United States
Environmental Protection
Agency
Research and Development

National Risk Management
Research Laboratory
Ada, OK 74820

EPA/600/SR-98/058 August 1998

EPA

Project Summary

Application of the Electromagnetic Borehole Flowmeter

Steven C. Young, Hank E. Julian, Hubert S. Pearson,
Fred J. Molz and Gerald K. Boman

Interpretation and prediction of contaminant transport in the saturated zone requires knowledge of the hydraulic conductivity distribution in granular media and flowpath distribution in fractured media. Spatial variability of saturated zone hydraulic properties has important implications with regard to design of monitoring wells for sampling water quality parameters, use of conventional methods to estimate transmissivity, and remedial system design. Characterization of subsurface heterogeneity requires an effective technique for measuring spatial variations in physical properties. Sensitive vertical-component borehole flowmeters are effective tools for measuring vertical variations in ground-water flow within a well or borehole and evaluating hydrostratigraphy from these data. This report describes an electromagnetic (EM) borehole flowmeter, developed by the Tennessee Valley Authority (TVA), which is based on Faraday's law of induction and produces a voltage proportional to the velocity of water passing through the central cylindrical channel of the meter. The threshold velocity for a prototype instrument is less than 8.8 +/- 0.9 cm/min. This meter has the sensitivity, precision, and physical dimensions necessary for application in many hydrogeologic settings. The report describes methodology and application of the EM flowmeter to the characterization of the vertical distribution of ground-water flow to a well and estimation of hydraulic conductivity distribution from this information under appropriate conditions.

This Project Summary was developed by EPA's National Risk Management Research Laboratory's Subsurface Protection and Remediation Division, Ada, OK, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Underestimation of subsurface heterogeneity may significantly contribute to improper design and, consequently, inadequate performance of many remediation systems. Characterization of hydraulic structure requires an effective method for measuring vertical variation in hydraulic properties. Alternative methods for measuring vertical variation of hydraulic conductivity in the saturated zone include small-scale tracer tests, multi-level slug tests, laboratory permeameter tests, equations based on grain-size distributions, and borehole flowmeter tests. Of these methods, the borehole flowmeter offers one of the more direct and versatile techniques for estimating variation in subsurface hydraulic properties.

Various types of flowmeters have been developed and a few ground-water applications have been reported. Impeller meters have been used for several decades in the petroleum industry. However, historical limitation to widespread use of borehole flowmeters in the ground-water/environmental area has been the relative lack of commercially available instruments of sufficient sensitivity and precision. Within the last ten years, three different types of flowmeters have been developed and used in such applications. These meters have been based on improved impeller, heat-pulse, and electromagnetic technologies. An EM flowmeter with high sensitivity has been developed based on Faraday's law of induction by the TVA Engineering Laboratory in Norris, Tennessee. This vertical-component flowmeter can operate in both the high and low flow rate ranges required for many ground-water studies and has a durable construction without any moving parts. Commercialization of this technology has recently been completed.

Objectives of this project included refinement of a compact, reliable, and versatile EM borehole flowmeter; development of techniques for meter application and data analysis; and application of the meter in various hydrogeologic settings. The report describes the operation and utility of the prototype EM borehole flowmeter, including theory, design, calibration, basic field applications, data analysis procedures, and potential effects of various well construction and development procedures on flowmeter data. In addition, case studies describing test objectives, designs, and results are also discussed. Information in the report is of interest to investigators planning hydrogeologic characterization studies.

Electromagnetic Borehole Flowmeter

The flowmeter (Figure 1) consists of an electromagnet and a pair of electrodes mounted 180° apart at right angles to pole pieces of the magnet and cast in a durable epoxy. The epoxy is molded in a cylindrical shape to minimize turbulence associated with channeling water through the hollow core of the meter. The flowmeter operates according to Faraday's law of induction which states that the voltage induced across a conductor moving at right angles through a magnetic field is directly proportional to the velocity of the conductor. The electromagnet creates a strong magnetic field across the flow passage. As water (electrical conductor) flows through the magnetic field, a voltage is generated which is proportional to average water velocity across the magnetic field. Induced voltage across the electrodes is measured by the electronics package. Polarity of the generated voltage is dependent on direction of flow.

The prototype EM flowmeters described in the report are 30-cm long with an outer diameter of 4.8 cm and 1.27-cm or 2.54-cm inner diameters (ID). The 1.27-cm and 2.54-cm ID flowmeters are typically used to measure low flow rates and high flow rates, respectively. The threshold average discharge velocity for the 1.27-cm ID flowmeter is less than 8.8 +/- 0.9 cm/min which translates to a flow rate of approximately 10 ml/min and is measured with a precision of approximately 10%. Linear response ranges of the 1.27-cm ID and 2.54-cm ID meters are approximately 30 ml/min to 10 l/min and 100 ml/min to over 40 l/min, respectively. Both flowmeters are designed to operate under a maximum hydraulic head not exceeding 600 m.

In wells or boreholes with relatively large diameters, sensitivity of the flowmeter diminishes due to increased flow around the meter which is not detectable using a probe of this design. In order to direct flow through the inside of the flowmeter in a large-diameter well, a packer assembly is used. Both a mechanical collar consisting of a rubber gasket held between two plexiglass rings and an inflatable packer have been developed for use in wells with diameters of approximately 20 cm or less.

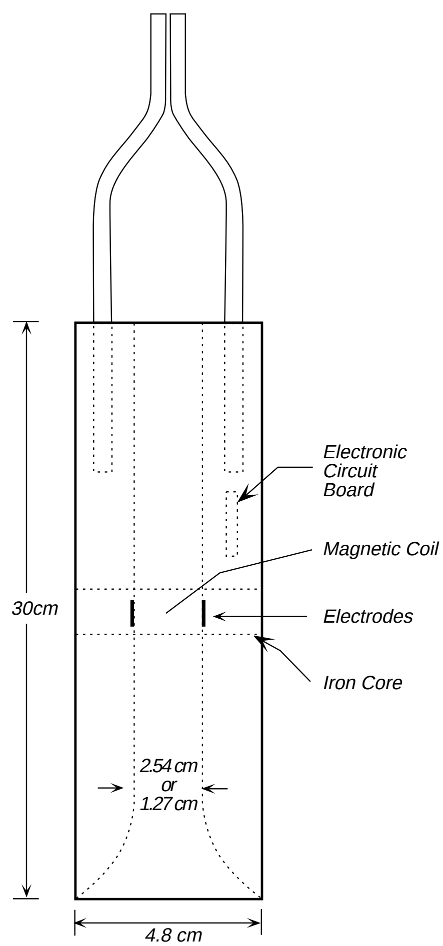

Figure 1. *Schematic diagram of the Tennessee Valley Authority electromagnetic borehole flowmeter.*

Above-ground electronics include the electromagnet drive, circuitry to measure voltage generated by flow through the meter, and computer hardware/software. The signal that is produced is in the microvolt range and will typically be several orders of magnitude less than background noise. Due to the high noise level, synchronous demodulation is used to extract the signal. With additional amplification and filtering, a direct current signal proportional to water velocity through the flowmeter is generated. The electronics collect and process signals from the flowmeter every second. At the end of a pre-set time interval or upon keyboard command, signals are averaged and the standard deviation is calculated. This average flow rate and standard deviation are displayed, stored on disk, and printed.

Collection and Analysis of Flowmeter Logs

Borehole flowmeter tests using a tool of this design focus on measuring the vertical distribution of horizontal flow into a screened well or open hole. Such tests are useful for characterizing both granular and fractured media. Data obtained in the field are vertical ground-water flow rates measured at selected elevations within the well or borehole. Measurements are typically performed under ambient (natural) and induced flow (pumping) conditions. Flow profiles obtained under ambient conditions provide information on the magnitude and direction of the vertical hydraulic gradient. Flow profiles measured during ground-water extraction show the proportion of total discharge provided by each monitored interval. If certain conditions are met, these data may be used to estimate relative differences in hydraulic conductivity of selected aquifer intervals in granular materials. Flow profiles in fractured rock provide information regarding the locations of hydraulically active features.

Single well tests may be performed as illustrated in Figure 2. First, a caliper log is recorded or examined to ascertain that the borehole/screen diameter is constant. If it is not constant, variations must be taken into account during data analysis. Flowmeter measurements are then recorded at selected intervals prior to pumping to measure any vertical water movement within the well under ambient conditions. Following recording of the ambient flow distribution, ground water is pumped from the well at a constant rate. After a stable flow condition is achieved, the flowmeter is lowered to the bottom of the well and used to measure cumulative discharge at positions where ambient flow rates were measured. This results in a series of data points describing cumulative discharge from the aquifer as a function of depth (Figure 3). Such tests may be performed in confined and unconfined aquifers. Alternative test designs involving injection of water instead of ground-water extraction and monitoring flow distribution in an observation well during ground-water extraction from another well are also possible.

Well Construction and Development

Studies were conducted to investigate effects of various well construction and development methods on flow distributions. In an investigation performed near Columbus, Mississippi, three well installation techniques (i.e., a modified rotary wash method/installation using a natural filter pack, use of a 19.4-cm hollow-stem auger/installation using a natural filter pack, and use of a 27.0-cm hollow-stem auger/installation using an artificial filter pack) were evaluated. A second study of well development effects was conducted in sedimentary deposits near Mobile, Alabama, using wells constructed with natural filter packs in boreholes drilled using mud rotary techniques. In both studies, well development was conducted in stages with flowmeter tests performed between each stage.

Each well development stage was approximately twenty minutes in length and included air development at the Mobile test site and overpumping, backwashing, and mechanical surging at the Columbus test site. Analyses included comparison of drawdown response, ambient flow profiles, and induced flow profiles after successive well development. Test results demonstrated that the importance of well development is site dependent but that the effect may be significant. The most dramatic difference occurred between pre-development and the first well development stage. Changes in direction and magnitude of ambient flow profiles between these two stages were not uncommon. Significant, but less notable changes occurred in the drawdown response to pumping and induced flow profiles.

Flowmeter results suggest a convergence to a stabilized flow profile under pumping conditions for all wells. The amount of well development required to obtain stability appeared to be influenced by characteristics of the aquifer materials with greater percentage of fine-grained materials increasing development required for stabilization. Aquifer heterogeneity at the Columbus test site obscured sensitivity of flowmeter results to well type. An additional observation was that wells installed with a rotary wash method had the least sensitivity to well development beyond initial phase of development. Results from these study sites demonstrate that well development is an important aspect of characterization using the borehole flowmeter. The optimum level of well development will depend on flowmeter test objectives, well design/construction, and properties of aquifer materials.

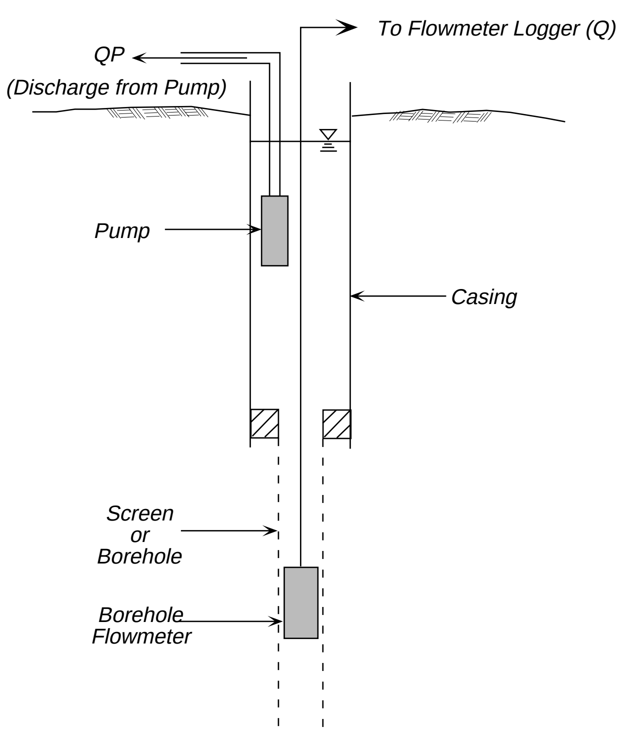

Figure 2. *Apparatus and geometry associated with a borehole flowmeter test.*

Electromagnetic Flowmeter Applications

The EM borehole flowmeter has been used in hydrogeologic characterization at several sites. The first major application of this flowmeter in a granular aquifer was at Columbus Air Force Base in Columbus, Mississippi. The test site, which is approximately one hectare in area, overlies highly heterogeneous, unconsolidated, unconfined fluvial deposits. The aquifer is composed of approximately 11 m of terrace deposits consisting of poorly to well sorted sandy gravel and gravelly sand that often occur in irregular lenses and layers containing significant amounts of clay. Numerous pumping tests, flowmeter tests, and recirculating tracer tests had been performed to study site characterization techniques. Several EM flowmeter tests were performed in each well to characterize the horizontal hydraulic conductivity distribution. Detailed hydraulic conductivity fields generated from results of these tests provided sufficient data to delineate sand and gravel beds of two former river channels.

The flowmeter has been used to characterize ground-water flow patterns in fractured bedrock at sites including Oak Ridge National Laboratory in eastern Tennessee. Geologic units at this site consist of sequences of calcareous shale, siltstone, shaley limestone, and limestone. Ground-water flow paths are predominantly through bedrock joints and fractures. Flow rate profiles observed in wells differed among the various geologic units and areas of the site. In some regions, a relatively permeable zone located near the top of bedrock appears to serve as a pathway for significant shallow ground-water flow to nearby streams. Flowmeter results from a few open boreholes were used to identify zones with hydraulically active fractures for isolation using packers and subsequent ground-water quality sampling.

The versatility of the EM flowmeter and the value of even limited testing was demonstrated at three additional field sites

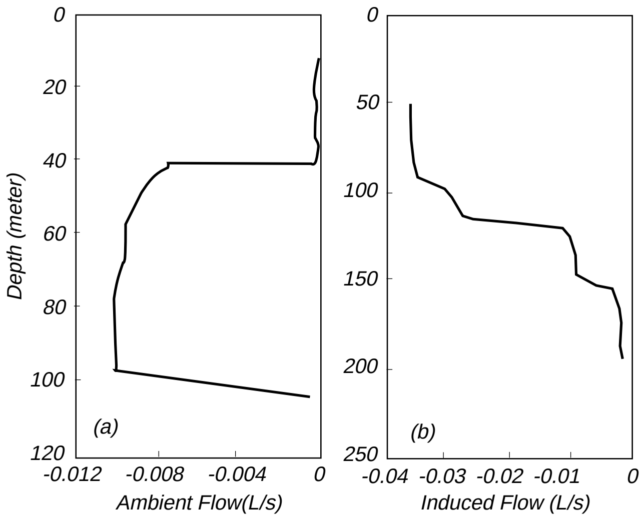

Figure 3. *Diagrams illustrating the ambient flow distribution in a well and the flow distribution induced by pumping.*

funded under this project. Geologic settings at these sites included sandstone, unconsolidated glacial deposits, and fractured igneous/metamorphic rock. For the majority of wells at each test site, the range in flow rates induced by pumping and, correspondingly, hydraulic conductivity among the tested intervals was two to three orders of magnitude or more. The report addresses the potential importance of flowmeter test results for subsurface remedial design and monitoring at each site. Additional case studies describing test objectives, designs, and results using borehole flowmeters are also discussed in the report.

Conclusions

In many geologic settings, the borehole flowmeter offers one of the most direct techniques available for developing information regarding the horizontal hydraulic conductivity distribution in granular media and ground-water flowpaths in fractured media. Such information is vital at many sites for conceptualization of contaminant transport/fate and development of effective and efficient remediation systems. Techniques for flowmeter use described in this report may be viewed as an extension of a standard pumping test. In a pumping test, only total discharge rate is measured, whereas both the vertical flow rate distribution within the screened interval and the total discharge rate are recorded during a flowmeter test. The EM flowmeter developed by TVA appears to be a versatile tool with high sensitivity and precision. Applications at test sites located in various hydrogeologic settings indicate the tool has the potential to significantly enhance site characterization through delineation of subsurface heterogeneity and preferential ground-water flow paths. Preliminary studies of the effects of various drilling technologies, well constructions, and well development techniques on hydraulic properties of materials adjacent to the well screen indicate appropriate methodologies depend to some degree on aquifer material properties.

Steven C. Young, Hank E. Julian, and Hubert S. Pearson are with the Tennessee Valley Authority, Engineering Laboratory, Norris, TN 37828. Fred J. Molz , previously with Auburn University, Auburn, AL, is currently with Clemson University, Clemson, SC 29634. Gerald K. Boman is with Auburn University, Auburn, AL 36849.

Steven D. Acree i*s the EPA Project Officer (see below).*
The complete report, entitled "Application of the Electromagnetic Borehole Flowmeter" (Order No. PB98- ; Cost: , subject to change) will be available only from:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone: 703-487-4650
The EPA Project Officer can be contacted at:

U.S. Environmental Protection Agency
National Risk Management Research Laboratory
Subsurface Protection and Remediation Division
P.O. Box 1198
Ada, OK 74820