high and in general can be neglected without incurring serious difficulties. However, interstitial pressures of 200 to 300 gm. per sq. sm. are not negligible, and in certain cases, e.g. under a foundation floor when the soil contains gypsum or marine salts, it is certainly desirable to check on whether the temperature conditions may be such as to produce a movement of water accompanied by settlements or expansions.

In the case of non-saturated media it has already been shown that appreciable increases of water content can be obtained, since it is possible to start with a mean initial content of 8% at the beginning of the test and arrive at a water content of the order of 13 or 14%. Such a variation may be accompanied by changes in the mechanical properties capable of producing trouble.

We therefore wished to see what took place when the phenomenon was more complex, and in order to go outside the framework of the sample we represented the natural conditions as found in the soil under a foundation on a reduced scale.

Fig. 6 represents the distribution of temperature under a foundation in a soil assumed to be homogeneous. The thermal field was established by electrical analogy and the figure represents only the left half of the field, which is symmetrical with respect to the axis of the foundation. The dimensions of the model were chosen so as to approximate a real foundation.

The lower temperature was 20°C., representing the mean temperature of the soil. The surface temperature was 50°C., which is very high. The purpose of this was to make the test clearer. The temperature of the foundation was 35°C. This distribution of thermal conditions to the boundaries of the model corresponds to summer conditions. The distribution of temperatures was checked by means of a preliminary model to make sure that the limiting conditions were realized and in particular that the thermal exchanges could proceed easily.

Fig. 7 represents the distribution of the water content below the foundation in the reduced model. The initial water content was 11% and after the test we found 5 to 6% at the surface and 13% at the base. Underneath the foundation a uniform zone was found where the water content remained in the vicinity of 13.2%.

It may be thought, therefore, that there is an accumulation of water below the foundation. However, this result must be taken with certain reservations and for that reason we shall present a somewhat tendentious argument, but one which will give an approximate idea of what may take place.

The water content distribution in Fig. 7 corresponds to a state of equilibrium. But this state has been obtained by means of a closed system, i.e., no water has been allowed to leave the model at any time. We are not speaking about the condition at the surface, where we have systematically avoided evaporation in order to have a simple phenomenon but, regardless of everything else, it can be assumed that migrations of water will take place below the surface of a soil, i.e., there is a possibility of its return to the water table, or conversely, of water being drawn from the water table.

In the model presented here, let us associate a mass of soil of water content again 13% and temperature 20° in equilibrium with a water table at a certain depth. The superposition of these two states in equilibrium gives us approximately the pattern of an open system. In the absence of a thermal field the mean water contant in the model would be determined by that of the base. For a shallow model containing loam we may expect to have a constant water content, hence, in this case, in the vicinity of 13%.

Finally, the water of the model would simply be drained towards the cool source. This is just what has been observed on samples. Below the foundation we note that a constant water content, perhaps slightly above 0.2%, is retained, which is very small, especially if we take into account the differences in the chosen temperatures.

We have said above that this argument was tendentious. Actually the equilibrium observed in unsaturated media is a dynamic one with a return circulation - vapour exchange towards the cool side and liquid exchange towards the warm side. When two masses in equilibrium, one of which is dynamic, are superimposed, there is certain to be a disturbance. Furthermore, a discontinuity of the thermal gradient is introduced into the zone of contact. The primary purpose of this argument is to show that the result obtained with a closed model cannot be transferred directly to the situation in nature when any liaison with the water table is possible.

Before concluding this paper we shall just touch briefly on certain associated problems relating to the migrations of water in the soil.

A number of authors who have studied the problems of thermo-osmosis have carried out measurements of the electric potential. These measurements are very important and we have also produced some measurements of this kind, although for a different purpose. We shall return to them subsequently.

There are several reasons for measuring electrical potentials. It can be supposed, for example, that mere application of a temperature difference leads to an electrical potential, somewhat like the classical thermo-electric effect. In such a case, if an electric potential did appear, then the observed water migrations might be due to electro-osmosis rather than thermo-osmosis, which would become a secondary phenomenon.

It may also be said, however, that as soon as a water migration takes place an electric potential may become associated with it due to a reciprocal electro-osmosis effect. The electric potential then becomes a phenomenon which is secondary in relation to the migration of the water.

The problem which we set ourselves was of a purely experimental nature. In order to discover the different parts played by the movements in the vapour and liquid phases we introduced radioactive salts[1] for the purpose of marking the interstitial water. This radioactive tracer (IK) was an ionized salt. The question was whether the existence of an electric field in a sample could not produce a migration of radioactive iodine atoms in the water of the soil.

The results of our potential measurements were disappointing. We were unable to measure anything, or rather we measured nothing in particular. The voltages were erratic and moved about without any relation to the direction of the thermo-osmotic migrations. This is especially distrubing in view of the fact that these measurements are very delicate. We shall not report here on the somewhat tiresome experimental details of these measurements, which may be found elsewhere(2). It may be stated, however, that it was necessary at times to measure currents of the order of 10^{-9} amp., at which point rather difficult problems of insulation and manipulation begin to arise.

Potentials were indeed observed, but these existed as soon as the electrodes were placed in the soil and a spontaneous discharge occurred independently of the movements of the water. This occurred both in closed and open systems, and in both saturated and unsaturated soils.

Fig. 8 indicates the extremely simple setup employed. At the left is the sample with the two tanks to ensure circulation of the water. This is an open saturated system. On the right is an electrical circuit with a galvanometer, a shunt, a resistance box and platinum electrodes as potential taps. With this apparatus no electric current could be associated with the movement of the water by thermo-osmosis.

Now, with a saturated system, since there is a movement of the water, there should be an electric current due to the reciprocal electro-osmosis effect. Casagrande, for example, goes so far as to suppose that the power of the water diviners may be nothing more than a special ability to detect the currents produced in the soil by the circulation of the water due to the reciprocal electro-osmosis effect.

On the other hand, an important problem is posed by the capillary stoppages which have been observed by many authors. If there is a reciprocal electro-osmosis effect the electromotive force which appears must be opposed to the generating motion. Now, in the shearing of a soil a certain interstitial pressure u is developed and if there is any capillary stoppage this pressure cannot find an escape.

All this needed to be verified by means of a simple seepage test. The measurments carried out were not able to show any electric potential.

Fig. 9 shows the spontaneous decrease observed when two electrodes are placed in the soil. This is an electric phenomenon where the decrease is almost a straight line in semi-logarithmic co-ordinates.

At different times we made water circulate through the sample,now in one direction, now in the other. These correspond to the jogs in the curve of Fig. 9. The increases are produced by the mechanical application of pressure on the electrodes, modifying their contact with the soil. The phenomenon is easily reproduced by applying a restraint to the soil. After this small disturbance has taken place it is observed that the slope of the decrease remains quite independent of the water seepage. The phenomenon is very clear. We reproduced it with four soils of different grain size and different permeability coefficients without observing any appreciable differences.

This places in doubt Helmoltz' theory of electro-osmosis.

According to Helmoltz the free positive ions of the double film surrounding the particles are attracted to the negative pole and carry the interstitial water with them. If the reciprocal does not exist this does not necessarily disprove Helmoltz' theory, but the doubts which arise are all the stronger since it has already been criticized. M. Darmois[3] has put forth a theory explaining electro-osmosis in terms of electrolysis phenomena. According to this theory the ions of the interstitial water are accompanied by a cloud of water molecules. The movement of the ions in the electric field is associated with transfers of water towards the electrodes. The balance sheet of water arriving at the positive and negative poles corresponds to what is transferred by electro-osmosis.

Darmois' theory arrives at exactly the same quantitative laws as Helmoltz', but it opens up new territory in the study of electro-osmosis. It has been shown experimentally, for example, that the electro-osmotic coefficient of permeability is independent of the nature of the soil. In Helmoltz' double film theory this is not very clear; however, if the movement is due to an electrolysis of the water it may be understood why it might be independent of the nature of the solid medium.

This concludes the considerations raised by the problem of thermos-osmosis and shows that phenomena involved are often complex and that what starts out as a practical problem often leads into a consideration of what takes place in an exceedingly detailed way at the very heart of matter.

References

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2. Habib, P. and Soeiro, F. Les Mouvements de l'eau dans les sols sous l'influence de la temperature (Movements of water in soils under the influence of the temperature) Cahiers de la Recherche CEBTP, 1957.

3. Darmois, E. Compl. Rend. 227: 339, 1948.

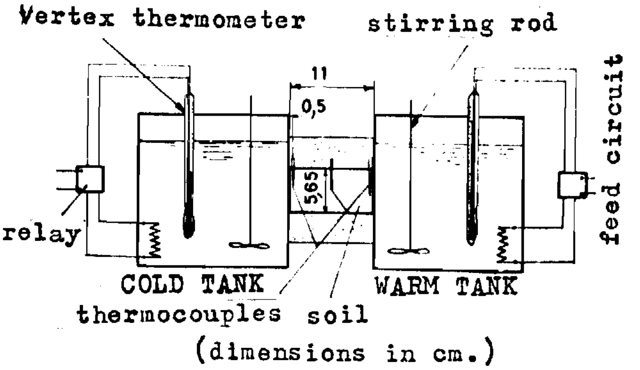


Fig. 1

Apparatus. Unsaturated medium closed system

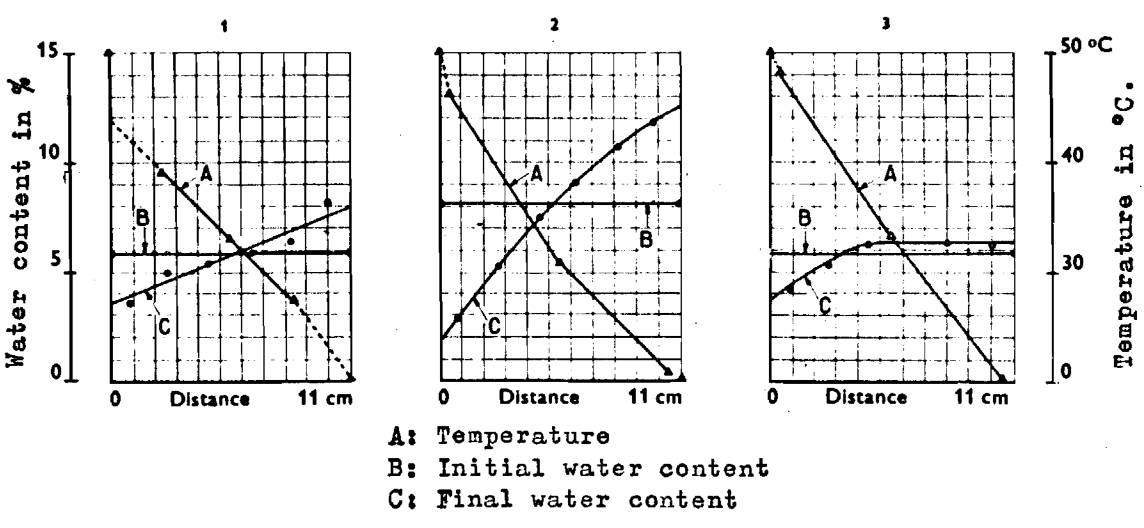
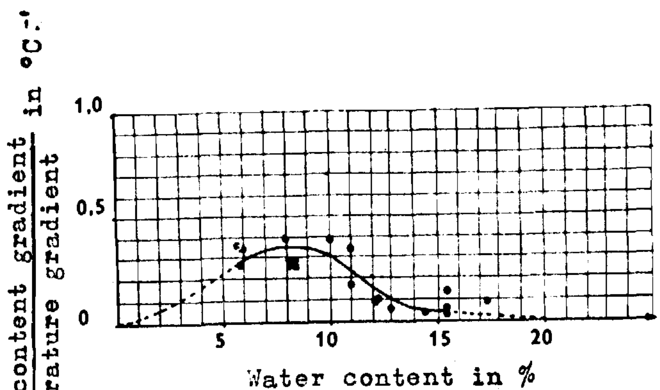


Fig. 2

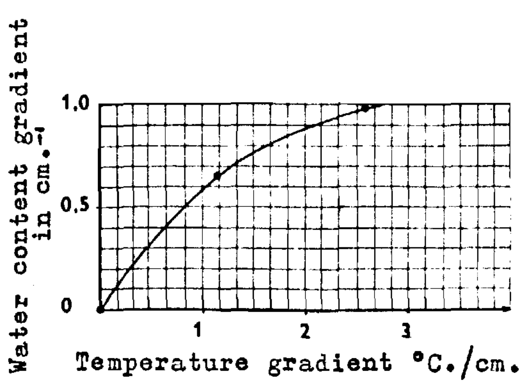
Distributions of water content and temperature in three samples



Mean temperature 33 to 34°C.
Water content at saturation 20 to 22%
Dry density = 1.7

Fig. 3.1

Effect of water content on the migration of water



Water content 8.1%
Air content 26% of total volume
Mean temperature 33°C.
Dry density = 1.7

Fig. 3.2

Effect of temperature gradient on moisture transfer

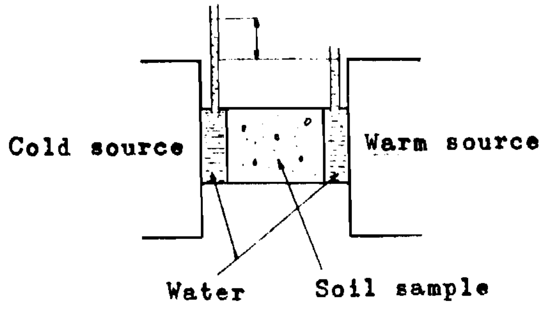


Fig. 4.1

Measurement of interstitial pressure in saturated soil samples

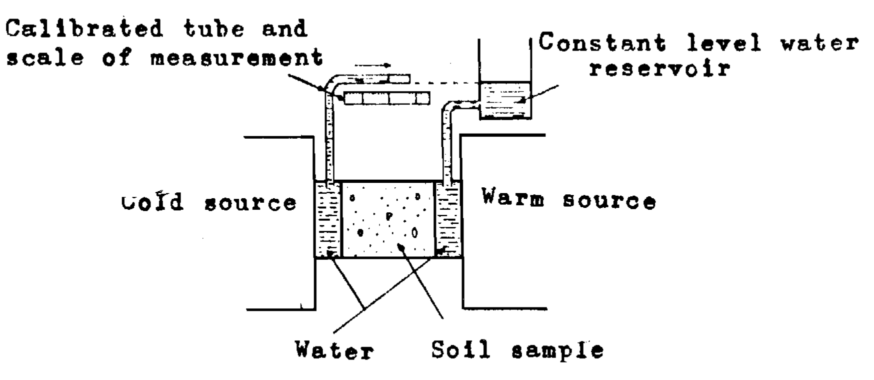


Fig. 4.2

Measurement of flow in saturated samples

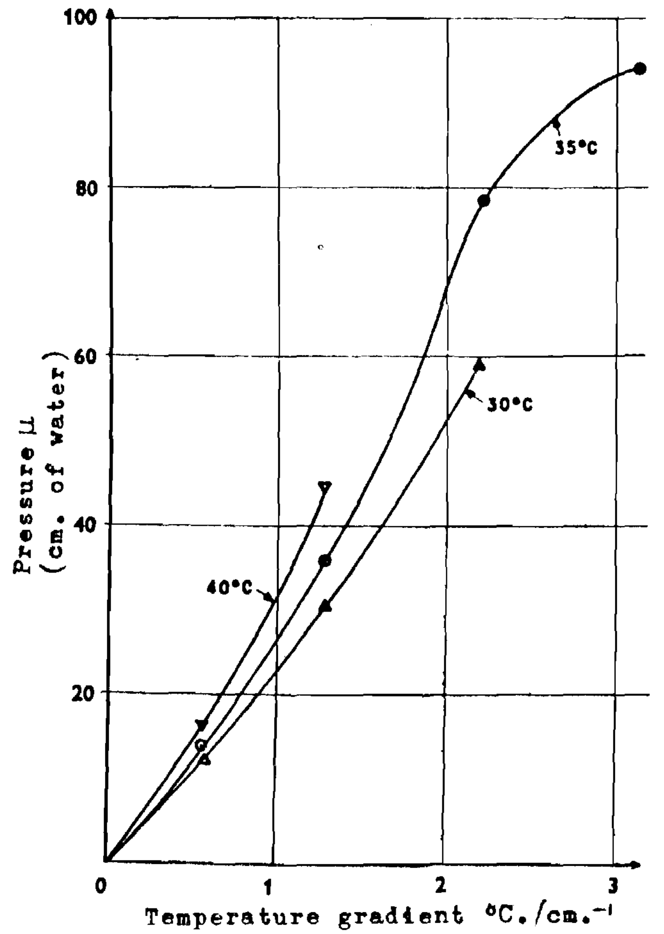


Fig. 5

Interstitial pressure as a function of the temperature gradient for various mean temperatures (30, 35 and 40°C.) measured in a sample of Orly loam

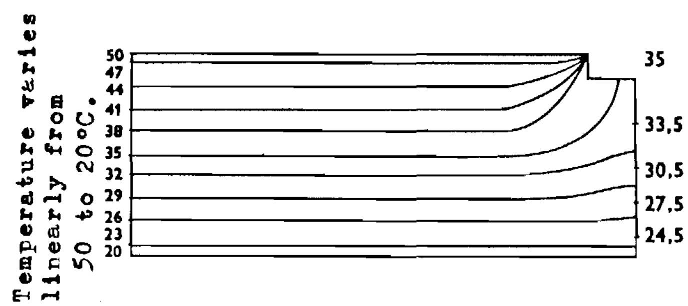


Fig. 6

Temperature field in the soil for a summer regime (temperature in °C.)

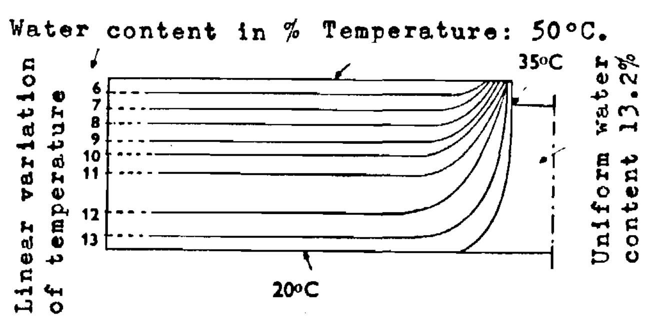


Fig. 7

Water content distribution in the model under the influence of a temperature field

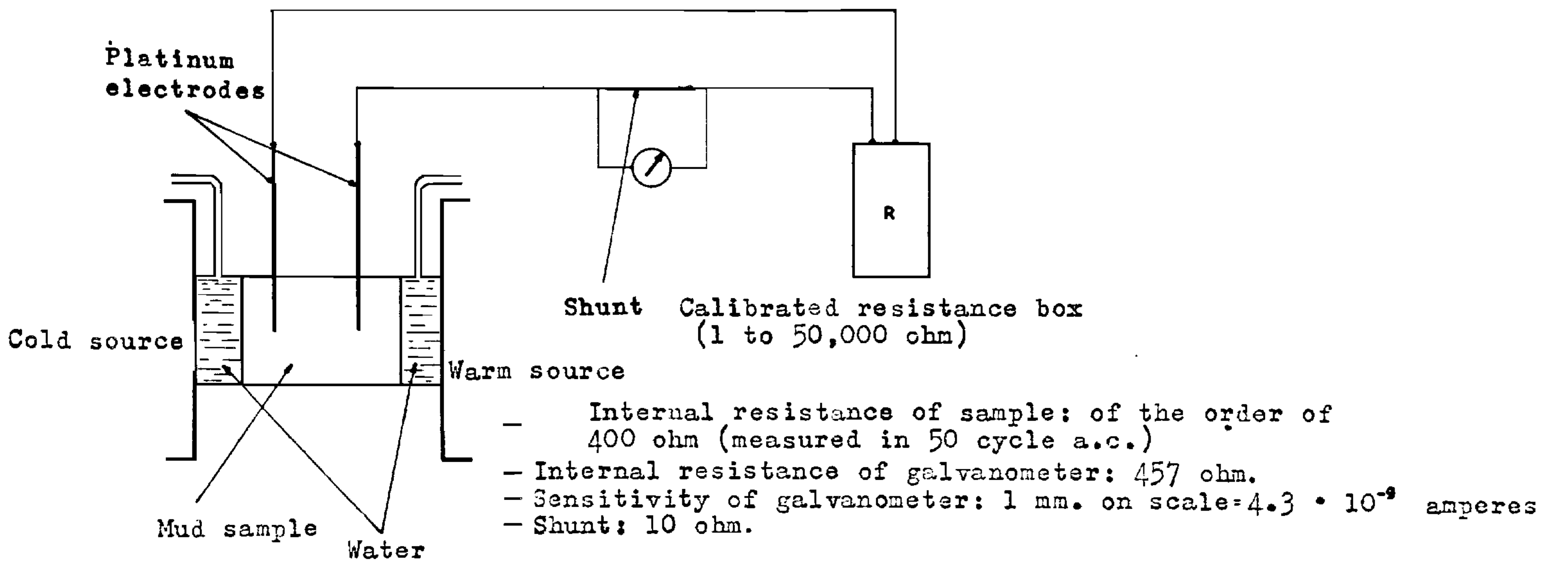


Fig. 8

Apparatus for measuring potentials

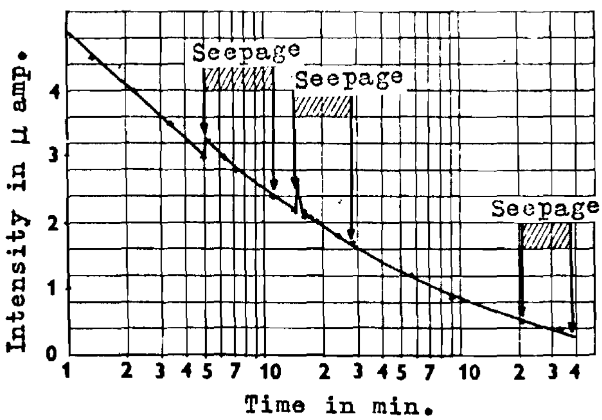


Fig. 9

Variation of electric current as a function of the time, with and without circulation