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[54] **METHOD AND APPARATUS FOR DETERMINING THE PERMEABILITY CHARACTERISTICS OF A POROUS OR FISSURED MEDIUM**

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[58] **Field of Search** 73/151, 152, 155; 166/120, 166/179

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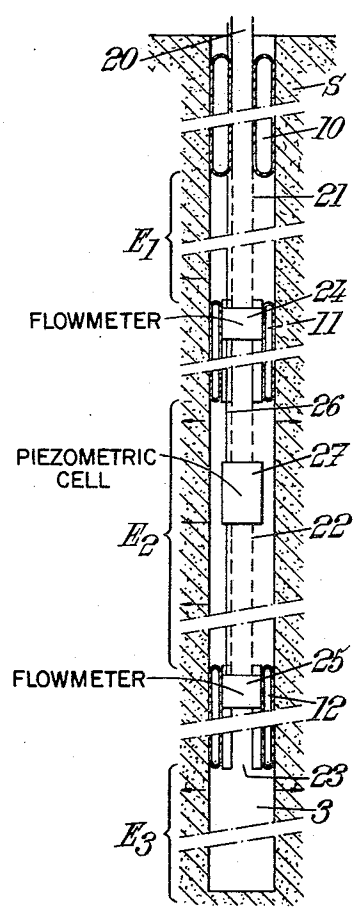
[57] **ABSTRACT**

A borehole is formed in the medium and divided along its axis into three adjacent cavities, separated from one another and comprising two protecting end cavities enclosing an intermediate measuring cavity. A flow of a liquid is produced in each of the cavities and in the regions of the corresponding medium. Measurements are effected of the flow-rate of liquid flowing in the intermediate cavity and of the liquid pressure in intermediate cavity and in the corresponding region of the medium, at known distances from the axis of the borehole.

7 Claims, 5 Drawing Figures



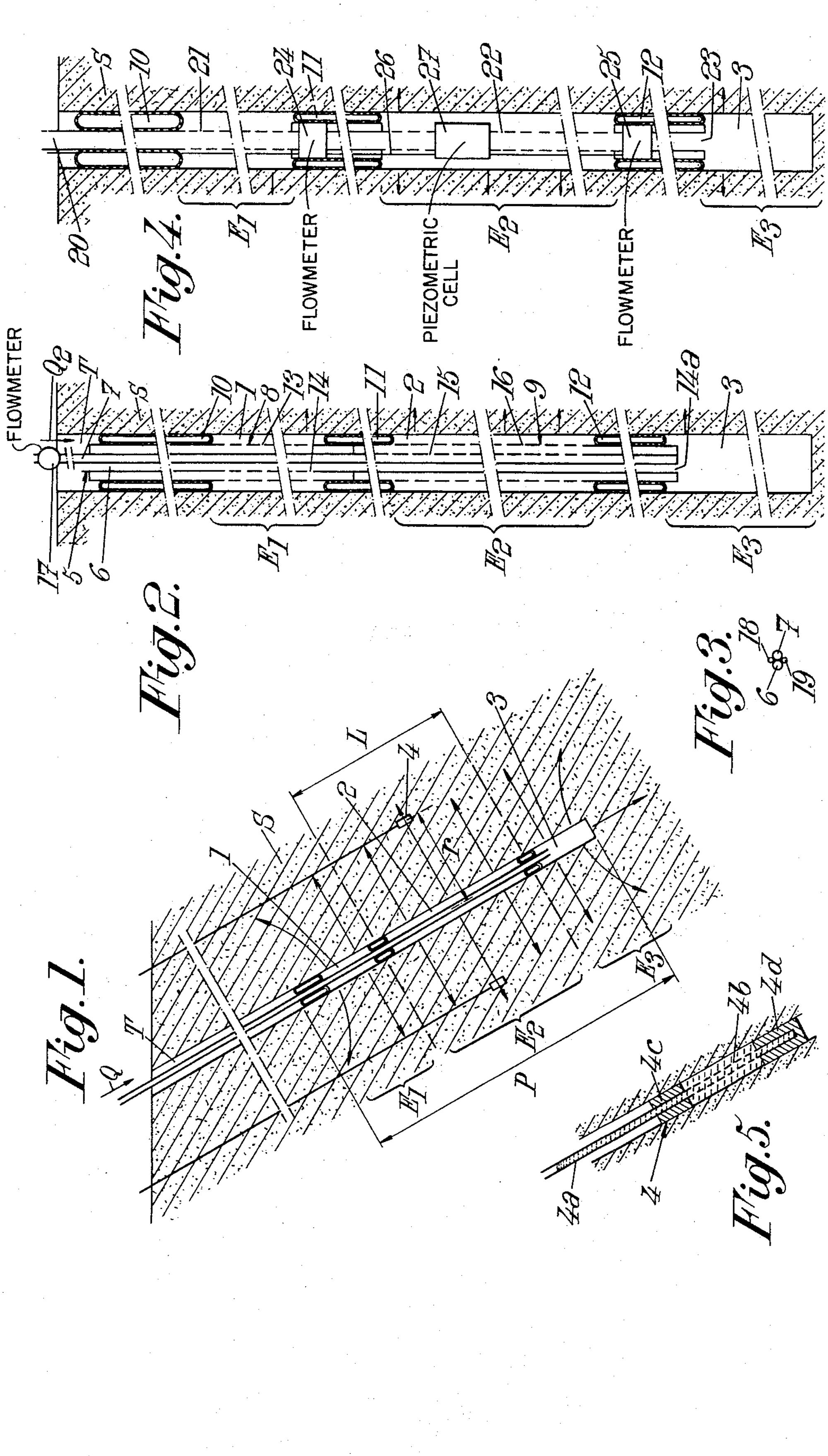


Fig.1.
Fig.2.
Fig.3.
Fig.4.
Fig.5.
FLOWMETER
FLOWMETER
PIEZOMETRIC CELL
FLOWMETER

METHOD AND APPARATUS FOR DETERMINING THE PERMEABILITY CHARACTERISTICS OF A POROUS OR FISSURED MEDIUM

The invention relates to a method for determining the permeability characteristics of a porous or fissured medium, especially of soils and of rocks, according to which there is used a flow of liquid, in the medium, caused by the injection or pumping of the liquid into a borehole.

The invention relates more particularly, because it is in this case that its application seems to present the most advantage, but not exclusively, to a method for the determination of the hydraulic parameters of the sub-soil.

It has already been proposed to carry out hydraulic tests in situ, on a large scale, of which the results are more significant than those of laboratory trials, but the interpretation of the results of these trials is rendered very difficult by the fact that, on the one hand, the test cavity is often badly defined and that, on the other hand, the nature of the flows is not known. Under these conditions, a strict interpretation of the results cannot be made since the contribution of each directional permeability is poorly known or, for anisotropic media, the directional or principal permeabilities are unequal. Even for isotropic media, the correct interpretation of the tests remains delicate since the relative importance of planar or cylindrical radial flows and of spherical flows is not known, the equations being different for each type of flow.

It is a particular object of the invention, to render the abovesaid method such that it responds to the various exigencies of practice better than hitherto and especially such that it no longer has, or has to a lesser degree, the above-mentioned drawbacks of the prior art.

According to the invention, a method for determining the permeability characteristics of a medium, especially of soils and of rocks, according to which there is used a flow of liquid, in the medium, caused by the injection or pumping of liquid into a borehole, is characterised by the fact that, on the one hand, at least a portion of the borehole is along the axis of this hole, into three adjacent cavities, separated from one another, comprising two protective end cavities, surrounding an intermediate measuring cavity, that on the other hand, there is produced in each of the cavities, and in the corresponding regions of the medium, a flow of liquid and that on the other hand lastly, there is effected a measurement of the flow-rate of liquid flowing in the intermediate cavity and measurements of the pressure of the liquid in this cavity and in the corresponding region of the medium, at known distances from the axis of the borehole.

Preferably, the axis of the borehole is parallel to an assumed principal direction of permeability, in the case of media considered as continuous.

In the case of a fissured discontinuous medium, having three families of parallel fissures, the axis of the borehole is taken as parallel to the direction of the intersection of two families of fissures.

The invention also relates to an apparatus for the application of the previously defined method.

In a first embodiment, such an apparatus is characterised by the fact that it comprises at least two separate tubular pipes, adapted to be introduced into the borehole and at least two closures adapted to close, at three different places, the annular space comprised between the outer walls of the pipes and the wall of the borehole, so as to bound, in a portion of the borehole, three separate adjacent cavities, the abovesaid pipes being provided with openings situated so that one of the pipes communicates with the intermediate cavity whilst the other pipe communicates with the two end cavities, a flow meter being provided at least in the pipe communicating with the intermediate cavity.

In another embodiment, the apparatus is characterised by the fact that it comprises a single tubular pipe adapted to be introduced into the borehole and at least three closures adapted to close, at three different places, the annular space comprised between the outer wall of the pipe and the wall of the borehole, so as to bound, in a portion of the borehole, three separate adjacent cavities, the abovesaid pipe being provided with openings terminating in each of the three cavities, two flow meters being provided, in the said pipe, respectively at the two ends of the intermediate cavity, for the measurement of the flow-rate of liquid at the inlet and at the outlet of this cavity.

The invention consists, apart from the features mentioned above, of certain other features which are preferably used at the same time and which will be more explicitly considered below with reference to preferred embodiments of the invention which will now be described in more detailed manner with reference to the accompanying drawing, but which are not of course to be regarded as in any way limiting.

FIG. **1** of this drawing is a diagram illustrating a determination of the permeability characteristics of a soil carried out by the method according to the invention.

FIG. **2** is a diagrammatic partial longitudinal section, of a first type of apparatus for the application of the method according to the invention.

FIG. **3** is a cross-section of the pipes of the apparatus of FIG. **2.**

FIG. **4** shows similarly to FIG. **2**, another type of apparatus.

FIG. **5**, lastly, is an enlarged diagrammatic section of a piezometer.

Referring to FIG. **1** it is seen that for determining the permeability of a medium, constituted by soil S or rock, a flow of liquid caused by the injection of this liquid into a borehole T is used. In certain cases, especially when the determination of the permeability of the soil takes place in a zone of the latter situated below the phreatic layer or water table, this determination can be effected by the pumping of water from the soil into the borehole, instead of the aforesaid injection.

The total flow-rate of the liquid injected into the borehole T is denoted by the letter Q which, in FIG. **1**, is arranged at the side of an arrow indicating the direction of flow of the liquid into the borehole T.

A portion P of the borehole T is divided, along the axis of this hole, into three adjacent cavities respectively **1**, **2** and **3**.

In FIG. **1**, the end cavity **3** most distant from the inlet of the borehole T is bounded, on one side, by the bottom of this borehole. However, the part P does not necessarily extend to the bottom of the borehole but can be bounded by a closure (not shown), especially if the flow-rate in this cavity is very great.

The three cavities are separated from one another, and the two end cavities **1** and **3** constitute protective cavities which enclose the intermediate cavity **2** constituting the measuring cavity.

The injection of liquid into the borehole T enables a flow to be caused in each of the cavities **1, 2** and **3** and in the corresponding regions of the soil. The flow E_2 of the intermediate cavity **2** can be characterised independently of the flows E_1 and E_3 of the end cavities.

The flow-rate of liquid Q_2 in the intermediate cavity **2** is measured. There is also measured the pressure of the liquid in this cavity and in the region of the soil S corresponding to this cavity, the measurements in the soil S being carried out at known distances *r* from the axis of the borehole. These pressure measurements are effected by means of piezometers **4** introduced into the soil and connected to the surface of the latter.

FIG. **5** shows a preferred embodiment of a piezometer **4**.

The latter comprises a tube **4***a*, extended at its lower end by a strainer **4***b*. Annular closures **4***c* and **4***d* are provided around the tube, at the longitudinal ends of the strainer **4***b*. The closure **4***d* closes the lower longitudinal end of this strainer **4***b*.

The piezometer **4** is introduced into an auxiliary borehole parallel to the principal borehole but of smaller diameter. The zone of the auxiliary borehole comprised between the closures **4***c*, **4***d* collects liquid coming from the intermediate cavity **2**. This liquid rises in the tube **4***a* under the effect of the pressure. In measuring the height of the rise of the liquid in the tube **4***a*, by means of an electric probe for example, the pressure of the liquid in the zone of the auxiliary borehole concerned is determined. This zone and the distance between the closures **4***c* and **4***d* can be much reduced so that the measurement of pressure is carried out substantially at one point in the soil.

From the results of the measurements, it is possible, by means of mathematical formulae, to deduce the permeability of the soil in the direction of flow E_2.

In the case of an isotropic medium and of a flow E_2, in directions perpendicular to the axis of the borehole, the difference in hydraulic potential $\Delta\Phi$ at two points of the soil S distant by r and r_o from the axis of the borehole is connected with the flow-rate liquid Q_2 by the following formula:

$$\Delta\Phi = Q_2/L1/2\pi K_R \operatorname{Log} r/r_o + \Phi e \quad (1)$$

in which formula:

Q_2 is the flow-rate measured,

L is the dimension of the cavity **2** along the axis of the borehole,

Kr is the average permeability of the soil, in a plane perpendicular to the axis of the borehole.

Φ_e is equal to the outer potential existing at the center of the bore before the test; to a first approximation this term Φ_e can be neglected.

FIG. 2 shows a first type of apparatus enabling the application of the method discussed above.

The measuring apparatus or probe **5** comprises two distinct tubular pipes **6** and **7** arranged side by side and tangential along a rectilinear generator. These pipes are arranged in two (or more) superposed sleeves **8** and **9**. However, the pipes **6** and **7** could be inserted into the borehole T, without being surrounded by sleeves **8** and **9**.

The probe **5** comprises also at least three closures **10** and **12** adapted to close, at three different places separated along the axis of the borehole, the annular space comprised between the wall of the borehole T and the outer walls of the sleeves **8** and **9**. In this way, there are obtained three adjacent cavities **1, 2** and **3**.

Preferably, the closures are of the pneumatic type and constituted by inflatable air chambers. Compressed air pipes (not shown) are provided in the borehole T for the inflation of these closures.

The upper closure **10**, that is to say that situated at the side of the inlet of the borehole T, has a length along the axis of the borehole, greater than that of the other closures. In fact, this closure is subjected to pressures very different at its two ends since on one side it is subjected to the liquid pressure occurring in the cavity **1** whilst, on the other side, it is subjected simply to the atmospheric pressure increased by that of the columns of water possibly present in the bore above the closure. There is given, for example, to the length of the closure **10**, a length three times that of the closures **11** and **12**.

Each sleeve **8** and **9** is formed by a cylindrical envelope generally metallic or of plastics material. At its two ends, this envelope is connected in fluidtight manner by a circular ring, to the outer wall of the pipes **6** and **7**. The contact zone of the sleeve **8** with the sleeve **9** is covered by the closure **11**.

The end zone of the sleeve **8** turned towards the inlet of the borehole T is surrounded by the closure **10**. The wall of the sleeve **8** comprises orifices **13** enabling a radial flow of the liquid towards the soil S. The wall of the conduit **6** comprises, in the zone comprised axially between the closures **10** and **11**, further orifices **14**, enabling a radial flow of liquid towards the soil S. The pipe **6**, in addition, opens through an orifice **14***a* into the end cavity **3**. The supply of liquid to the cavities **1** and **3** is hence ensured by the single pipe **6**. In a modification, there could be provided a supply pipe belonging to each cavity **1** and **3**.

The wall of the pipe **7** comprises orifices **15**, in the zone situated axially between the closures **11** and **12**, which enable a radial flow of the liquid towards the soil S. The wall of the sleeve **9** comprises orifices **16** enabling the passage of this liquid towards the soil S. The sleeve **9** and the pipe **7** are closed at their end turned towards the bottom of the hole T so that mixing of the fluids injected, respectively, through the pipes **6** and **7** cannot occur there.

A flow meter **17** is provided in the pipe **7**, at the surface, this flow meter enabling the flow-rate Q_2 of the flow E_2 to be known. Possibly, there could be provided another flow meter in the pipe **6** which would indicate the total of the flow rates of the flows E_1 and E_3.

An approximate value of the pressure of the liquid in the cavity **2** can be obtained by the measurement, at the surface, of the pressure of the liquid in the pipe **7**. However, by reason of the load losses which can be high if the length of the pipes **6** and **7** is great and if the flow-rates are high, it is preferable to measure the pressures directly in the test cavities **1, 2** and **3**, by providing either pressure detectors (not shown) lodged in these cavities, or auxiliary pipes **18, 19** (FIG. **3**) of small cross-section, connecting respectively the cavity **2** and the cavities **1** and **3** to the surface of the soil. The pipes **18** and **19**, in which no flow takes place, can be of small section without introducing load losses.

It will be noted, to conclude with this first type of apparatus, that the two pipes **6** and **7** can be produced in a different form from that described with reference to FIGS. **2** and **3.** For example, these two pipes can be obtained by a coaxial double casing, or by a single tube divided, in the direction of the length, by a partition extending in a diametric plane of this tube, the said partition separating the tube into two independent parts of which the cross-sections are semi-circles.

Referring to FIG. **4,** there can be seen a second type of probe comprising a single tubular pipe **20.** This probe comprises, as in the case of FIGS. **2** and **3,** the three closures **10, 11** and **12** bounding the cavities **1, 2** and **3.**

The pipe **20** comprises openings **21** in the portion of its wall comprised between the closures **10** and **11** and openings **22** in the portion of its wall comprised between the closures **11** and **12.** The pipe **20** opens at its lower end through an opening **23** into the cavity **3.**

The first flow meter **24** is provided at the inside of the pipe **20**; it is situated in the axial direction of the borehole, at the level of the closure **11,** that is to say at the separation of the cavities **1** and **2.** This flow meter **24** is hence adapted to measure the flow-rate of liquid entering the cavity **2.**

A second flow meter **25** is provided, at the level of the closure **12,** between the cavities **2** and **3.** This flow meter **25** is adapted to measure the flow-rate of the liquid which enters the cavity **5.** The flow-rate of liquid Q_2 of the flow E_2 is hence equal to the difference of the flow-rates measured respectively by the flow meter **24** and the flow meter **25.** These flow meters are of the electrical transmission type and are connected to the surface by electrical cables **26** adapted to transmit the information provided by these flow meters.

A piezometric cell **27,** also of the electrical transmission type, is provided in the cavity **2** for the measurement of the liquid pressure in this cavity. The pressure could be also measured by an auxiliary piezometric tube.

It will be noted that the probe of FIGS. **2** and **3** enables the establishment in the cavity **2** of a pressure different from that which exists in the cavities **1** and **3,** so that, as will be seen in the following, there can be introduced, in the course of a test, the permeability of the soil in a direction parallel to the axis of the borehole. On the other hand, the probe of FIG. **4,** due to the fact that it only comprises a single pipe **20** for the simultaneous supply of the cavities **1, 2** and **3,** only enables operation at the same pressure in the said cavities.

The two probes can be moved in the borehole for measurements in different places.

To carry out correct measurements of the permeability of a medium considered as continuous, the axis of the borehole is oriented in the direction of principal permeability, which must hence be assumed, so that all the principal permeabilities do not come into play simutaneously in the course of a test.

The flow E_2, coming from the measurement cavity **2,** being a flat radial flow at right angles to a principal direction of permeability, only the two other principal permeabilities will effect the flow-rate of this flow.

The abovesaid direction of principal permeability is an assumed direction deduced from geological knowledge. For example, for sedimentary terrains it is known that a direction of principal permeability is perpendicular to the sedimentary layers whilst the two other directions of principal permeability are parallel to these layers.

In the case of a discontinuous medium, for example in the case of fissured rocks, with three systems of parallel fissures, the direction of a bore, to test one of the fissured systems, will be taken parallel to the intersection of the planes of the two other systems of fissures.

Then, by keeping the pressures in the cavities **1, 2** and **3** equal, there is effected a flat radial flow E_2, in a certain region, of which the flow lines are at right angles to the assumed principal directions. On the other hand, the flows E_1, E_3 corresponding to the protective cavities **1** and **3,** are not entirely of the flat radial type.

In the case of a simple test, there is measured during this test, the hydraulic load Φ_o in the cavity **2.** This hydraulic load is constant in this cavity and especially for any point taken on the lateral wall of this cavity. Φ_o represents therefore the hydraulic load in the soil at a distance from the axis of the borehole equal to the radius r_o of this borehole.

There is carried at least one other pressure measurement to be able to use the formula (I) (or a formula more appropriate to the experimental conditions).

This pressure measurement can be replaced by a measurement, before the test, in the borehole. The result of this measurement Φ_x (static level of the phreatic layer) corresponds, during the test, to the pressure which exists at a point of the soil situated at a distance from the axis of the borehole, equal to the radius of the action of the test. This action radius can be calculated empirically.

If the medium is continuous but is not isotropic, the value K obtained by the formula (I) is equal to the geometric mean of the principal permeabilities in the plane perpendicular to the axis of the bore.

It is possible, by effecting several pressure measurements in the soil along vector radii, starting from the axis of the borehole, and at different polar angles, to trace ellipses corresponding to equipotential lines. By determining the directions of the axes of these ellipses, there is determined the principal directions of permeability in the plane at right angles to the axis of the borehole.

These directions of principal permeability being determined, an analytical calculation, using the result of the measurement of the flow-rate of the flow E_2, enables the determination of the values of the two principal permeabilities in a plane perpendicular to the axis of the borehole.

Whilst keeping equal the pressures in the cavities **1, 2** and **3,** it is possible to deduce the third principal permeability, that is to say the permeability along the axis of the borehole, while measuring the total flow-rate in the cavities **1, 2** and **3,** which brings into play the permeability along the axis of the borehole, and by bringing into play the results of the first test phase.

There could, however, in the case where the probe of FIG. **2** is used, be brought into play in more sensitive manner the permeability along the axis of the borehole by establishing a difference of pressure between, on one hand, the cavities **1** and **3** and, on the other hand, the cavity **2.**

To improve the accuracy of the measurements, that is to say particularly, in order that the flow E_2 may depart as little as possible from a theoretical radial plane flow, the length L, along the axis of the borehole, of the measuring cavity **2,** is limited.

To effect this limitation flow lines have been drawn, in a plane passing through the axis of the borehole, from probable hypotheses.

According to the distance to the axis of the borehole, at which the pressure measurements are made, the length of the measuring cavity is limited so that the flow lines coming from this cavity, do not separate, angularly, beyond a predetermined limit, (10° for example) from directions at right angles to the axis of the borehole.

For a study in depth of the permeability characteristics of a continuous medium, bores are made along the three presumed principal directions of permeability and measurements are made along these three directions.

In the case of a discontinuous medium constituted by fissured rocks having three parallel families of fissures, the bores are effected along the directions of the intersections of two families of parallel fissures.

The method and the apparatuses according to the invention can be used in numerous fields where problems of flow of fluids in porous or fissured media arise, as for example in civil engineering (subterranian hydraulics of soils and of rocks), in geohydrology, in the field of mining operations, of petroleum production, of techniques relating to artificial porous media such as filters for the chemical industry or ceramics, etc . . .

I claim:

1. Method for determining the permeability characteristics of a porous or fissured medium, comprising forming a borehole in situ in the medium, dividing said borehole along its axis into three adjacent cavities, separated from one another and comprising two protecting end cavities enclosing an intermediate measuring cavity, producing a flow of a liquid in each of the cavities and in the corresponding regions of corresponding medium, the direction of flow with respect to the medium being the same for each cavity, and effecting measurement of the flow-rate of liquid flowing in the intermediate cavity and measurements of the liquid pressure in said intermediate cavity and in the corresponding region of the medium, at known distances from the axis of the borehole and determining the permeability characteristics from said flow-rate and said liquid pressure measurements.

2. Method according to claim **1**, to determine the permeability characteristics of a fissured discontinuous medium having three families of parallel fissures, comprising orienting the axis of the borehole parallel to the direction of the intersection of two of said families of fissures.

3. Measuring apparatus for determining the permeability characteristics of a porous or fissured medium, comprising at least two separate main pipes adapted to be introduced into a borehole formed in said medium and at least three closures adapted to close, at three different places, the annular space comprised between the outer walls of the pipes and the wall of the borehole, in such a way as to define, in a part of the borehole, three adjacent separate cavities, the abovesaid pipes being provided with openings so-situated that one of the pipes communicates with the intermediate cavity and is closed at its lower end turned towards the bottom of the borehole so that mixing with fluid entering or leaving the other pipe does not occur while the other pipe communicates with the two end cavities, a flow meter being provided at least in the pipe communicating with the intermediate cavity.

4. Measuring apparatus according to claim **3**, comprising auxiliary pipes connected to the surface of the soil and terminating respectively in the end cavities and in the intermediate cavity and enabling the pressure to be measured in these cavities.

5. Measuring apparatus according to claim **4**, wherein the two main pipes and the two auxiliary pipes aie arranged side by side.

6. Measuring apparatus according to claim **3**, wherein the closures are of the pneumatic type.

7. Measuring apparatus according to claim **6**, wherein the closure situated at the extremity of an end cavity, distant from the intermediate cavity, has a greater length than that of the closures situated at the two extremities of the intermediate cavity.

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