SLUG TESTS AND HYDRAULIC CONDUCTIVITY

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Abstract

Standard aquifer tests in low-permeability sediments are of doubtful value because of the ambiguity and spread of the derived plots that drive the calculations. Recent literature on laboratory determinations of in situ hydraulic conductivity concludes that permeameters and grain-size analyses are not acceptable for fine-grained sediments and soils. Slug tests are of value in low-permeability sediments and produce valid approximations of hydraulic conductivity within one order of magnitude. We compare the various methods of analyzing slug test data, discuss their relative merits and shortcomings, and make recommendations on preferred methods. Future studies will involve field investigations on slug tests combined with tracer tests under controlled conditions, on related computational handling of slug test data, and on monitoring well installation methods to minimize permeability reduction at the formation-borehole face during drilling.

Introduction

Over the past 50 years, highly permeable sediments provided the basis (and the flow) for developing many sound analytical charactizations of an aquifer's permeability, transmissivity and storage which, when combined with pumping a well, allow for the prediction of drawdown as a function of time and position (Theis, 1935). We have had no serious need to estimate aquifer flow of less than one gpm until recently. However, sites of low permeability are often sites which contain and restrain contaminants from moving offsite for many years (see Dunn (1983) and Fawcett (1989)). But, the need notwithstanding, the methods of evaluation and characterization of sediments with intermediate to high permeability are not applicable to low permeability conditions because the inherent low pumping rates produce drawdown data of dubious value. The plots of such data and the associated scatter illustrate the problem and confounds analytical treatment regardless of how elegant the numerical/analytical method. Without meaningful data, the results are useless and misleading.

Over the past 15 years, the need for improved methods and technology has become obvious as hazardous waste investigations have expanded in number and complexity. In one response to this need, our ability to identify, define and characterize organic hydrocarbons, for example, in ground water at low concentrations has advanced significantly. In another response, developments in instrumentation such as in pressure transducers and useful, personal computers and associated applications software (see Pedler et al.(1990) and Bradbury and Rothschild (1985)), have placed powerful data acquisition and computational tools in the hands of hydrogeologists, remediation engineers, and other professionals involved in environmental investigations (for pitfalls, remember: Dansby (1987) and Smith (1987)).

We now can identify the contaminant and, given sound mathematical equations, we have the ability to investigate complex relationships by modeling subsurface behavior over time. However, the inherently weak link in the modeling appears to be the methods employed to estimate hydraulic conductivity (previously known as the coefficient of permeability, see Campbell and Lehr, 1973) for sites containing fine-grained sediments and soils of low permeability.

The state of the world's industrialization requires that we now must estimate the rate of ground-water movement even at such slow rates as 5.0×10^{-7} cm/sec. We must also have some confidence that our estimates of hydraulic conductivity have validity. The equivalent flow of a few feet per day for a toxic contaminant present in a dissolved concentration of a few thousand micrograms per liter assumes important implications to human health, which is the essential purpose of the concern of any meaningful environmental investigations involving ground water.

There are a number of methods available to estimate hydraulic conductivity. In the course of our companys' consulting business throughout the U.S. and overseas, we conduct numerous environmental and geotechnical investigations for a broad base of industrial clients. These projects include reviewing other consultants' reports, drilling and installing monitoring wells and conducting aquifer tests and ground-water sampling programs for contamination associated with underground storage tanks, environmental assessments for property transfers and associated CERCLA and RCRA projects. In all of these, the issues of ground-water flow direction and flow rate are of primary importance and require investigation.

The U.S. Code of Federal Regulations require that hydraulic conductivity be determined at hazardous waste sites but does not stipulate the method(s) to be used (U.S.C.F.R.,1988). The Alpha Research Group was formed within the Law Companies Group, Inc. in response to the growing industry debate concerning method selection. The purpose of the Alpha Research Group is to assess the issues and to conduct ongoing research into the subject, with special emphasis on low permeability applications. This is a progress report of the group's findings to date. In this paper, we will review: 1) the various methods of estimating hydraulic conductivity, obtained both in the laboratory and in the field, 2) the relative merits and shortcomings of the methods, 3) our general observations and conclusions at this stage of our investigations, and 4) the direction of the applied research we intend to pursue on the subject.

Hydraulic Conductivity: Laboratory and Field Tests

Historically, non-pumping methods include a variety of approaches involving two basic types of tests, i.e., laboratory and field tests. Laboratory tests employing permeameters and grain size analysis are widely used for geotechnical engineering studies. Melby (1989) summarizes the recent literature on laboratory determinations of hydraulic conductivity and concludes that permeameters produce reasonable results for high permeability conditions but are not acceptable for fine-grained sediments and soils. Herzog, et al.(1989) make similar comments by noting that their field-determined values of horizontal hydraulic conductivity were 10 to 1,000 times greater than laboratory-determined values. Cleary (1990) also observes that the use of laboratory values in contaminant/ground-water studies often results in poor estimations of travel times.

Laboratory Tests: High Permeability

In a study of unconsolidated sediments in the Netherlands, Ridder and Wit (1965) report that laboratory test results on "undisturbed" coarse-grained sands were in agreement with classical aquifer test results and with results produced by grain-size distribution of the samples. MacFarlane, et.al (1983) found similar results on an unconfined sand aquifer using aquifer and in situ field tests. Permeameter tests and grain size analyses were similar but were slightly higher than in situ field tests. In an earlier review of the literature, Taylor, et.al (1987) indicate that majority consensus supported the view that grain-size-derived hydraulic conductivity values differed by several orders of magnitude from field determinations. However, in their investigations on a moderately- to well-sorted sand aquifer, grain-size estimates were in the same order of magnitude as their field results. Fetter (1988) found similar results for a well-sorted medium sand.

Laboratory Tests: Low Permeability

For fine-grained sediments and soils, Olson and Daniel (1981) reviewed the literature of the period and concluded that field tests are preferred over laboratory permeameter tests because the former permits a larger volume to be tested which would incorporate the effects of macrostructures and macropores, such as root openings and fissures (slickensides). Pollock, et.al (1983) in a study of clayey mine spoil found the following hydraulic conductivity values for the three methods:

TEST TYPE	Average Horizontal Hydraulic Conductivity (cm/sec)
Based on Aquifer Tests:	$x10^{-4}$ to $x10^{-3}$
Based on In Situ Tests:	$x10^{-4}$
Based on Laboratory Tests:	$x10^{-8}$ to $x10^{-6}$

They concluded that "the differences between laboratory and field results probably were due to the measurement of different flow directions and [to] the absence of fracture [macropore] flow in the laboratory samples. Other investigators found similar results. Herzog and Morse (1984) conducted a comparative study of laboratory and field tests at a waste disposal site. Their results indicate that laboratory values of hydraulic conductivity were at least one order of magnitude lower than field values. They recommended that field tests be conducted for waste disposal sites rather than laboratory tests.

The emerging conclusion is that fined-grained sediments have higher permeability than indicated by small cores used in laboratory permeameters. Keller, et.al (1986) conducted both laboratory and field tests on an unweathered clayey till in Canada. They showed that the bulk permeability of the till was larger than its matrix permeability by some two orders of magnitude. Examinations were performed to establish visual evidence of fractures and other macropores in Shelby tube samples but none were found. Sample scale was again suspected as being responsible for the difference in bulk and matrix permeability. Hendry (1982) and Prudic (1982) found similar conditions.

In studies on clay liners of hazardous waste sites, Melby (1989) and Daniel (1987, p.15)) cite evidence that laboratory tests have consistently yielded values that were "much too low" and that field tests should be employed to determine the permeability of compacted clay liners. In general then, for fine-grained sediments, the laboratory methods used for estimating hydraulic conductivity have serious shortcomings. Olson and Daniel (1981) indicate that under laboratory conditions increasing the hydraulic gradient resulted in increases as well as decreases in hydraulic conductivity values (see Follmer (1984), Schwartzendruber (1968) and Mitchell and Younger (1967)). In addition, undisturbed samples are required for laboratory tests, although such a condition would be difficult to achieve.

In Situ Field Tests

Field tests involve either classical aquifer testing (via pumping), tracer studies (to estimate travel direction and velocity), flow-meter tests (although low-flow studies have not been successful), and so-called "slug" and "bailer" tests. The latter tests are widely used because: 1) some method is required to determine in situ permeability, and 2) these tests are the only widely accepted approaches presently available.

Aquifer Tests

Aquifer tests are usually considered to be the most reliable method to determine hydraulic conductivity. But, in sediments where a constant-rate aquifer pumping test does not produce a sustained flow rate, such tests will not be possible. In addition, even when a small, but sustained flow rate can be maintained, in applications where pumping would accumulate a large volume of contaminated ground water for subsequent storage or disposal, such pumping would be prohibitive.

Tracer and Flow-Meter Tests

Tracer tests are time consuming and often costly to perform. Results are ambiguous on occasion but are usually used to confirm other tests where test duration is not a project issue. Davis, et al., (1980) reviews tracers used in ground-water studies to determine direction and velocity of flow. Schroeder (1982) treats the state of instrumentation in aquifer testing under a variety of environmental conditions.

Slug Tests

Slug tests involve a short-term introduction or removal of water via a well or boring into (or out of) a subsurface interval of sediment, soil, or fractured rock. For information on slug tests in fractured rocks, see Schwartz (1975). Monitoring the water level rise (or fall) as it returns to quasi-equilibrium conditions produces data on the basis of which numerous researchers have developed methods to determine hydraulic conductivity and transmissivity. In general, slug tests are limited to sediments with a transmissivity of less than 7,000 ft^2/day. With high-speed instrumentation (transducers and recorders), even highly permeable aquifers with horizontal hydraulic conductivities greater than 10^{-1} cm/sec can be evaluated by using slug tests (see Prosser (1981) and McLane, et al.(1990)), although the classical aquifer test methods provide more information on aquifer conditions than site-specific slug tests. Slug tests originated out of the needs of geotechnical engineering projects where shallow subsurface conditions, pore pressure distribution, and dewatering were important factors in construction and foundation engineering for buildings, dams, and bridges (Bouwer, 1978).

The inherent problem with slug tests in clay-rich sediments is that the hole or boring wall is usually smeared during construction by augering which further reduces permeability at the face exposed to the screen of the monitoring well. This applies to sites with low permeability where clay content is high. Smearing of coarse-grained sands without significant clay content would not have an impact on flow into the well, unless the hole was drilled with clay-rich muds. In this case, well development would be important, after installation of the monitoring well, to remove fine-grained material that could reduce permeability at the borehole-formation face.

Each slug test method was developed in response to a particular subsurface condition, but on the whole, each method is related in some way to some extent to the other methods. One method was developed to accommodate certain features that previous methods either overlooked or ignored. The following methods will be reviewed:

Slug Test Method:	Date Published:
1. Hvorslev Method	1951
2. Cooper-Bredehoeft-Papadopulos Method	1967
3. Ferris-Knowles Method	1963
4. Theis (Modified) Method	1935
5. Bureau of Reclamation Method	1960
6. Nguyen-Pinder Method	1984
7. Bouwer-Rice Method	1976

1. Hvorslev Method

Hvorslev (1951) pioneered the development of in situ field tests, particularly the slug test. The need existed to estimate in situ hydraulic conductivity for both confined and unconfined aquifers under a variety of well geometries and aquifer conditions. The method has been described by Fetter (1988) and by Cedergren (1977), and involves determining the ratio "H/H(0)", where "H(0)" or "H_0" is the distance the water level declines upon removal of a slug of water, and "H" is the height of the water level below the static water level at some time, "t", after the slug is removed. The ratio is plotted versus time on semilogrithmic graph paper. A straight line should be evident.

A restriction imposed by the Hvorslev method is that the length of the well must be greater than eight times the radius of the well screen. Meeting this restriction would be a problem for only very shallow or large diameter wells. The following is considered to be the general form of the Hvorslev equation:

$$K = \frac{r^2 \, Ln(L/R)}{2LT_0}$$

where:

K= hydraulic conductivity
r= radius of well casing
R= radius of well screen
L= length of well screen
T_0= time required for the water level to rise to 37% of the initial change, obtained from the graph of $H/H(0)$

Hvorslev ignored the effects of compressive storage, and for water table cases, he assumed that the aquifer has an "infinite" thickness. The "saturated thickness" factor in water table considerations also is not incorporated in the Hvorslev method. In a review of the method, Chirlin (1989) addresses the shortcomings of the Hvorslev method by recasting the approach into a framework where compressibility and quasi-steady state conditions are considered, i.e., the Cooper, et al.(1967) model.

Chirlin emphasizes that Hvorslev provides no physical basis for selecting "effective radius" (or r_e) and introduces the Cooper approach to correct for the deficiency in Hvorslev and to act as a standard against which to judge the effect of the incompressibility assumption by Hvorslev. Chirlin is continuing his efforts along these lines.

Summers, et.al (1983) evaluated the commonly used slug test methods during a field program on the Pierre Shale in New Mexico and found that in using Hvorslev the volume of the slug was neither important nor required, and that only a few depth-to-water measurements were needed to obtain a straight line. However, they also found that in several cases a straight line could not be achieved with the data produced. At the present time, the Hvorslev method is used widely for reasons that are more related to historical precedence than to technical justification. The method has widespread acceptance and meets the perceived needs of the engineering profession because the method has produced results that seem to be reasonable approximations of in situ permeability. Modifications to the method are expected to evolve through the work of Chirlin, Melby, Summers and others. Patterson and Devlin (1985) suggest a down-hole packer to improve upon the reliability of the early water-level data.

An associated method commonly used in geotechnical engineering companies is termed: NAVFAC (DM-7.1), which is a restatement of the Hvorslev approach (see Anon.,1982).

2. Cooper-Bredehoeft-Papadopulos Method

The Cooper-Bredehoeft-Papadopulos (1967) method is widely regarded by most hydrogeologists and engineers as the most appropriate approach to estimating in situ permeability. The method uses a type-curve to obtain a match point which produces the input value for time in the following equation:

$$K = \frac{1440 \, r_c^2}{bt}$$

where:

K = hydraulic conductivity

r_c = radius of casing
b = length of screen
t = time since slug was inserted

According to Lohman (1979), the Cooper, et al. method was designed for confined, homogeneous aquifers of infinite areal extent where the well is fully penetrating and the diameter is small enough to ignore well storage effects. It is also reported to be strictly applicable to formations with low transmissivities of less than 7,000 ft^2/day.

Cleary (1990) indicates that although in principle the storage coefficient (S) may be estimated with this method, the reliability of such is questionable because of the similarity and related ambiguity of the type curves for different values of S. If S is required and if the formation is suffiently permeable that a reliable aquifer test via pumping is possible, then an aquifer test could provide the parameter: S. In an attempt to offset the problem with getting a reasonable value of S, Walter and Thompson (1982) offer a "repeated pulse" technique as a modification to the Cooper, et al. method for use in formations of low permeability. This approach yields information similar to conventional aquifer tests.

Summers, et al.(1983) found that if the data do not match one of the family of curves provided by the method, there is no possible estimate of K. The greater the degree to which the curve fits the field data, the greater the reliability of the derived results. In order to obtain a good "fit", data for both "tails" are required. That is, several measurements of the water level are required during the early decline period and after 90% of the decline has occurred. The principal shortcoming of the method is that the field data did not fit just one curve but had characteristics that fit other curves as well. In order to offset this problem, many measurements are required and the duration of the test may require many hours.

Further refinements of the Cooper, et al. approach were made on the various functions by Papadopulos, et al.(1973) and by Reed (1980). The Cooper, et al. model is used by Chirlin (1989) to generate "observations", while the Horslev model is applied to these observations to estimate hydraulic conductivity. This apparently provides a quantitative comparison of the two models, and defines the conditions for which the Hvorslev estimate of hydraulic conductivity is led astray by the assumption of incompressibility.

3. Ferris-Knowles Method

Ferris-Knowles (1963) made the assumptions in their method that the well was fully penetrating in an aquifer under confined conditions, radially infinite, homogeneous and isotropic. In contrast to Hvorslev (1951), their method allows for aquifer storage but ignores wellbore storage. The Cooper, et al. model has essentially replaced the Ferris and Knowles model.

The method involves the following relationship:

$$K = \frac{15.28\, q(1/t)}{bs}$$

where:

K = hydraulic conductivity (in ft/day)
q = volume of the slug (in gallons)
t = the time (in minutes) since the slug was injected
s = residual head (in feet) at elapsed time t
b = contributing interval of the piezometer

Summers, et al.(1983) used the Ferris-Knowles method in their study and plotted measured depth to water verus 1/t. Toward late times in the test, the plot should produce a straight line as the levels approach zero (0). If this fails to occur then the method will not function on the particular data set. If a straight line occurs then the slope of the line is equal to s/(1/t) and the equation can be solved for K. The group found that many measurements were required after half of the water-level decline had occurred. Furthermore, while the method gave what appeared to be reasonable results, they were often inconsistent with the results produced by other methods and substantial time was required to conduct the test.

4. Theis (Modified) Method

This method is essentially the same approach employed for the conventional aquifer testing. The Summers, et al. (1983) group made the assumption the slug was instantaneous and that one gallon of water was added to a piezometer, a short-term injection test. They plotted H versus log of the time since injection ended, to solve for the following model:

$$K = \frac{35.3\ Q}{bs}$$

where:

K = hydraulic conductivity
Q = injection rate (in gpm)
b = screen length (feet)
s = water-level change indicated by a straight-line segment during one log-cycle.

Summers, et al.(1983) suggest that the Theis (modified) method gave inconsistent results, and in some cases, provided results that were obviously unique.

5. Bureau of Reclamation Method

This method is one of many approaches developed by the U.S.B.R. (Anon, 1960), and assumes a constant rate of injection, according to the following equation:

$$K = \frac{261.8\ Q}{rH_0}$$

where:

K = hydraulic conductivity
Q = injection rate (gpm) determined from the average rate at which water drains from the casing.
r = radius of casing
H_0 = calculated water-level rise caused by the slug

The U.S.B.R. method provided values in the range that were either in good agreement or were an order of magnitude higher (and lower). In a continuation of the U.S.B.R. work, the "new" U.S. Water and Power Resources Service produced an engineering manual that contains descriptions of many specialized permeability tests (see Anon., 1981). Another Federal Government document is of interest concerning slug tests, see (Anon., 1961).

6. Nguyen-Pinder Method

The Nguyen and Pinder (1984) method is applicable to partially penetrating wells. Plots of: 1) Log H(t) vesus log t, and 2) log -H/t versus 1/t are prepared and the slopes of the graphs, C1 and C2, are generated. The hydraulic conductivity can be calculated by using the following relationship:

$$K = \frac{r_c^2 C_1}{4C_2(z_2 - z_1)}$$

where:

K = hydraulic conductivity
r_c = radius of casing
C_1 = slope of plot: log H(t) vs. log t
C_2 = slope of plot: log -H/t vs. 1/t
z_1 = distance from bottom of screen to bottom of aquifer
z_2 = distance from top of screen to bottom of aquifer

According to Melby (1989), his comparative analysis of four of the slug test methods indicates that the Nguyen and Pinder (1984) method produced consistently low values for hydraulic conductivity when compared to the results of the other methods. The plots required for this method generally did not yield good straight-line solutions, according to Melby. This was supported by Nguyen and Pinder (1984) wherein they caution that any significant deviation from a straight-line plot indicates either inaccurate data (i.e., for the water-level measurements) or an inappropriate mathematical model.

7. Bouwer-Rice Method

The Bouwer and Rice (1976,1989) method is used widely for unconfined and confined conditions, partially penetrating to fully penetrating, screened, perforated or otherwise open wells. The method is based on a modification of the Thiem equation for steady-state flow (Thiem, 1906). The recent update from Bouwer (1989) indicates that the approach is applicable to confined or stratified aquifers if the top of the screen or perforated section is some distance below the upper confining layer. The governing equation, supported by others, is as follows:

$$K = \frac{r_c^2 \, Ln(R_e/r_w)}{2L_e} \; \frac{1}{t} Ln \frac{y_0}{y_t}$$

where:

K = hydraulic conductivity
r_c = radius of casing

R_e = a dimentionless ratio describing system geometry
r_w = radius of screen plus thickness of sand pack or developed zone.
L_e = length of screen
y_0 = vertical difference between water level inside well and static-water level outside well at time 0
y_t = as above, but y at time t.

This method has many of the attributes and shortcomings of the Hvorslev method but advances the approach by accommodating previous difficult issues. It accounts for the geometry of the screen, gravel pack, finite saturated thickness and an effective radial distance over which the initial drawdown is dissipated. Using electrical analog modeling to characterize R_e, Bouwer and Rice (1976) and Bouwer (1989) provide a convenient set of curves relating R_e to other known well dimensions (Pandit and Miner, 1986). However, the issue of aquifer compressive storage effects remains unattended in the Bouwer and Rice method and Hvorslev method.

Field tests using the Bouwer and Rice method produce consistent results that generally compare favorably with other methods, with the exception of the Nguyen and Pinder method and a few others reviewed above. For example, Summers, et al.(1983) found that in their study this method was the method of choice because it produced consistent results under a variety of conditions. Melby's investigation found that the method compared favorably with Cooper, et al., even without corrections for compressibility. His slug test results also compared well to the constant-rate aquifer test. Could it be that the methods (Bouwer and Rice and Hvorslev) are correct for the wrong reasons and that Cooper, et al. are correct for the appropriate reasons? In an attempt to address this issue, Black (1978) adapted the Bouwer and Rice method for application with the procedures used by Cooper, et al., although the adaption has been put to little use to date.

Comparison of Slug Test Results

A vast set of data exists that contains results of slug tests from wells in various geologic settings. We are accumulating and organizing these data for further evaluation. The first two sets of data (from Summers, et al.(1983) and Melby (1989)) are presented in Figures 1 and 2; the latter is an expansion of the Oklahoma results presented in Figure 1 (upper right). The Bouwer and Rice results shown include the results from two analyses. One set was derived by the standard method (Bouwer and Rice, 1976), while the second data set was calculated by estimating the fluid-level rise from the volume of slug and the diameter of the casing, then plotted according to the standard procedure. In the New Mexico results, the spread between the two sets of results converge with increasing hydraulic conductivity, and the absolute variation is well within one order of magnitude. The figures illustrate the relationships between the methods over a broad range of low to intermediate values for hydraulic conductivity, from 10^{-6} to 10^{-2} cm/sec. The Summers data are from tests in a shale unit in New Mexico while the Melby data are from tests in alluvium in eastern Oklahoma.

Conclusions and Observations

Based on our investigations to date, we have come to the following conclusions:

1) Laboratory analyses (both from permeameters and from grain-size analyses) representing hydraulic conductivity are of doubtful value, especially for fine-grained materials, for the following reasons:

   A. There is a difference between bulk and matrix hydraulic conductivity because macropores (i.e., critter borings, root holes (refilled), slickensides and other site-specific causes of increased permeability) play a major role in determining the permeability of any area of unlithified sediment or rock. The small sample size used in laboratory tests could only represent matrix permeability, with the exception of the occasional interception of a

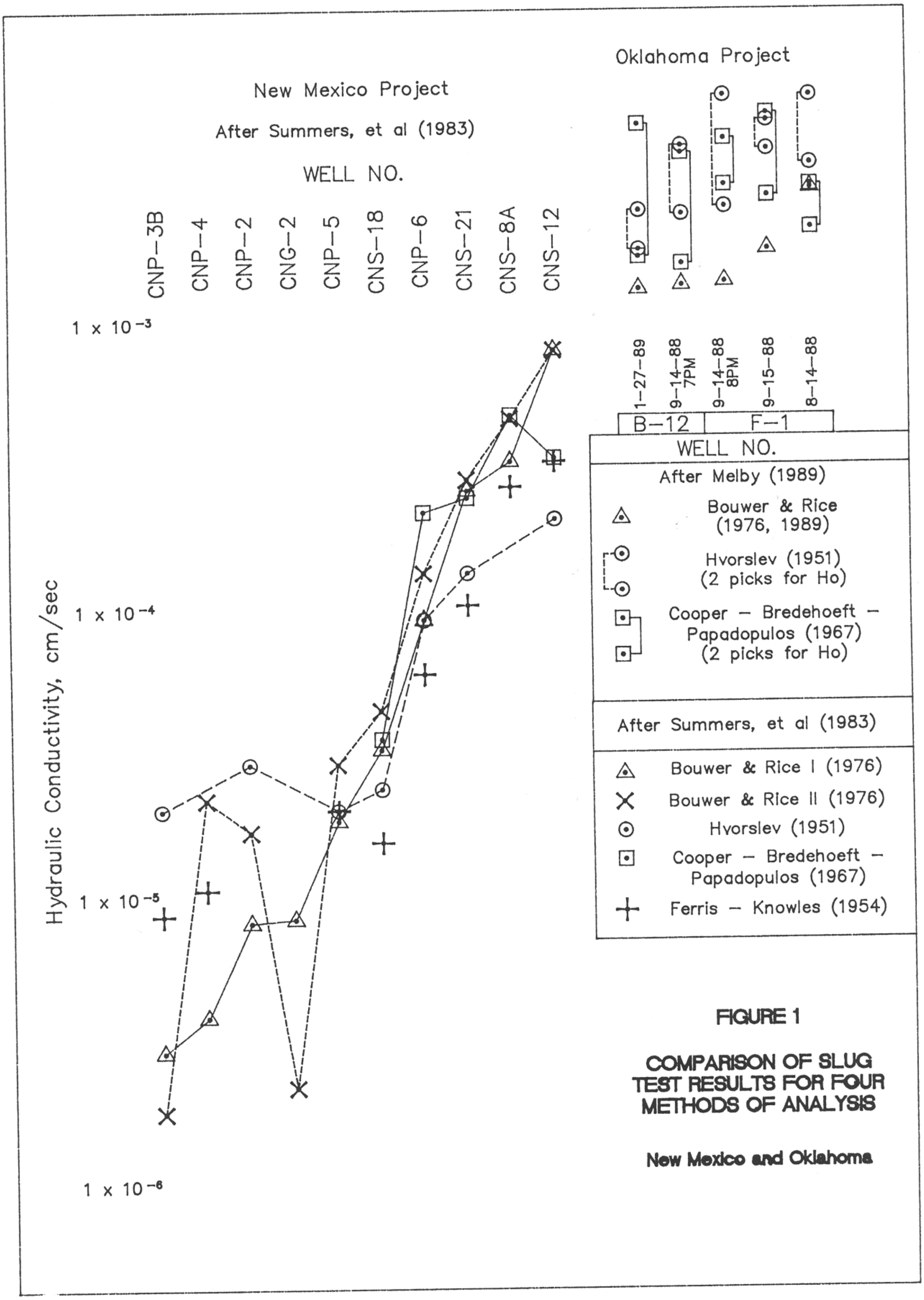

FIGURE 1

COMPARISON OF SLUG TEST RESULTS FOR FOUR METHODS OF ANALYSIS

New Mexico and Oklahoma

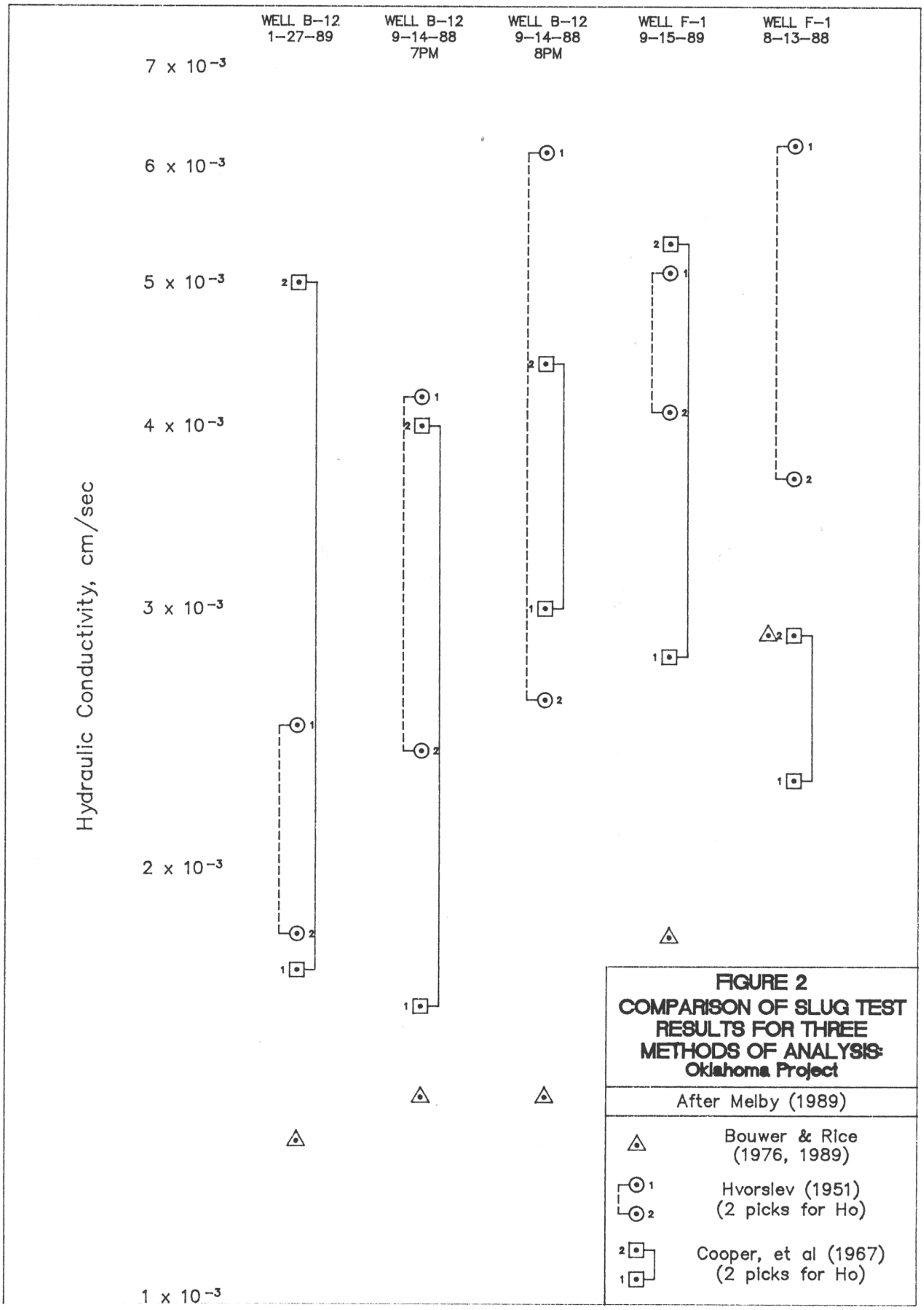

FIGURE 2
COMPARISON OF SLUG TEST RESULTS FOR THREE METHODS OF ANALYSIS:
Oklahoma Project

After Melby (1989)

macropore.

B. The laboratory method imposes unnatural pore pressures on the contained sample which affects the fined-grained material contained in the sample by either compressing or otherwise moving or bending particles into existing pore space. If the hydraulic gradient in the lab were adjusted to the point where these effects were no longer prevalent, the time required to test one sample would be prohibitive.

2) The Bouwer and Rice method is the method of choice for slug tests because the method's results are consistent with other more cumbersome and time-consuming methods.

3) Data acquisition, handling and computational processing should be assigned to the computer for quick response. The primary constants and intermediate equations can be converted to algorithms. However, the responsibility for the nature of the input data and associated results rests with the hydrogeologist or environmental engineer.

4) By the nature of the inherent variability in the subsurface, slug test results in fine-grained materials should be only considered valid over a range of one order of magnitude for contaminant transport studies.

5) Slug test results should be evaluated in context with a detailed boring/geologic log, preferably a geophysical log (natural gamma) or cone penetrometer log in order to have a direct comparison between geologic and hydraulic properties of the particular site.

Direction of Future Investigations

We intend to pursue the following direction in our research on slug tests and hydraulic conductivity:

1) Continue to compile and organize data sets of slug test results from our projects throughout the U.S. and from other sources.

2) Install monitor wells on company property to conduct ongoing investigations on: 1) monitor well installation to evaluate ways to minimize formation face damage via downhole scratchers or other methods, and 2) conduct slug tests combined with tracer tests under controlled conditions and over various periods of time to serve as cross-checks on slug test results.

3) Develop spreadsheet and other solutions to handle the various slug test computations and for comparing and and assessing the results and relative merits of the available slug test methods. Some possible solutions have already appeared (see Bumb and Ramesh, 1990; Kemblowski and Klein, 1988; and Thompson, 1987).

References

Anonymous, 1961, Design Manual, Soil Mechanics Foundations and Earth Structures:U. S. Dept. Navy, Bureau of Yards and Docks, DM-7, Chap. 4.

Anonymous, 1960, Earth Manual: U.S. Dept of Interior, Bur. Reclamation, Designation E-18, pp 546-562.

Anonymous, 1981, Ground Water Manual, A Water Resources Technical Publication, Water and Power Service, (see Chapter X, pp. 247-285.

Anonymous, 1982, Aquifer Tests: Design Manual 7.1: Soil Mechanics, NAVFAC DM-7.1, May pp.7.1-97 to 7.1-108.

Black, J. H., 1978, "The Use of the Slug Test in Groundwater Investigations", Water Resources, March, pp. 174-178.

Bouwer, H., 1978, Groundwater Hydrology, McGraw-Hill, New York, 480 pp.

Bouwer, H., 1989, "The Bouwer and Rice Slug Test - An Update", Ground Water, Vol. 27, No. 3, pp. 304-309, (Also see Discussion: Vol 27, No.5, p.715.

Bouwer, H., and Rice, R. C., 1976, "A Slug Test for Determining Hydraulic Conductivity of Unconfined Aquifers with Completely or Partially Penetrating Wells", Water Resources Research, Vol. 12, No.3, pp. 424-428.

Bradbury, K. R., and Rothschild, E. R., 1985, "A Computerized Technique for Estimating the Hydraulic Conductivity of Aquifers from Specific Capacity Data", Ground Water, Vol. 23, No. 2, pp. 240-246.

Bumb, A. C., and Ramesh, M. S., 1990, "Automated Analysis of Slug Test Data", Proceedings of the Outdoor Action Conference - 1990, NWWA, pp. 151-159.

Campbell, M. D., and Lehr, J. H., 1973, Water Well Technology, McGraw-Hill Book Company, New York, 641 p.

Cedergren, H. R., 1977, Seepage, Drainage, and Flownets, 2nd ed., John Wiley & Sons, 534 pp.

Chirlin, G. R., 1989, "A Critique of the Hvorslev Method for Slug Test Analysis: The Fully Penetrating Well", Ground Water Monitoring Review, Spring 1989, pp. 130-138.

Cleary, R. W., 1990, The Princeton Course: Ground-Water Pollution and Hydrology, Short Course Notes, approx. 500p.

Cooper, H. H., Bredehoeft, H. D., and Papadopulos, I. S., 1967, "Response of a Finite-Diameter Well to an Instantaneous Charge of Water", Water Resouces Journal, Vol. 1, pp. 263-269.

Daniel, D. E., 1987, "Hydraulic Conductivity Tests for Clay Liners", In Van Zyl, D. J. A., Abt, S. R., Nelson, J. D., and Shepard, T. A., (Eds.) Geotechnical and Geohydological Aspects of Waste Management, Proceedings of the 9th Annual Symposium on Geo-Aspects of Waste Management, February 1-6, Colorado State University, Fort Collins Colorado, Lewis Publishers, Inc., Chelsea, Michigan, pp. 15-34.

Dansby, D. A., 1987, "More Comments On: A Generation of Aquifer-Analyzing Illiterates", Ground Water, Vol. 25, No. 1, pp. 94-95.

Davis, S.N., et al.,1980, "Ground-Water Tracers-A Short Review," Ground Water, Vol. 18, No. 1, pp. 14-23

Dunn, R. J., 1983, "Hydraulic Conductivity of Soils in Relation to the Subsurface Movement of Hazardous Wastes", Ph.D. Thesis, University of California, Berkeley, 338 pp.

Fawcett, J. D., 1989, "Hydrogeologic Assessment, Design and Remediation of a Shallow Groundwater Contaminated Zone", Proceedings of the Outdoor Action Conference, NWWA, pp. 591-605.

Ferris, J. G., and Knowles, D. B., 1963, "The Slug-Injection Test for Estimating the Coefficient of Transmissibility of an Aquifer", U. S. Geol. Survey Water SupplyPaper1536-I.

Fetter, C. W., 1988, Applied Hydrogeology, Second Edition, Merrill Publishing Company, Columbus, Ohio, 592 pp.

Follmer, L. R., 1984, "Soil - An Uncertain Medium for Waste Disposal", Proceedings of the 7th Annual Madison Waste Conference, September 11-12, Department of Engineering and Applied Sciences, Univ. of Wisconsin, pp. 296-311.

Hendry, M. J., 1982, "Hydraulic Conductivity of a Glacial Till in Alberta", Ground Water, Vol. 20, No. 2, pp. 162-169.

Herzog, B. L., and Morse, W. J., 1984, "A Comparison of Laboratory and Field Determined Values of Hydraulic Conductivity at a Waste Disposal Site", Proceedings of the 7th Annual Madison Waste Conference, September 11-12, Department of Engineering and Applied Science, University of Wisconsin, pp. 30-52.

Herzog, et al., 1989, "Investigation of Failure Mechanisms and Migration of Organic Chemicals at Wilsonville, Illinois," Ground Water, Vol. 9, No.2, pp. 82-89.

Hvorslev, M. J., 1951, "Time Lag and Soil Permeability in Ground-Water Observations", Bull. No. 36, Waterways Experiment Station, Corps. of Engineers, U. S. Army, 50 pp.

Keller, C. K., Van Der Kamp, G., and Cherry, J. A., 1986, "Fracture Permeability and Groundwater Flow in Clayey Till Near Saskatoon, Saskatchewan", Canadian Geotechnical Journal, Vol. 23, pp. 229-240.

Kemblowski, M. W., and Klein, C. L., 1988, "An Automated Numerical Evaluation of Slug Test Data", Ground Water, Vol. 26, No. 4, pp. 435-438.

Lohman, S.W., 1979, "Ground-Water Hydraulics," U.S. Geological Survey Prof. Paper 708, 70 pp.(see page 27).

MacFarlane, D. S., Cherry, J. A., Gillham, R. W., and Sudicky, E. A., 1983, "Migration of Contaminants in Groundwater at a Landfill: A Case Study", Journal of Hydrology, Vol. 63, pp. 1-29.

McLane, G. A., Harrity, D. A., and Thomsen, K. O., 1990, "A Pneumatic Method for Conducting Rising and Falling Head Tests in Highly Permeable Aquifers", Proceedings of the Outdoor Action Conference - 1990, NWWA, pp. 1219-1231.

Melby, J. T., 1989, " A Comparative Study of Hydraulic Conductivity Determinations for a Fine-grained Alluvium Aquifer," Master's Thesis, Oklahoma State University, 172 p.

Mitchell, J. K., and Younger, J. S., 1967, "Abnormalities in Capillary Flow through Fine-Grained Soils", ASTM STP 417, Philadelphia, Pennsylvania, pp. 106-139.

Nguyen, S. P., and Pinder, G. F., 1984, "Direct Calculation of Aquifer Parameters in Slug Test Analysis", Water Resources Monograph Series 9, pp. 222-239.

Olsen, R. E., and Daniel, D. E., 1981, "Measurement of the Hydraulic Conductivity of Fine-Grained Soils", In Permeability and Groundwater Contaminant Transport, ASTM STP 746, pp. 18-64.

Pandit, N. S., and Miner, R. F., 1986, "Interpretation of Slug Test Data", Ground Water, Vol. 24, No. 6, pp. 743-749.

Papadopulos, S. S., Bredehoeft, J. D., and Cooper, H. H., 1973, "On the Analysis of Slug Test Data", Water Resources Research, Vol. 9, No. 4, pp. 1087-1089.

Patterson, R. J., and Devlin, J. F., 1985, "An Improved Method for Slug Tests in Small-Diameter Piezometers", Ground Water, Vol. 23, No. 6, pp. 804-805.

Pedler, W. H., Barvenik, M. J., Tsang, C. F., and Hale, F. V., 1990, "Determination of Bedrock Hydraulic Conductivity and Hydrochemistry Using a Wellbore Fluid Logging Method", Proceedings of the Outdoor Action Conference - 1990, NWWA, pp. 39-53.

Pollock, C. R., Robbins, G. A., and Mathewson, C. C., 1983, "Ground-Water Monitoring in Clay-Rich Strata - Techniques, Difficulties, and Potential Solutions", Proceedings of the 3rd National Symposium on Aquifer Restoration and Ground-Water Monitoring, NWWA, Dublin, Ohio.

Prosser, D.W., 1981, "A Method of Performing Response Tests on a Highly Permeable Aquifer," Ground Water, Vol. 19, No. 6, pp. 588-592.

Prudic, D. E., 1982, "Hydraulic Conductivity of a Fine-Grained Till, Cattaraugus County, New York", Ground Water, Vol. 20, No. 2, pp. 194-203.

Ridder, N. A., and Wit, K. E., 1965, "A Comparative Study on the Hydraulic Conductivity of Unconsolidated Sediments", Journal of Hydrology, Vol. 3, pp. 180-206.

Reed, J. E., 1980, "Type Curves for Selected Problems of Flow to Wells in Confined Aquifers," Chapter B-3, Applications of Hydraulics, Techniques of Water Resources Investigations of the U.S. Geological Survey, 106 p.(see page 45).

Smith, S. M., 1987, "Comments On A Generation of Aquifer-Analyzing Illiterates", Ground Water, Vol.25, No. 1, p. 94.

Schroeder, R.C., 1982, "Instrumentation for Well Tests,"in Geol. Soc. America Special Paper 189, pp 199-206

Schwartz, F. W., 1975, "Response Testing of Piezometers in Fractured Porous Media", Canadian Geotechnical Journal, Vol. 12, pp. 408-412.

Schwartzendruber, D., 1968, "The Applicability of Darcy's Law", Soil Science of America Proceedings, Vol. 32, No. 1, pp. 11-18.

Summers, W.K., et al., 1983, "The Hydraulic Properties of the Pierre Shale: A Comparison of Methods," (Private Distribution), 15p.

Taylor, S. R., Moltyaner, G. L., Howard, K. W. F., and Killey, R. W. D., 1987, "A Comparison of Field and Laboratory Methods for Determining Contaminant Flow Parameters", Ground Water, Vol. 25, No. 3, pp. 321-330.

Theis, C. V., 1935, "The Relation Between the Lowering of the Piezometric Surface and the Rate of Discharge of a Well Using Groundwater Storage", American Geophysical Union, Transactions, Vol. 2, pp. 519-524.

Thiem, G., 1906, Hydrologische Methoden, Leipzig, Gephardt, 56 pp.

Thompson, D. B., 1987, "A Microcomputer Program for Interpreting Time-Lag Permeability Tests", Ground Water, Vol. 25, No. 2, pp. 212-213.

Walter, G. R., and Thompson, G. M., 1982, "A Repeated Pulse Technique for Determining the Hydraulic Properties of Tight Formations", Ground Water, Vol. 20, No. 2, pp. 186-193.

U.S. Code of Federal Regulations, 1988, CFR, Title 40, Parts 190-399. U.S. Printing Office, Washington, D.C.

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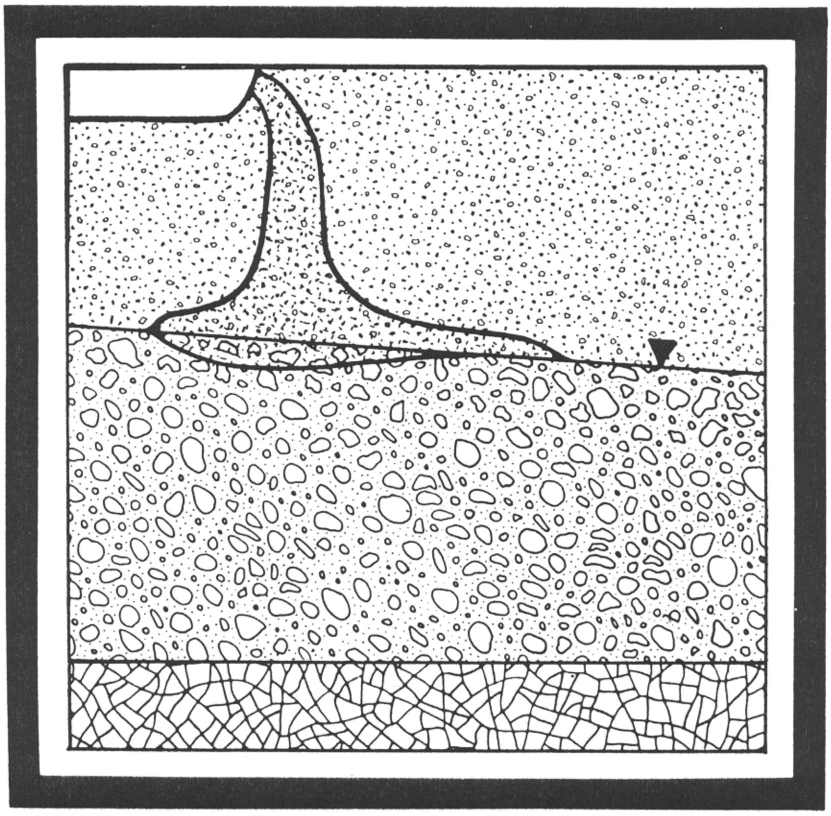

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