Kim, Y., Park, J., Application of a geophysical well log technique for determining permeability in borehole.
International Symposium on the Fusion Technology of Geosystem Engineering, Rock Engineering and Geophysical Exploration
Seoul, Korea, Nov. 18-19, 2003

Application of a geophysical well log technique for determining permeability in borehole

Y. Kim, J. Park
Kangwon National University, Chunchon, Korea

Abstract: Geophysical well logging techniques which are useful for delineating permeability of geological formation have been reviewed. A new technique for obtaining permeability using conductivity log technique has been discussed. This conductivity logging technique has been tested by monitoring the conductivity change within the model hole using borehole environment water and incoming-outgoing water of different salinity with constant flow rate by maintaining balance between inflow and outflow. Conductivity variation features depended mainly on flow rate, density contrasts due to salinity and temperature contrasts between fluid within the hole and incoming-outgoing fluid. The results of the experiment show uniform change of fluid conductivity within bore hole with time and a fairly good correlation between the flow rate and the conductivity change rate. This conductivity logging technique is expected to be an efficient tool for determining permeability.

1. Introduction

Various methods for obtaining permeability of the aquifer in the borehole have been suggested by many researchers(Lambe,1951; Theis, 1935; Cooper and Jacob, 1946). Geophysical logging technique is one of the potential methods for deducing permeability (Buffin, 1996, Seevers, D.O., 1966; Paillet, 1998) Petrophysical parameters are used to estimate permeability(Tang et al., 1998). Porosity, formation factor, clay volume, NMR relaxation time, and tube wave attenuation are the best well known petrophysical parameters having close relationship with permeability. Conventional log approaches to delineate formation permeability is based on the relationship exists between permeability and porosity(Coates and Dunanoir, 1973; Temple and Waddell, 1996), permeability and formation factor (Archie, 1942; Pickett, 1973), and permeability and clay volume(Asquith, 1990). Porosity has been on the center of log permeability studies. However, many of empirical models predict the permeability of sedimentary rocks with a fair level of accuracy came from the comprehensive studies of porosity with other petrophysical parameters such as grain size, sorting, pore size distribution, irreducible water saturation and/or capillary pressure. We are going to discuss the possibility and limitation of the conventional well log techniques and introduce a new potential technique in determining permeability of the target geology.

2. Geophysical Logging Methods available for permeability determination

Classification of geophysical well logs as a permeability indicator

Permeability is one of the most difficult parameters to drive from geophysical well log data. Geophysical logging methods use physical responses in obtaining permeability. Correspondingly geophysical well log is considered to be a theoretically indirect method of obtaining permeability. But some can be regarded as semi direct to direct relationship. Geophysical well log methods available for permeability determination can be grouped into three; indirect method, semi-direct method, and direct method. Most of conventional log methods are subjected to theoretically indirect method in obtaining permeability of formation. They can be grouped into two parts; 1) logs using the close relationship between permeability and petrophysical parameters such as porosity, formation factor, clay volume, and 2) logs those are efficient for defining fractures- frequency, orientation and aperture. Most of the conventional logs, such as electric resistivity log, gamma log, gamma gamma log, sonic log are in the first group. Televiewer log and sonic log are the second group. While temperature log, conductivity log, tube wave attenuation method and NMR Log(NMR relaxation time) measure characteristics related to the fluid column in the borehole or surrounding rocks. Although those cannot give direct information of formation permeability, particularly temperature log and conductivity log can provide the information of the movement of water in the borehole. Tube wave attenuation method and NMR log reflect water characteristics within fractures. Upon this characteristics, the above four log methods can be grouped into semi-direct method for obtaining permeability.

Flow measurement using flowmeter is the most well known method to get direct information of fluid flow in the borehole. Flow measurement with logging probes includes mechanical(impeller), thermal(heat pulse), and electromagnetic methods. Most of them are limited within measuring vertical flow in the borehole, however recently lateral flow through a single well or flow between wells can be recorded.

Limitation of existing logging methods and importance of conductivity logging technique as a permeability tool

In spite of its being used efficiently in deducing the aquifer constants, most of the conventional geophysical logging techniques has critical problem in the fact that they are based on the relationship between physical response and permeability. Fluid log, sonic Log, and NMR Log which are grouped into semi- direct logging method above have better chance of obtaining rock permeability. However they still remain in the domain for measurement of background geology of formation permeability. Flowmeter log has the best chance in obtaining permeability itself in the borehole. However the discrimination of vertical and lateral flow is still remain in unclear because of disturbed flow caused by borehole penetration and the resolution of devices. Thus obtaining permeability distribution in the borehole is far from satisfaction.

We pay attention to conductivity log from the view point that conductivity log data can reflect the detailed flow state of formation water in the borehole with simple and easy procedure. Electric conductivity logging technique has a log history in determining permeability of aquifers coordinated with dilution method although they remain in the qualitative approach. Lately a quantitative approaches for this purpose has been made by Tsang and Hale(1989). A successful result in obtaining permeability distribution of aquifers has been obtained by analysing the change of electric conductivity distribution within boreholes where more conductive formation fluid comes into less conductive hole fluid. However it is not easy to find sharp conductivity contrast between formation fluid and hole water in field. Artificial displacement of hole fluid with very conductive fluid can be the only solution to increase the conductivity contrast for detecting fluid flow.

3. New approach for obtaining permeability with conductivity log technique

Methods and Apparatus

We adopted a method to delineate electric conductivity from the resistance of fluid using two utmost outer electrodes as the current electrodes and two inner electrodes as the potential electrodes. The apparatus consists of a model bore hole and the measuring system for the electrical conductivity determination of the fluid within the hole and for the properties of outgoing fluid(Fig. 1). The model bore hole is composed of a transparent plastic tube with the diameter of 75cm, and devices for controlling the amount of incoming and outgoing fluid. The amount of outgoing fluid was designed to be controlled equivalent to the amount of incoming water by constant hydraulic head. For measuring the fluid conductivity within the hole, 20 silver electrodes were installed at every 5cm inside the plastic tube; outer two silver plates for current electrodes and 18 line electrodes for potential measurement. Each potential electrode is composed of two silver lines crossed each other. We set up an automatic system for fluid resistivity measurement using a digital multimeter, a CB-68LP terminal block with Labview 6.0 software provided by National Instruments Co. Electric conductivity was obtained by the reciprocal relationship with resistivity. Distilled water(0% NaCl solution) was used for the incoming fluid, and various concentration (0.01%, 0.03%, 0.05%, 0.08% and 0.1%) of NaCl solution were tried for the hole fluid.

Emphasis was made on observing conductivity decrease of the fluid within the hole with time as the less conductive incoming water advances into the hole, and on finding the effect of conductivity and temperature contrast between hole fluid and incoming fluid, and flow rate. Density contrast was controlled by both salinity and temperature contrasts. The salinity contrast was selected for easy detection of incoming fluid in the hole fluid since the higher the salinity contrast is, the easier it is to detect the effect of the incoming water. While temperature contrast was adopted in order to restrain the rapid upcoming of the incoming fluid due to salinity contrast.

Salinity contrast and Conductivity variation Curves

Conductivity variation along the model hole with time was observed since nonconductive formation fluid began to flow into conductive hole fluid. The NaCl concentration of hole water and flow rate of incoming fluid are 0.01% and 11.92 g/min, 0.03% and 13.96 g/min, 0.05% and 14.28g/min, and 0.08% and 13.72g/min, respectively. Temperatures of hole fluid and formation fluid were held constant without temperature difference between the two. The conductivity curves show conspicuous variation trends, and expend their sizes of peaks according to the expansion of incoming fluid flow of different conductivity(Fig. 1). The amplitude of conductivity decrease shows proportional relationship with salinity difference between hole and incoming fluids although upward movement of light weighted and low salinity fluid is dominant over lateral contribution of conductivity by salinity difference between the two fluids as the salinity difference between hole and incoming fluids increases.

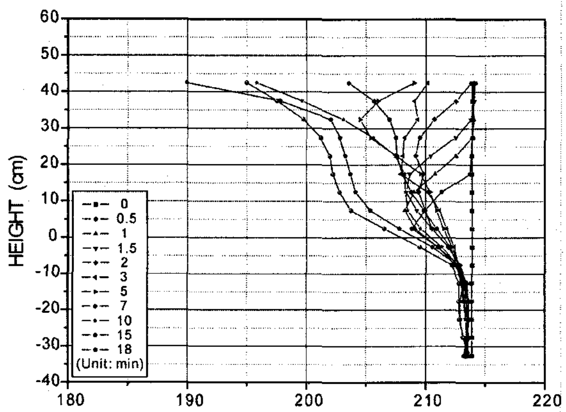

Fig. 1. Conductivity variation curves with time since formation fluid began to flow into hole fluid of 0.01% NaCl solution. Flow rate was 11.92 g/min. Temperatures of hole fluid and formation fluid were held constant without temperature difference between the two.

Temperature control and Conductivity variation Curves

Although conductivity anomaly caused by salinity difference between hole and incoming fluids is the basis for this measurement, upward movement of formation fluid whose NaCl concentration is smaller than NaCl concentration of hole water is an obstacle in measuring the lateral contribution of non conductive fluid inflow by electric conductivity measurement. We paid attention to the density change of fluid due to temperature change. The importance of controlling temperature difference between hole and incoming fluids was shown well by comparing the electric conductivity variation curves obtained by temperature control with the curves obtained without temperature control; fairly conspicuous peaks from successful temperature control between hole and incoming fluids, and divergent curves from without temperature control due to rapid upcoming of incoming fluid of low concentration. The surplus in weight caused by 0.05% higher salinity of hole water was compensated effectively by lowering the temperature of incoming fluid about 3°C compared to the hole fluid. This result meets the expectation deduced from fluid density measurement in different temperature (Johnson et al., 1991).

Flow rate control and conductivity variation curves

Seven stages of flow rate ranging from 2.99 g/min to 51.82 g/min were examined to see the effect of flow rate on electric conductivity curve. Data were obtained in the hole water of 0.05% NaCl Solution, and with the temperature difference of approximately 2.8 ℃. Significant conductivity anomalies were firstly observed from the flow rate 7.91 g/min. And anomaly peaks gradually increase in amplitude as flow rates increase(Fig. 2). The peak amplitude of conductivity variation curves shows approximately proportional relationship with the corresponding flow rate. Particularly symmetrical peaks were obtained from the flow rate of 35 g/min while upward convergent peaks from the lower and downward convergent peaks from the higher flow rates, 35 g/min as the boundary. This downward convergence is considered to be a rather favorable condition in detecting fluid flow in multi-aquifer situation considering its deviation from the balanced peak is weaker than the deviation shown from upward convergence.

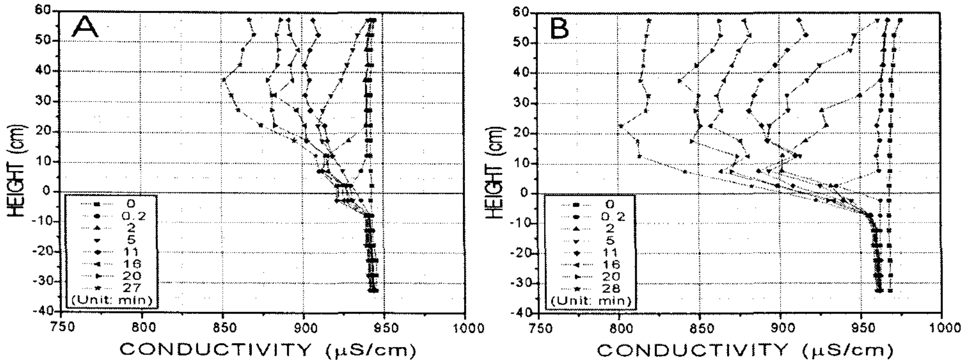

Fig. 2. Conductivity variation curves obtained with the flow rate of 5.1 g/min(A) and 16.6 g/min(B). 0.05% NaCl solution was used for hole fluid and temperature difference between hole fluid and formation fluid were held at 1.8 ℃.

4. Delineation of permeability from Conductivity Curves

The most conspicuous result of this experiment is that flow rates are reflected well on the conductivity curves quite independently of salinity contrast and temperature difference between hole and formation fluids. Small amplitude of conductivity decrease matches well with lower flow rate while large amplitude with higher flow rate. The close relationship between flow rate and conductivity decrease has been confirmed mainly by plotting the average values of conductivity throughout the hole with time. The distributions of average conductivity values plotted in terms of time show simple linear trends that indicate the proportional dilution of the fluid within the hole with time on condition that conductivity is proportional to the salt concentration. Every gradient of conductivity decrease was deduced by linear polynomial fit. The result indicates a proportional relationship between gradients of conductivity decrease and flow rates. This proportionality is shown more clearly in Fig. 3, where the flow rate values are cross-plotted with the gradient values of conductivity with time. The model equation particularly from the data obtained from high density contrast between hole and formation fluids coincide well with the predicted equation obtained on the assumption of simple replacement of ionic fluid by non-ionic fluid. These equations show nearly the same result obtained from previous study(Kim and Lim, 2001). This suggests that conductivity logging technique can be an efficient tool for determining permeability of aquifers in borehole.

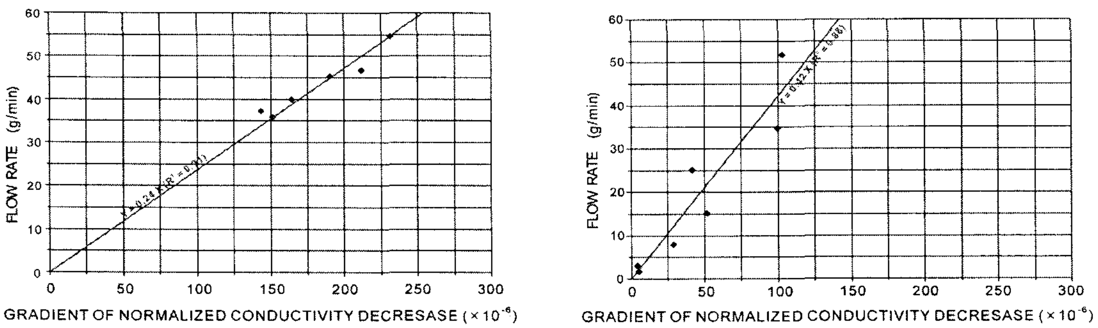

Fig. 3. Cross plot of flow rate and gradient of conductivity decrease obtained from data obtained from high density contrast(left) and from controlled density contrast(right) between hole and formation fluids.

5. Conclusions

Geophysical well logging techniques which are useful for delineating permeability of geological formation have been reviewed, and a new technique for obtaining permeability using conductivity log technique has been discussed The possibility and mandatory environment for adopting this technique has been tested with a simplified physical model that depicts the borehole condition. Experiment has been made by monitoring the conductivity change within 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 feature is shown to be depended mainly on flow rate and density contrast caused by salinity and temperature contrasts between fluid within the hole and incoming-outgoing fluid. Result of the experiment shows the uniform change of fluid conductivity within hole with time, and a fairly good correlation between flow rates and conductivity change rates. The model equation obtained from the fairly good correlation between flow rates and conductivity change rates for determining log permeability shows nearly the same result obtained from previous study. This result suggests that conductivity logging technique can be an efficient method in determining the permeability.

Acknowledgements

This work was supported by the Korea Science and Engineering Foundation (KOSEF) under grant No. R05-2002-000-01321-0.

References

Archie, G.E., 1942, The electrical log as an aid in determining some reservoir characteristics, Trans. Am. Inst. Min. Metall.Eng., 146: 54-62

Buffin, A., 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, GG1-GG11.

Coates, G.R. and Dumnanoir, J.L. 1974 "A new approach to improved log-derived permeability", Log Analyst, v. 15 (no. 1), 17-31.

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, 526-534.

Johnson J. W., Oelkers, E. H. and Helgeson, H. C., 1991, SUPCRT92: A software for calculationg the molal thermodynamic properties of minerals, gases, aqueous species, and reactions from 1 to 5000 bars and 0 to 100℃, Univ. Californian, Berkley, USA.

Kim, Y. and Lim, H., 2001, A physical model hole experiment for determining hydraulic constants in borehole using an electrical conductivity log technique. 2001 Annual Conference of the International Association of Mathematical Geology, Cancun, Mexico, A1-11.

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

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

Pickett, G.R., 1973, pattern recognition as a mean of formation evaluation, The Log analysts, 14-4, 3-11.

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.

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, 523-531.

Tang et al, Tang, X.M., Altunbay, M., and Shorey, D., 1998, "Joint interpretation of formation permeability from wireline acoustic, NMR, and image log data", Society of Professional Well Log Analysts Annual Logging Symposium, 39th, Houston, Tex., Transactions, p. KK 1-14.

Tsang, C.F. and Hale, F., 1989, "A direct integral method for the analysis of borehole fluid conductivity logs to determine fracture inflow parameters", Nagra-Doe Cooperative Project Report, Earth Science Division, Lawrence Berkeley Laboratory, p. 1-21.

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, 519-524.