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A Physical Model Hole Experiment for Determining Hydraulic Constants in Boreholes using an Electrical Conductivity Log Technique.

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ABSTRACT: A geophysical conductivity logging technique has been adopted to determine hydraulic constants using a simplified physical model that depicts the borehole condition. This study has been made as a preliminary test preceding the in-situ borehole test, and the emphasis was made on finding a model equation for determining hydraulic constants from the relationship between the conductivity change and the actual flow rate. An experiment has been made by monitoring the conductivity change within the model hole using borehole environment water and incoming-outgoing water of different salinity, under the state of constant flow rate by maintaining balance between inflow and outflow. Conductivity variation features were observed that depended on flow rate, salinity contrasts between fluid within the hole and incoming-outgoing fluid, and density contrasts between fluid within the hole and incoming fluid. The results of the experiment show that the change of fluid conductivity within the hole is very uniform with time, and that a fairly good correlation exists between the flow rate and the conductivity change rate. The best result is expected when the density contrast between the borehole fluid and the incoming fluid is as small as possible while the conductivity contrast is as large as possible. The geophysical conductivity logging technique can be an efficient way to determine the hydraulic constants if the model equation is verified by comparing the log hydraulic constants with conventional hydraulic constants.

Introduction

Characterizing the distribution and hydraulic properties of the aquifer in the borehole environment is very important in solving groundwater, petroleum and environmental problems. Methods for obtaining hydraulic conductivity or permeability of an aquifer have been suggested by many researchers (Theis, 1935; Cooper and Jacob, 1946; Lambe,1951; Drost et al., 1968).

Geophysical logging techniques are also expected to be potential methods for deducing aquifer constants, although permeability or hydraulic conductivity is a difficult parameter to drive from logs. Various kinds of logging techniques have been adopted for this purpose, for example, resistivity, sonic, natural gamma, and NMR . Most of them are based on the relationships that exist between permeability and petrophysical parameters such as porosity, formation factor, shale content, sonic wave attenuation and NMR relaxation times(Gaur and Singh, 1965, Seevers, 1966; Nelson, 1994; Denicol et al, 1996; Buffin, 1996; Temple and Waddell, 1996; Vernik, 2000).

Fluid logging which measures the flows within the borehole can be a kind of direct permeability measurement. In particular, an electrical conductivity log that is originated from the dilution method(Drost et al., 1968; Grisak et al., 1977) can be a potential direct method for determining permeability effectively. Lately the electric conductivity logging technique shows signs of being used as an efficient method in determining hydraulic constants(Paillet, 1998) particularly in engineering companies(Colog, 2001) after a fairly long period of stagnation. However, it is hard to find reports on the basic experiments for this technique. This study was made as a prototype experiment to confirm the basic conditions, limitations, and possibilities of the technique for permeability determination of aquifers.

Setting up the Apparatus and Methods

The apparatus consists of a model borehole and the measuring system for the electrical conductivity determination of the fluid within the hole (hereinafter "borehole fluid") and for the properties of incoming and outgoing fluid(Fig. 1). The model borehole is composed of a transparent plastic tube with a diameter of 63 millimeters and a height of 1.3 meters, and devices for controlling the amount of incoming and outgoing fluids that depict the formation fluid. The amount of outgoing fluid was held equal to the amount of incoming fluid(hereinafter "formation fluid") according to the constant hydraulic head.

The measuring system for the electrical conductivity of the borehole fluids consist of 24 silver electrodes installed at every 50 milimeters inside the plastic tube, an electrode exchanger, and a resistivity meter for obtaining fluid conductivity. The electrode is composed of two line electrodes crossing each other, and the resistivity meter was used for determining the resistivity of borehole fluid. Electric conductivity was obtained by the reciprocal relationship with resistivity. Specific gravity, conductivity and weight of outgoing fluid have been measured also for comparison.

The point of the experiment is to observe the conductivity increase or decrease of the borehole fluid with time as the formation fluid advances into the hole. An emphasis was made on finding the best conductivity contrast between the borehole fluid and the formation fluid, time range of measurement, and the characteristics of salt movement from inside to outside the hole with time. The density contrast between borehole fluid and formation fluid was controlled to be as small as possible while keeping the conductivity contrast as large as possible.

The density contrast in this experiment was controlled by both salinity and temperature contrasts. The salinity contrast was given for easy detection of the formation fluid in the model hole since the larger the salinity contrast is the easier it is to detect the effect of the formation fluid. The temperature contrast was adopted to restrain the rapid upward or downward movement of the formation fluid caused by the salinity contrast.

In this study, distilled water(0% NaCl solution) was used for the formation fluid, and three kinds of NaCl solution(0.3%, 0.1%, and 0.05%) were used for the borehole fluid. All the data presented here were obtained using the borehole fluid of 0.05% NaCl solution, which gives a significant salinity contrast and
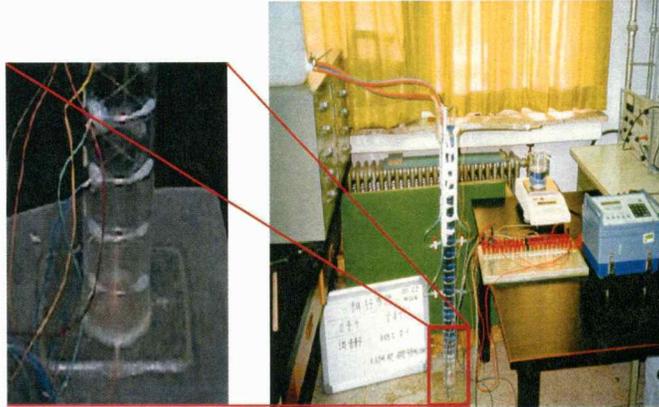
Fig. 1. Apparatus setup for conductivity measurement.

also restrains the rapid rising of the formation fluid under the assumption that the temperature between the two fluids is controlled well. Conductivity measurement continued until the conductivity distribution curve had lost its characteristic form of peak due to the significant upward or downward movement of the formation fluid.

Conductivity Determination of Fluid within a Hole

Since we adopted a method that measures the resistance(R) of fluid using two outer electrodes as the current electrodes and two inner electrodes as the potential electrodes, the first step for obtaining fluid conductivity(C) is to delineate the configuration factors(F) for every configuration. The configuration factors were delineated on the condition that the fluid resistivity(ρ) is constant throughout the model hole, which has the same sectional area(S) and nearly the same electrode spacing(h). The fluid resistivity(ρ) can be obtained from following relations:

$$R = \rho h/S$$

$$\sum R(i) = \sum \rho(i) h(i)/S(i) = \rho \sum h(i) /S \quad (\rho, S \text{ are constants})$$

$$\therefore \quad \rho = S\sum R(i)/\sum h(i)$$

This equation makes it easy to get the fluid resistivity from inaccurate electrode spacing. Once the fluid resistivity was obtained, electrode configuration factor at every location(F(i)) can be deduced from the resistance - resistivity relationship(Telford 1976).

$$F(i) = \rho/R(i)$$

Fig. 2 shows the electrode configuration factors obtained for every potential electrode pair. The configuration factors were obtained by taking the average from several measurements with different
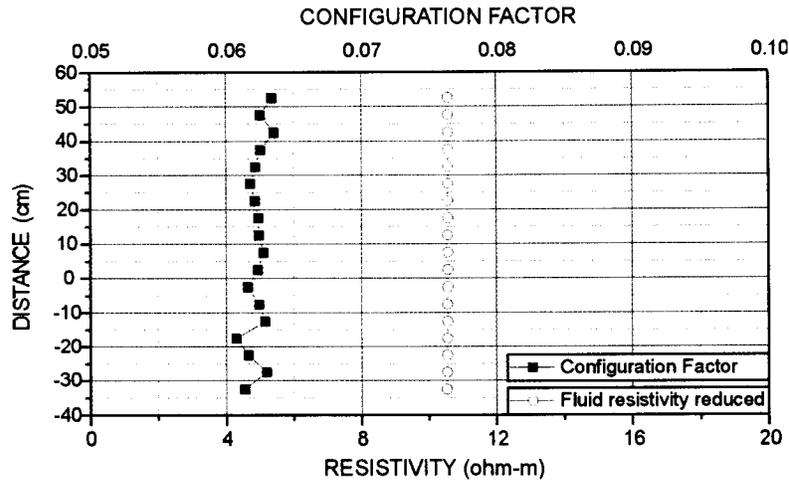
CONFIGURATION FACTOR

Fig. 2. Configuration factors of electrode arrays and uniform resistivity distribution delineated from resistance and configuration factors.

solution for every electrode pair. A comparatively large variation is revealed between the electrode pairs considering the initial design for equally spaced electrodes. The resistivity value of the fluid between every electrode pair can be obtained from resistance and electrode configuration values.

$$\rho(i) = F(i) \times R(i)$$

Finally conductivity values are obtained by taking the reciprocal of the resistivity values.

$$C(i) = 1/\rho(i)$$

Fig. 2 shows fairly stable and consistent resistivity distribution of the borehole fluid obtained according to this procedure.

Conductivity Variation Features and Hydraulic Constants

Fig. 3, 4, 5 and 6 are the examples of conductivity curves obtained by sequential measurements since the formation fluid has begun to flow into the model hole. The distance 0 represents the location of intake and outtake at the model hole. The conductivity curves show conspicuous peaks whose sizes are increasing according to the expansion of formation fluid that has different conductivity. The conductivity curves indicate that their variation features depend on flow rate and density contrast between the borehole fluid and formation fluid.
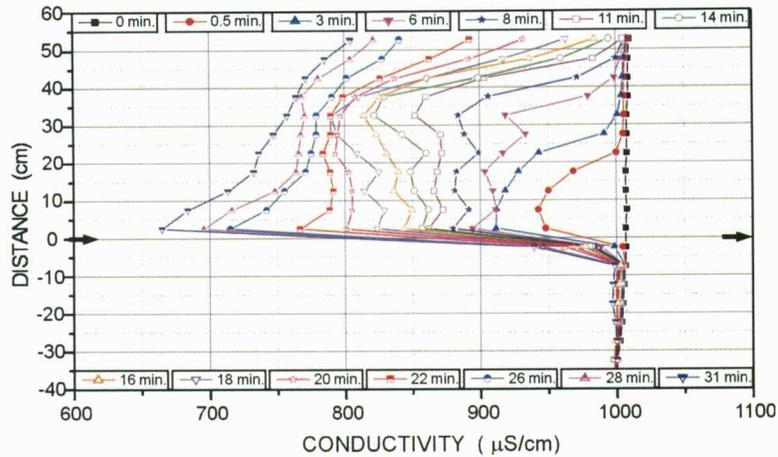
Fig. 3. Conductivity variation curves with time since formation fluid(0 % NaCl solution) began to flow into hole(0.05% NaCl solution) with flow rate of 20 cc/min. Fluid temperature within hole and inlets was held constant at 24°C and 21°C, respectively.
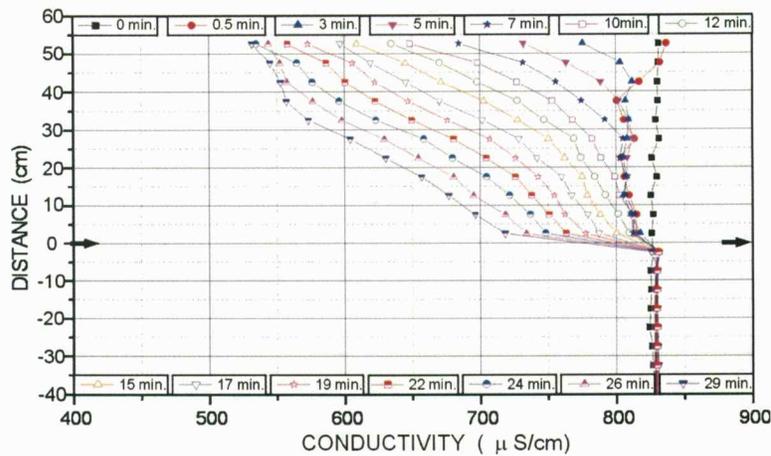

Fig. 4. Conductivity variation curves, which indicate rapid upcoming of formation fluid. This is result of higher density contrast caused by larger temperature difference between hole(22°C) and formation fluids(24°C) as well as salinity difference between formation fluid(0 % NaCl solution) and hole water(NaCl Solution a little higher than 0.05%). Flow rate is 18.5 cc/min.
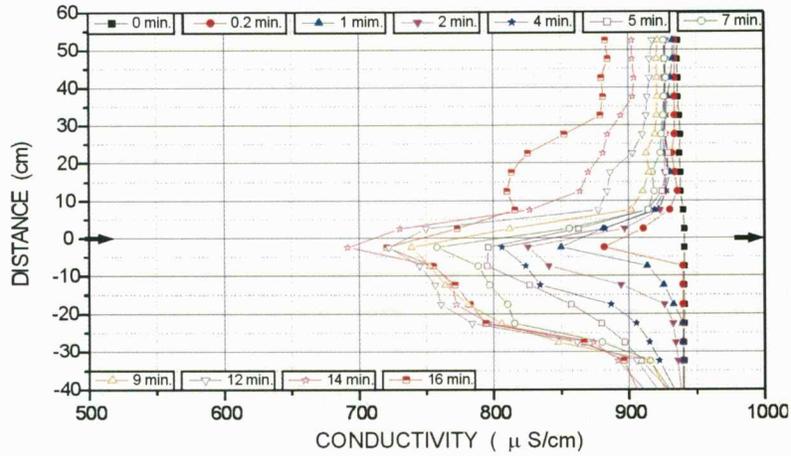
Fig. 5. Conductivity variation curves with time since formation fluid(0 % NaCl solution) began to flow into hole(0.05% NaCl solution) with flow rate of 34 cc/min. Fluid temperatures within hole and inlets were held constant at 20.2°C and 14.0°C, respectively.
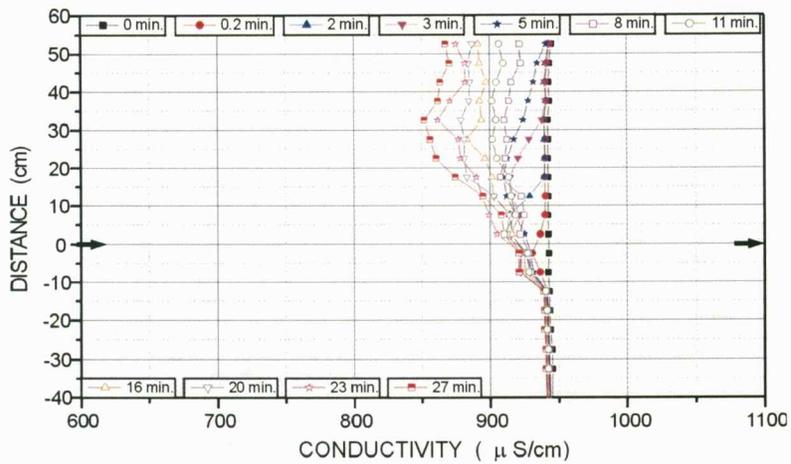

Fig. 6. Conductivity variation curves with time since formation fluid(0 % NaCl solution) began to flow into hole(0.05% NaCl solution) with flow rate of 5.1 cc/min. Temperatures of hole and formation fluids were held constant 20°C and 18.5°C, respectively.

We can compare particularly the effect of temperature on the conductivity curves from Figs. 3, 4 and 5. Fig. 3 shows an example of a successful temperature control between two fluids and correspondingly fairly conspicuous peaks. In this case, the surplus of weight caused by the higher salinity of borehole fluid is believed to be compensated effectively by controlling the temperature of formation fluid about 3°C lower than the temperature of the borehole fluid. When the temperature of the formation fluid is 3°C higher than the temperature of the borehole fluid, the curves suggest the rapid rising of formation fluid that has low conductivity(Fig. 4). Fig. 5 shows the result of density reversals caused by excessive temperature control of the formation fluid, about 6°C lower than the borehole fluid. The conductivity curves still show the significant peaks from which the inflow of different salinity can be predicted. These two extreme experiments are believed to be effective only in the single aquifer model.

The conductivity curves reveal a consistent trend depending on the flow rate of the formation fluid; the conductivity curve obtained at a higher flow rate(Fig. 3, 5) shows more distinct peaks than at the lower flow rate(Fig. 6). The dependency of conductivity variation on the flow rate is conspicuous throughout the whole data set, and a close relationship is revealed between the flow rate and the conductivity value of the borehole fluid. Taking and plotting the average values of the conductivity throughout the hole with time(Fig 7) can be one of the simplest and most basic approaches in pursuing the relationship between flow rate and conductivity variation. The average conductivity in Fig 7 is the normalized value, which lets the initial fluid conductivity be unity. The normalized conductivity distribution shows a simple linear trend, and the corresponding proportional dilution of the borehole fluid with time provided that conductivity is proportional to the amount of salt within the hole. The proportionality between gradients of conductivity decrease(X) and flow rates(Q) shown in Fig. 7 is more clearly observed in Fig. 8, where the flow rate values are cross-plotted with the gradient values with time. The high value (0.94) of the correlation coefficient in the model equation deduced from the least square fitting suggests that the total flow rate across the wall can be predicted precisely from the gradient value.

It is also noted that the data obtained from the high density contrast between hole and formation fluid fall on the lower part of the regression line(solid square), while the data from the small density contrast on upper part(open square). It seems to be very optimistic that the result obtained from a high density contrast coincides well with the model equation obtained under the assumption that the outgoing fluid conductivity is the same as initial condition. And the result suggests that a much higher coefficient can be expected by defining the data according to the experimental condition.

Another emphasis in this experiment was on getting the information about the resolution for discriminating the flow unit from multi-layered flows. Fig. 9 shows the results of a model hole experiment having another intake/outtake pair at location 20(with the flow rate of 25cc/min) as well as the initial intake/outtake pair at location 0(with the flow rate of 30cc/min). The conductivity variation curves show two peaks up to the measurement of 10 minutes. Particularly conspicuous peaks have been obtained within the initial 1.7 minutes, and the corresponding fluid flow units can be discriminated well within that period. Fig.10 was obtained by taking the average of the three values around each peak, and it shows a linear trend
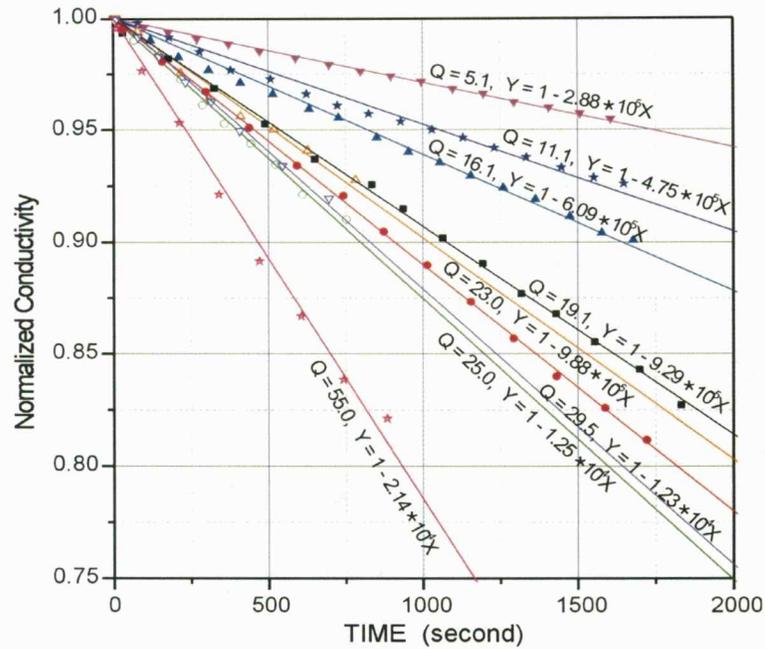
Fig. 7. Average conductivity values of borehole fluid plotted in terms of time since incoming flow began. Linear decrease in conductivity is observed throughout all experiments, and gradients of conductivity change with time have been deduced by linear polynomial fit. Conductivity has been normalized as initial conductivity to be unity.
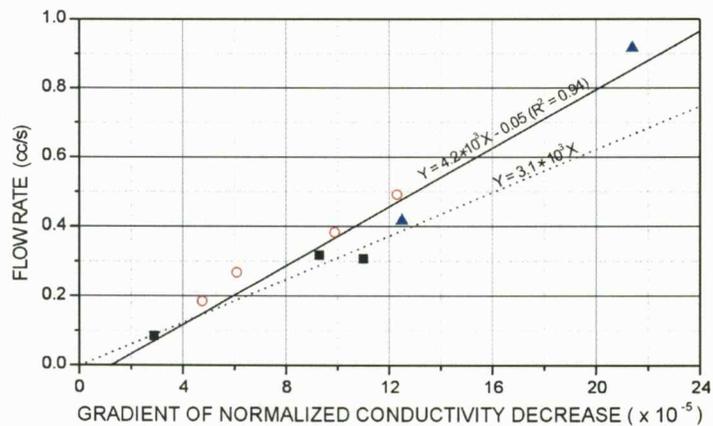

Fig. 8. Cross plot of flow rate and gradient of conductivity change with time obtained in Fig. 7. Fairly good correlation is observed between flow rate and gradient of conductivity. Result obtained from high density contrast between hole and incoming fluid fall on lower part of regression line, while results in small contrast fall on upper part. Results obtained from high density contrast seem to coincide with model equation obtained under the assumption that outgoing fluid conductivity is the same as initial condition.
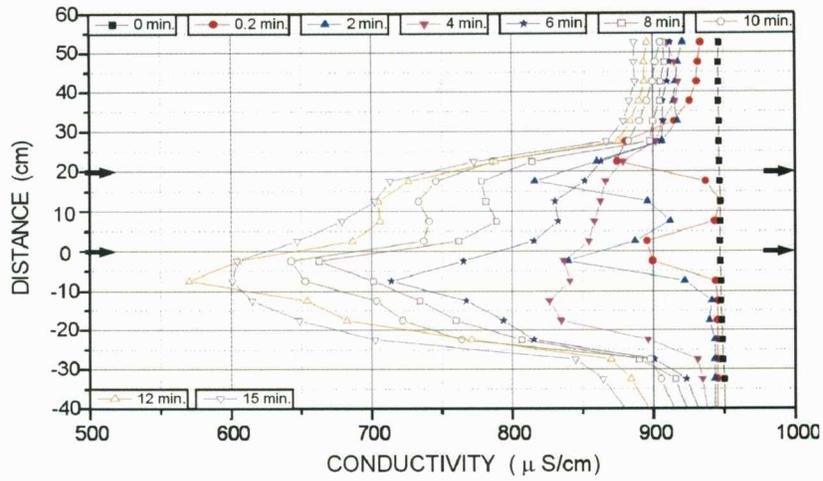
Fig. 9. Conductivity variation curves obtained from pair of additional inlet and outlet (flow rate of 25 cc/min at point 20) as well as original pair of inlet and outlet (30cc/min at point 0). Temperatures of hole and formation fluids were held constant at 20.5°C and 15°C, respectively.
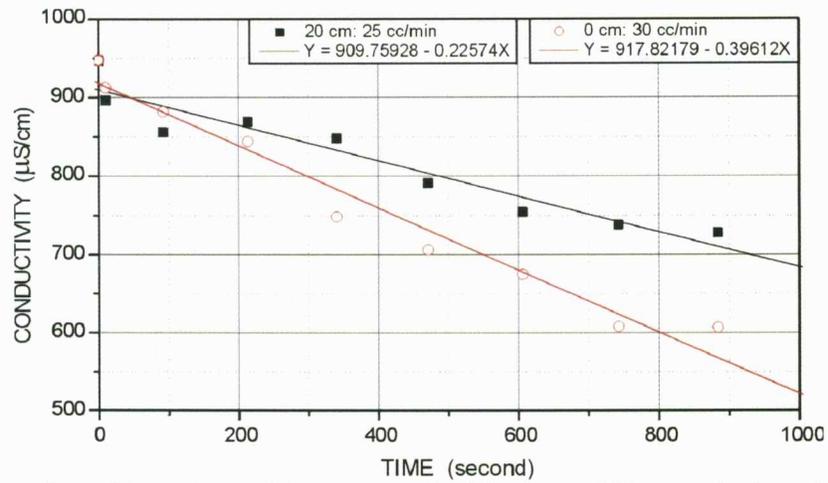

Fig.10. Comparison of decreasing trend in average conductivity for two different peaks shown in Fig. 9. Linear decrease with time in conductivity is observed, and gradients still maintain proportional relation with flow rate.

like in Fig. 8. The result suggests that it is possible to discriminate effectively the closely spaced multi-layered aquifers provided that an appropriate density contrast is applied.

Discussion and Conclusions

The basic conditions and control factors for the experiment have been tested. The density contrast between borehole fluid and formation fluid is controlled to be as small as possible while having the conductivity contrast as large as possible. Temperature is also shown to be a very useful factor as well as salinity in controlling the density contrast.

The borehole fluid shows very uniform decrease in conductivity with time during the measurement. And a fairly good correlation has been obtained between the flow rate and the conductivity decrease rate. A model equation for determining the log hydraulic constant could be delineated. In particular, the gradients of conductivity decrease at the lower flow rate, and coincide well with the predicted gradients obtained under the assumption that a simple replacement of ionic fluid with non-ionic fluid takes place. This result indicates that the conductivity logging technique can be more powerful than has been expected in delineating the hydraulic constants.

This model experiment was designed for fracture flow, and the flow rates adopted here correspond to hydraulic conductivity of 1×10^{-5} - 1×10^{-3} m/sec provided that we assume a significant fracture or fracture zone for every 5 meters with the hydraulic gradient of 0.2. This condition is believed to cover the usual in-situ fracture flow. Correspondingly, the conductivity logging technique can be used effectively for determining the hydraulic conductivity in usual fracture flows.

Acknowledgement

References

Buffin, Andrew, 1996, Permeability from wave form sonic data in the Otway basin, Society of Professional Well Log Analysts Annual Logging Symposium, 37th, New Orleans. La, Transactions, p. GG1-GG11.
Colog, 2001, Hydrophysical [TM] and water quality logging. http://www.colog.com/hplwql.htm. pp.7.
Cooper, H.H. Jr., and Jacob, C.E., 1946, A generalized graphical method for evaluating formation constants and summarizing well field history, Trans. Amer. Geophy. Union, vol. 27, pp.526-534.
Denicol, P., Petrobrs, S.A., and Jing,X., 1996, Estimating permeability of reservoir rocks from complex resistivity data, Society of Professional Well Log Analysts Annual Logging Symposium, 37th, New Orleans. La, Transactions, p. XX1-XX11.
Drost et al., 1968, Point dilution methods of investigating grounwater flow by means of radioisotopes, Water Resources Research, Vol.4, no.1, pp.125-145.

Gaur, R.S., and Singh, Inderjit, 1965, Relationship between permeability and gamma ray intensity for the Oligocene sand of the Indian field. Oil and Natural gas commission of Indian Bulletin, vol.2 no. 1, p.74-77.

Grisak, G.E., Merritt, W.F., and Williams, D.W., 1977, A fluoride borehole dilution apparatus for groundwater velocity measurements, Canadian Geotechnical Jour., v.14, no.4, pp.554-566.

Lambe, T.W, 1951, Soil Testing for Engineers, John Wiley & Sons, New York, 165pp

Nelson, P.H., 1994, Permeability-porosity relationships in sedimentary rocks. The Log Analyst, vol 35 no.3, 38-62.

Paillet, F.L., 1998, Flow modeling and permeability estimation using borehole flow logs in heterogeneous fracture formations. Water Resources Research, vol. 34, no.5, p.997-1010.

Seevers, D.O., 1966, A nuclear magnetic method for determining the permeability of sandstone. Society of Professional Well Log Analysts Annual Logging Symposium, 7th, Tulsa. Okla, Transactions, 14p.

Telford, W.M., Geldart, I.P., and Sheriff, R.E., 1990, Applied Geophysics, 2nd edtion: Cambridge, Cambridge University Press, 770p.

Temple, T.J., and Waddell, 1996, Application of petroleum geophysical well logging and sampling techniques for evaluating aquifer characteristics: Ground Water, v. 34, no. 3, p. 523-531.

Theiss, C.V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage. Trans. Amer. Geophy. Union, vol. 2, pp.519-524.

Vernik, L., 2000, Permeability prediction in poorly consolidated siliclastics based on porosity and clay volume logs, Petrophysics, v. 41(2), p. 138-147.