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ABSTRACT

Effective porosity of geologic materials is a very important parameter for estimating groundwater travel time and modeling contaminant transport in hydrologic systems. Determination of a representative effective porosity for nonideal systems is a problem still challenging hydrogeologists. In this paper, some of the conventional field geophysical and hydrological methods for estimating effective porosity of geologic materials are reviewed. The limitations and uncertainties associated with each method are discussed.

INTRODUCTION

Porosity of geologic materials plays an important role in controlling groundwater travel time and transport of hazardous substances between sources and the accessible environment. Therefore, determination of a representative value of porosity for a given volume of geologic materials, or a statistical distribution of this parameter, is of great interest in predicting the transport of hazardous waste substances in projects such as radioactive waste isolation and underground injection of hazardous waste liquids. Another important area of such need is in projects related to groundwater contamination and remediation. In this paper, some of the conventional methods used for the field measurement of porosity will be reviewed. The limitations and uncertainties related to each method will be discussed.

The porosity of a material is defined as the ratio of void space to total bulk volume. Sometimes some of the voids are isolated and do not play a role in transmitting fluid. This is the reason for introducing the concept of effective porosity, which is defined as the ratio of the volume of connected pores to the bulk volume of the material. Porosity is a scalar property of the rock, which means it is independent of direction.

METHODS OF MEASUREMENT

There are several methods which are commonly used in the laboratory to measure the porosity of a rock core sample. These techniques, including the direct method, mercury injection, gas expansion, and imbibition have been fully discussed in an American Petroleum Institute report (1960). Because laboratory techniques are not the scope of this paper, we shall not discuss them further.

In the field, porosity may be obtained by several methods including well logging and tracer tests. The following is a brief discussion of several of these techniques, such as Sonic, Formation Density, and Neutron Logs, and tracer tests.

Sonic Log Method

A more detailed description of this method and additional references are given in Schlumberger (1972). Generally, for a given rock, when porosity increases the sonic velocity decreases. The Sonic Log is a recording of interval transit time (Δt) versus depth. The interval transit time is the time required for a compressional sound wave to traverse through one foot of formation. The interval transit time for a given formation is a function of its lithology and porosity. The Sonic Log is therefore a useful mean for obtaining porosity, provided the lithology is known.

Theory and Procedure

A Sonic tool, consisting of two transmitters and two pairs of receivers, is lowered into an uncased well filled with drilling mud or other fluid, (see Figure 1). A pulse is generated by each of the two transmitters and the difference between the arrival times of the first wave at the corresponding pair of receivers is measured. The Δt from the two sets of receivers are averaged and recorded as a function of depth.

The wave generated by the transmitter will travel through different available media. However, since the speed of the wave in the formation is generally larger than that in the drilling fluid or the sonde itself, the wave which will first arrive at the receivers is the one which has traveled through the formation very close to the wall of the hole. As we measure the difference in travel time to the two receivers, the period of time corresponding to travel through the drilling fluid is cancelled out. As a result, knowing the constant of the instrument, the measured Δt can be adjusted to show the reciprocal of the velocity in the formation. Δt is generally recorded in microsecond/foot (μsec/ft) and it varies between about 44 μsec/ft (for dense, zero porosity dolomite) to about 190 μsec/ft for pure water.

Wyllie et al. (1956, 1958) have proposed the following empirical formula for determining the porosity ϕ of a consolidated formation with uniformly distributed pores:

$$\phi = \frac{\Delta t_{log} - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}} \tag{1}$$

where

Δt_{log} = transit time reading on the Sonic Log, in μsec/ft

Δt_{ma} = transit time for the rock matrix material (values for different rocks are given in Table 1)

Δt_f = the inverse of the velocity of a Sonic Wave in the pore fluid (about 189 μsec/ft).

To calculate porosity at a given depth, one should identify the type of rock from cores and/or cuttings and determine the value of Δt_{ma} from Table 1, or other sources. Δt_{log} from the Sonic Log is then measured for that particular depth. Equation (1) may then be used to calculate porosity at the depth under consideration.

Table 1. Values of transit time for common rocks and casing (modified from Schlumberger, 1972)

Rock	Δt_{ma} (μsec/ft)
Sandstones	51.0 - 55.5
Limestones	47.5
Dolomites	43.5
Anhydrite	50.0
Salt	67.0
Casing (iron)	57.0

Uncertainties

- The depth of penetration of the recorded wave is only a few inches from the borehole wall. Thus, the value of porosity obtained by this method is limited to a very small zone around the well.
- According to Wyllie et al. (1956, 1958), the sound velocity in vuggy materials depends mostly on the primary porosity. Therefore, the sonic method tends to ignore secondary porosity such as fractures. The Sonic

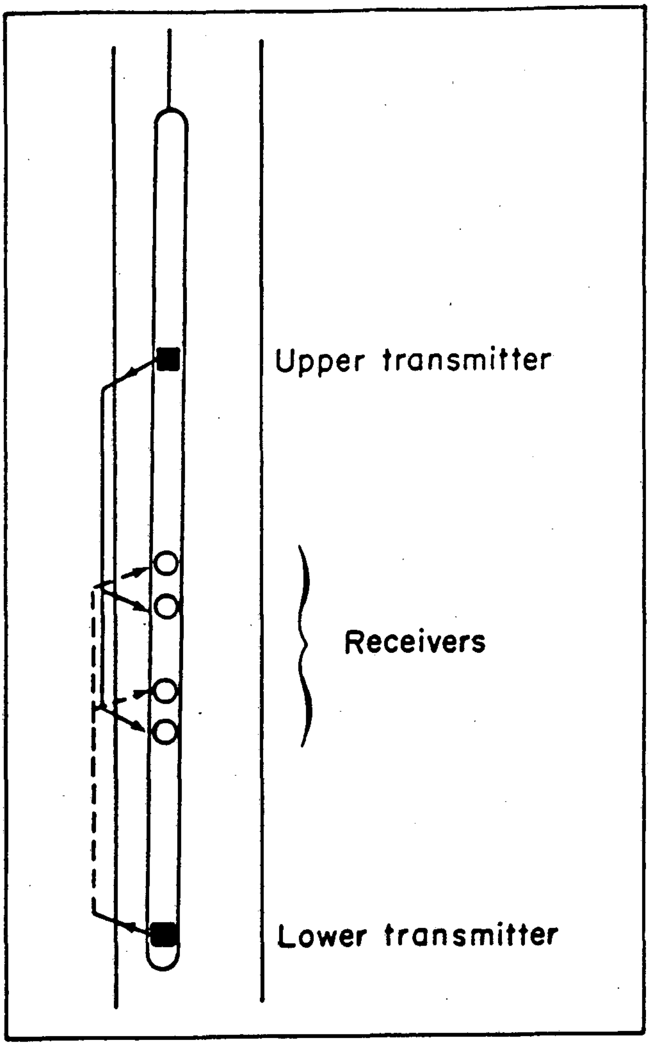

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Figure 1. Sketch of a sonic tool, showing ray paths for transmitter-receiver sets (modified from Kokesh et al., 1965).

Logs in comparison with the Density Logs and Neutron Logs could, however, give a measure of secondary porosity.

- The method is not suitable for determining effective porosity if there is a significant volume of isolated pore space.

Density Log Method

A downhole radioactive source, in contact with the borehole wall, emits medium-energy gamma rays into the surrounding formation. After colliding with electrons in the formation, the scattered gamma rays are counted by a detector placed at a fixed distance from the source. The response to such a bombardment is determined essentially by the electron density of the formation, which is a function of the true bulk density, ρ_b. Therefore the porosity of the formation may be calculated if the densities of the rock matrix and the pore fluid are known.

Theory and Procedure

A Formation Density logging device, consisting of a source and one or two detectors attached to a skid, is lowered into an uncased well filled with drilling mud or other fluid. The device is designed such that the source and detectors come in contact with the borehole wall. The variation of bulk density against depth is recorded. These tools are usually calibrated to indicate apparent bulk density. For some types of rock such as sandstone, limestone and dolomite, in the saturated zone the apparent bulk density is essentially equal to the bulk density itself. Other types of rock bulk density should be estimated from apparent values using available graphs (Schlumberger, 1972). The porosity, ϕ, of the rock can be estimated from

$$\phi = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f} \tag{2}$$

where

ρ_b = bulk density of the rock obtained from the log.

ρ_f = the density of pore fluids close to the well.

ρ_{ma} = rock matrix density

Uncertainties

- This method determines total porosity. It does not differentiate between connected and isolated pore spaces within the formation.
- The presence of shale or clay in the formation introduces some errors into the results.

Neutron Log Method

This method can determine the amount of in situ liquid-filled porosity of a given material. This technique is essentially based on a measurement of the amount of hydrogen present in the formation. If the pore space of the rock is filled water and there is no other source of hydrogen, such as the water in gypsum ($CaSO_4 + 2H_2O$), is present, then the response of this test is a measure of porosity.

Theory and Procedure

There are at least three different kinds of Neutron Logs which are currently available. GNT (Gamma Ray Neutron Tool), SNP (Sidewall Neutron Porosity), and CNL (Compensated Neutron Log) use plutonium-beryllium or americium-beryllium as sources of neutrons with initial energies of several million electron volts (Schlumberger, 1972). Here, we shall only address the SNP method. Information about other tools and additional references on those tools may be obtained from Schlumberger (1972).

In the SNP, a neutron source and a detector are mounted on a skid which is lowered into an uncased well, preferably without fluid and drilling mud. This tool is designed such that it comes in contact with the borehole wall. The neutrons emitted by the source, after penetrating the formation and colliding with the nuclei of the formation materials are received by the detector. The response is measured against depth. A surface panel automatically makes necessary corrections for salinity, temperature, and hole diameter variations, and records the porosity directly. If the hole is filled with drilling mud, porosity values should be corrected for the mud-cake thickness, using available charts (Schlumberger, 1972).

Neutrons are electrically neutral particles, each with the mass of a hydrogen atom (Tittman, 1956). The source on the tool continuously emits fast neutrons. These neutrons collide with nuclei of the formation materials and lose some of their energy. The amount of energy which a neutron loses in each collision depends on the relative mass of the nucleus against which the neutron collides. Collision with a hydrogen nucleus causes the maximum energy loss. Thus, the slow-down of neutrons depends largely on the amount of hydrogen in the formation, which in turn is related to the amount of water in the formation. The SNP method has the advantages that borehole effects are minimized (Schlumberger, 1972) and that most of the corrections required are performed automatically in the panel.

Uncertainties

- This method can measure effective porosity only if the isolated pores are free of liquid, otherwise the method does not differentiate between connected and isolated pores.
- The tool responds to all the hydrogen atoms in the formation including those chemically bound to formation materials.
- In shaly formations the porosity derived from the neutron response will be greater than the effective porosity.
- The zone of influence of this method depends on the porosity of the formation, but generally it is limited to a short distance from the wall of the hole.

TRACER TECHNIQUES

There are several tracer methods for determination of aquifer properties such as effective porosity and dispersivity. The literature is replete with descriptions of theory and practice of tracer tests, see for example, Nir and Kirk (1982); Klett et al. (1981); Benson (1988); Fried (1975); Hoehn and Roberts (1982); Malaszowski and Zuber (1985); Lenda and Zuber (1970); Ivanovich and Smith (1978) and Güven et al. (1986). Many types of radioactive and nonradioactive tracers have been used. A list of some of the tracers which have been used in groundwater studies has been given by Davis et al. (1980) and Thompson (1981).

Tracer tests used for estimating porosity of geologic materials in the field, may fall into the following categories: Uniform flow field tests, radially convergent tests, radially divergent tests, and two well recirculating tests. Other types of tracer tests, such as single well injection/withdrawal test, have been used to estimate the porosity and dispersivity of the geologic materials (Mercado and Halvey, 1966; Pickens and Grisak, 1981). These methods will not be discussed here. Two patterns of injection may be selected in each case. A tracer may be injected continuously for a relatively long period of time, or the period of injection is kept small relative to travel time between injection and observation point (slug injection). The following is a brief discussion of each of these four techniques.

Uniform Flow Field Tests

A: Continuous Injection

Consider a two-dimensional homogeneous aquifer with a uniform flow field. If a tracer with concentration C_O is continuously injected into a well that is open along the total thickness of the aquifer (see Fig. 2), the concentration C(x,y,t) of the tracer at a point (x,y) and at a time t may be expressed as (Fried, 1975; Sauty 1980):

$$C_D(a,t'_D) = W(a^2/4t'_D, a/2)/2\,K_0(a/2) \tag{3}$$

where,

$$C_D = \frac{C}{C_{max}}$$
$$a = \left[\frac{x^2}{\alpha_L^2} + \frac{y^2}{\alpha_L\,\alpha_T}\right]^{½} \tag{4}$$

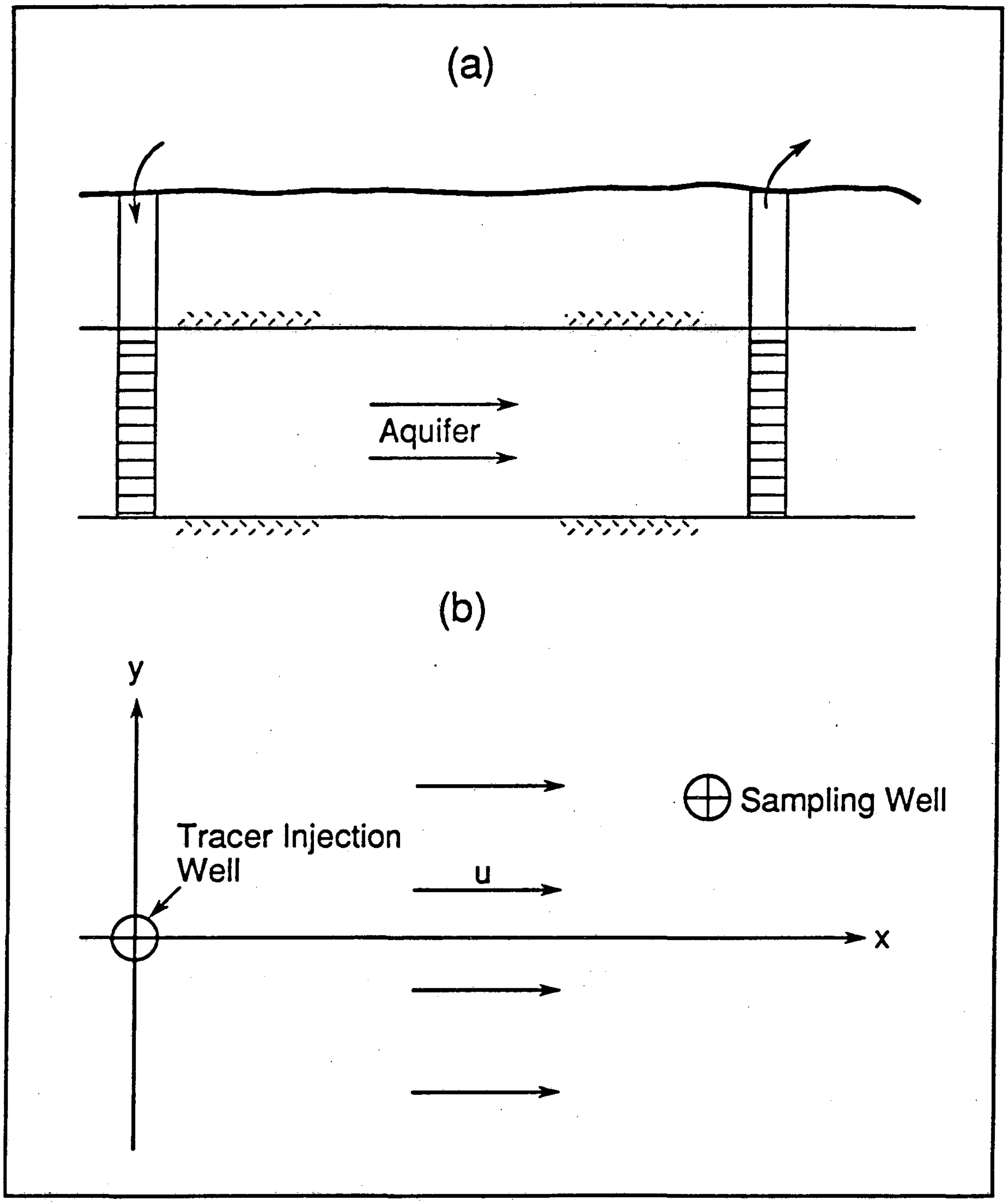

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Figure 2. a) A vertical section passing through both injection and sampling wells, and
b) a plan view showing the position of wells and regional groundwater flow direction relative to the coordinate system.

$$t_D' = \frac{ut}{\alpha_L} \qquad (5)$$

$$W(\alpha,\beta) = \int_{\alpha}^{\infty} y^{-1} \exp\left[-y - \frac{\beta^2}{4y}\right] dy, \qquad (6)$$

α_L and α_T are longitudinal and transverse dispersivities, respectively, u is average pore water velocity, K_0 is the modified Bessel function of second kind and zero order, and C_{max} is the maximum value of concentration at the observation well. In these tests, the volume of tracer injected is small enough not to disturb the uniform flow field.

If the observation is made somewhere along the x axis, the above expression may be simplified to

$$C_D\,(P_e, t_D) = W(P_e/4t_D, P_e/2)/2\,K_0(P_e/2) \qquad (7)$$

where $P_e = X/\alpha_L$ is a Peclet number, $t_D = ut/X$ is dimensionless time, and X is the distance between injection and observation wells.

Equation (7) may be used to develop a family of type curves to illustrate the variation of C_D versus t_D with Peclet number as a running parameter. Figure 3 shows a family of these curves on a semilogarithmic plot. It is of interest to note that the value of dimensionless concentration $C_D = 0.5$ occurs at $t_D = 1$ for all values of Peclet number. This implies that in a tracer test where P_e is relatively large and one can estimate the time corresponding to $C = 0.5\ C_{max}$, pore water velocity may be directly calculated from

$$u = \frac{X}{t_{0.5}} \qquad (8)$$

Effective porosity may then be calculated if one has hydraulic conductivity and gradient from other information. However, for smaller values of P_e the time required to arrive at the C_{max} could be so long to make the test prohibitive.

B: Slug Injection

If a certain mass of tracer is introduced into the well in a relatively short period of time, the time variation of concentration at an observation well downstream may be expressed by (Fried and Combarnous, 1971):

$$C_D(a, t'_D) = \frac{K}{t'_D} \exp\left\{-\frac{a^2 + t'^2_D}{4t'_D}\right\} \qquad (9)$$

where

$$K = t'_m \exp\left\{\frac{a^2 + t'^2_m}{4\,t'_m}\right\} \qquad (10)$$

and

$$t'_m = (a^2 + 4)^{1/2} - 2 \qquad (11)$$

Again, if the observation well is located on the x-axis, the solution may be simplified to

$$C_D(P_e, t_D) = \frac{K'}{t_D} \exp\left\{-\frac{P_e(1 - t^2_D)}{4t_D}\right\} \qquad (12)$$

where

$$K' = t_m \exp\left\{\frac{P_e(1 - t_m)^2}{4t_m}\right\} \qquad (13)$$

and

$$t_m = (1 + \frac{4}{P_e^2})^{1/2} - \frac{2}{P_e} \qquad (14)$$

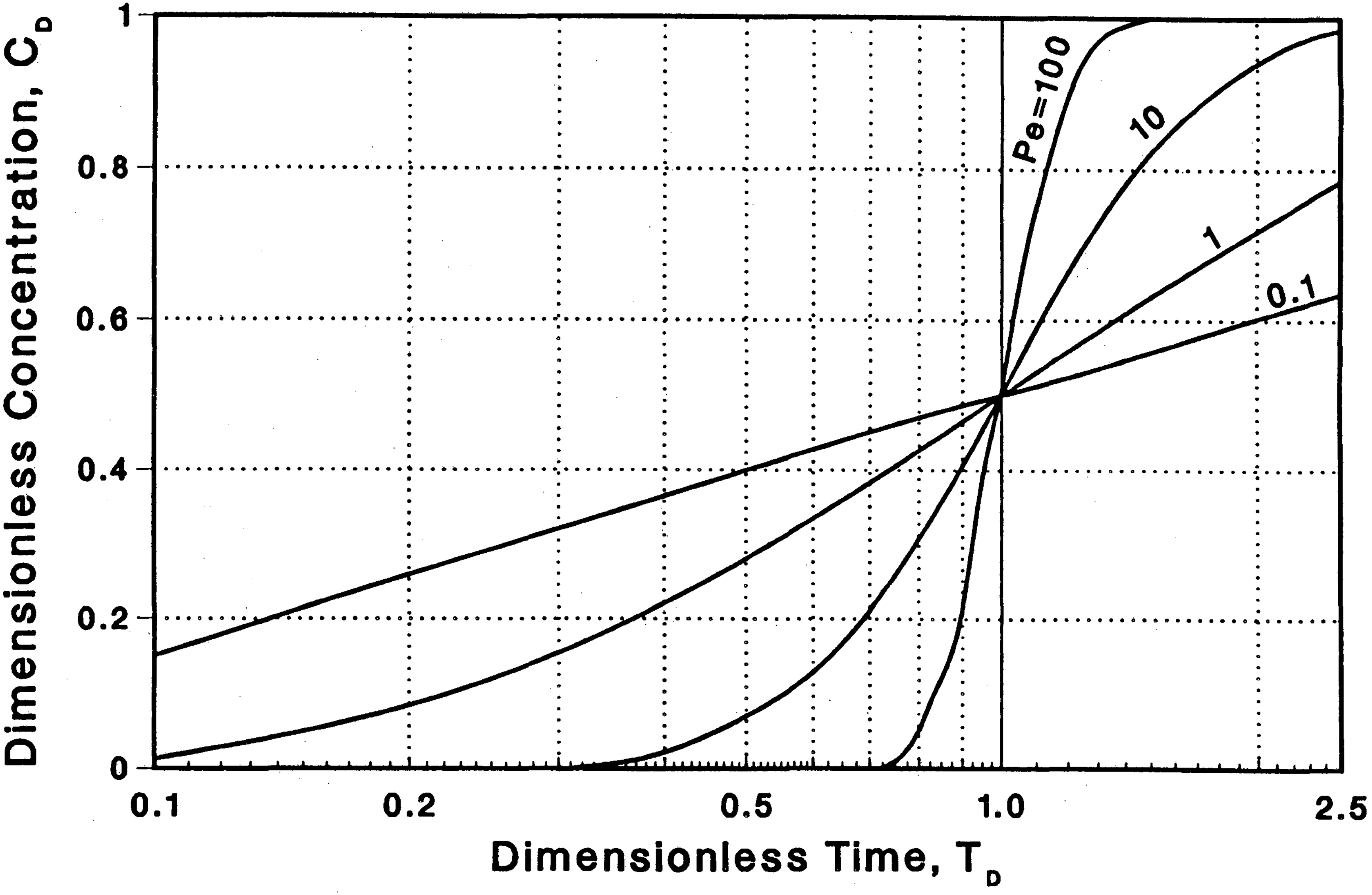

Figure 3. Type curves for continuous tracer injection in a two-dimensional uniform flow field, (modified from Sauty, 1980).

Figure 4 shows a family of type curves prepared from equation (12). Using curve matching techniques, type curves given in figure 4 together with the field data obtained from the tracer test allows one to estimate effective porosity of the aquifer material between the injection and monitoring wells.

Uncertainties

- Unless one knows the direction of regional flow very accurately, the error associated with the estimated value of the porosity obtained from this method could be significant (Sauty, 1980). One way to alleviate this problem is to collect samples from several wells located either on a line perpendicular to the approximate direction of flow or on an arc around the injection well (Fried, 1975).
- In general, the natural gradient of the groundwater flow is very small (in the order of 0.001). This magnitude of hydraulic gradient leads to a relatively long and impractical test period even for aquifers with relatively high conductivity. For example, the travel time of water particles between two wells, 20 meters apart, aligned parallel to the flow direction in an aquifer with hydraulic conductivity of 10^{-4} m/s and porosity of 30 percent, is about 2 years.

Radially Convergent Tests

Consider a homogeneous aquifer with a pumping well open along the total thickness of the aquifer. Once the flow regime is stablized and steady state is achieved, a tracer may be introduced in another well in the vicinity of the pumping well and the time variation of tracer concentration measured in samples taken at the pumping well.

In the analysis of these tests, the effect of natural groundwater flow is generally neglected. Therefore, the distance between the injection and withdrawal wells are selected in a manner to minimize the effect of the regional flow. Among others, Sauty (1980) has used a finite difference code to develop type curves for the case of continuous injection of a tracer. Figure 5 shows a set of these type curves on a semilogarithmic paper. If a tracer is injected in the form of a slug, then another set of type curves developed by (Sauty, 1980) may be used for interpreting the results. Figure 6 illustrates a family of type curves for the case of slug injection in radially convergent tracer tests. This figure shows the variation of dimensionless concentration versus dimensionless time for several Peclet number values.

Radially Divergent Tests

In this type of test, water with a constant tracer concentration is injected into a well that fully penetrates and is open along the total thickness of an aquifer. However, before adding any tracer, water is injected long enough to achieve a steady state flow regime within the aquifer. It is assumed that the aquifer is confined and of a uniform thickness. To simplify the analysis, the rate of injection and tracer concentration in the injected water are kept constant. Time variation of concentration at an observation well nearby is monitored and recorded. Ogata (1958) developed an analytical solution for calculating tracer concentration in the observation well as a function of time. The numerical evaluation of that solution is cumbersome and has not been done.

Later, Moench and Ogata (1981) rewrote the solution of the above problem in the Laplace transform domain and inverted numerically. Values of dimensionless concentration as a function of dimensionless time and dimensionless radius from the above solution are available (Javandel et al., 1984). Others have presented approximate solutions to this problem (Hooper and Harleman, 1967). Sauty (1980) has used a finite difference code to prepare a set of type curves for this problem when tracer injection is limited to a short period of time (slug test). Figure 7 shows a family of type curves for radially divergent slug tests.

Uncertainties

- Although one can easily take into account numerically the effect of regional groundwater flow, almost all of the type curves available in the literature and presented here ignore the effect of regional flow on the breakthrough curves. The amount of error introduced by this assumption depends on the relative position of points of tracer introduction and sampling with respect to the direction of regional flow. The error is also a function of the magnitude of the regional groundwater velocity relative to the rate of pumping or injection. In general, the error increases with the distance between points of tracer introduction and sampling.

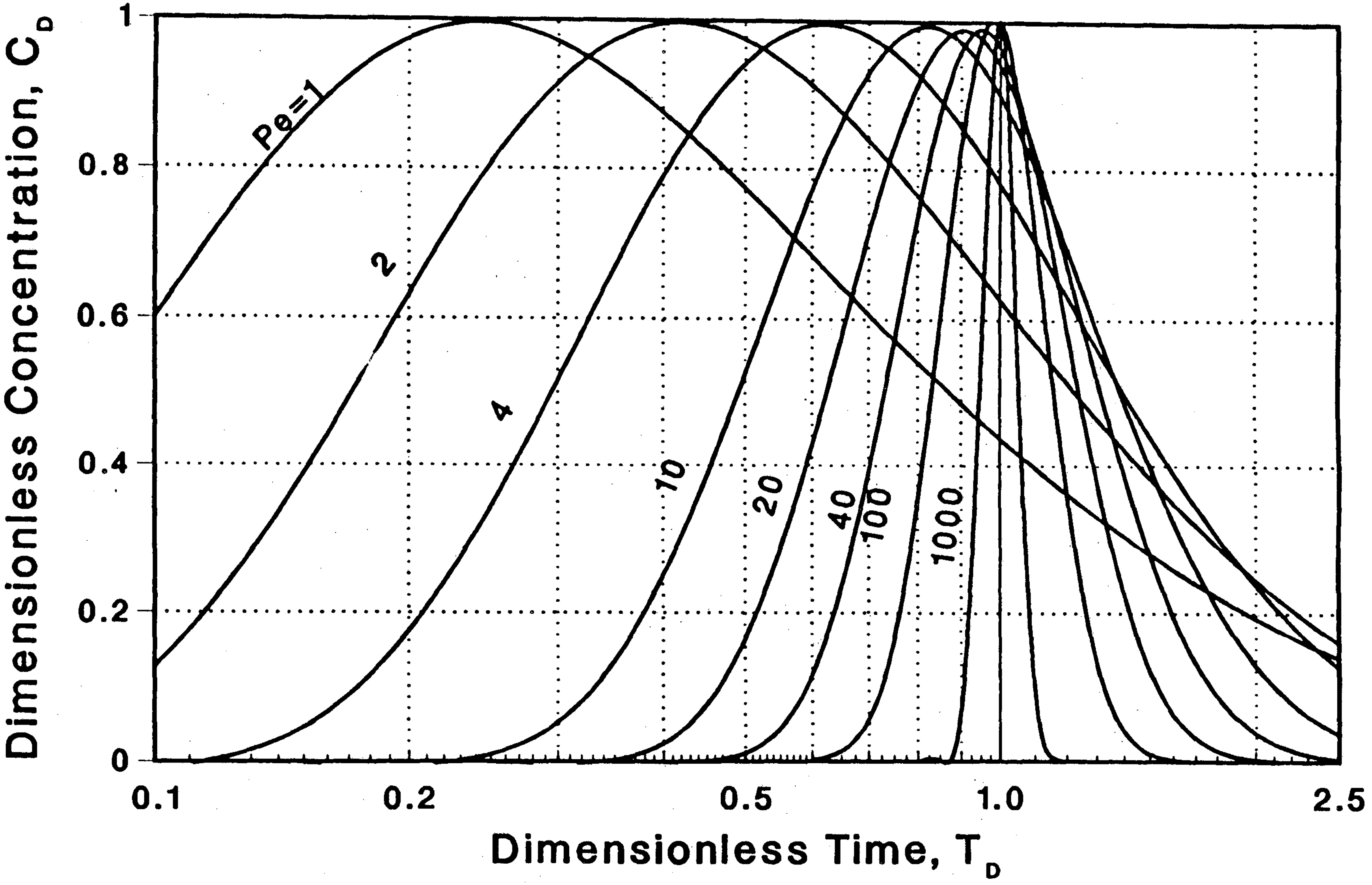

Figure 4. Type curves for instantaneous tracer injection in a two-dimensional uniform flow field.

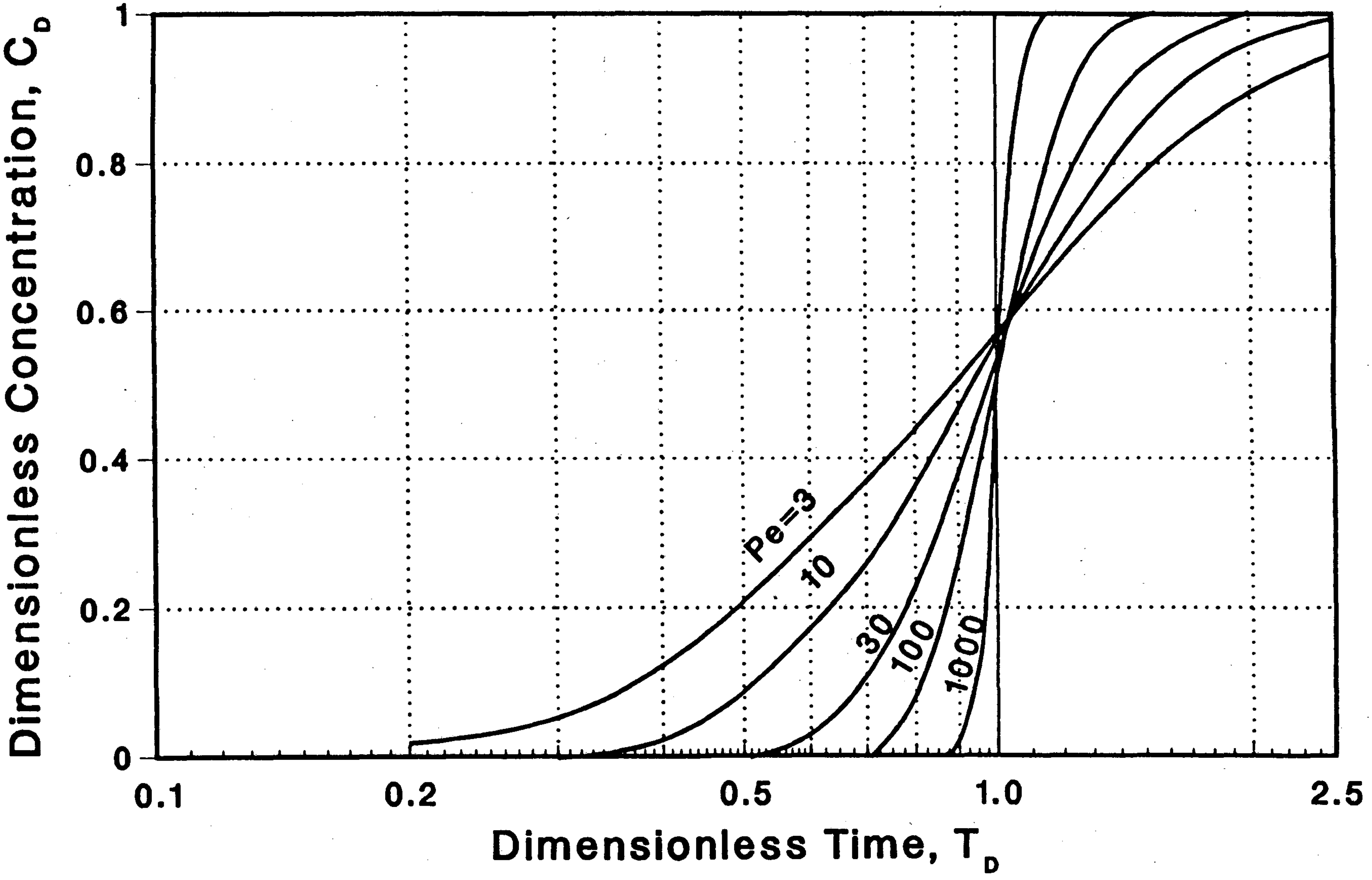

Figure 5. Type curves for continuous tracer injection in a radially converging flow field (modified from Sauty, 1980).

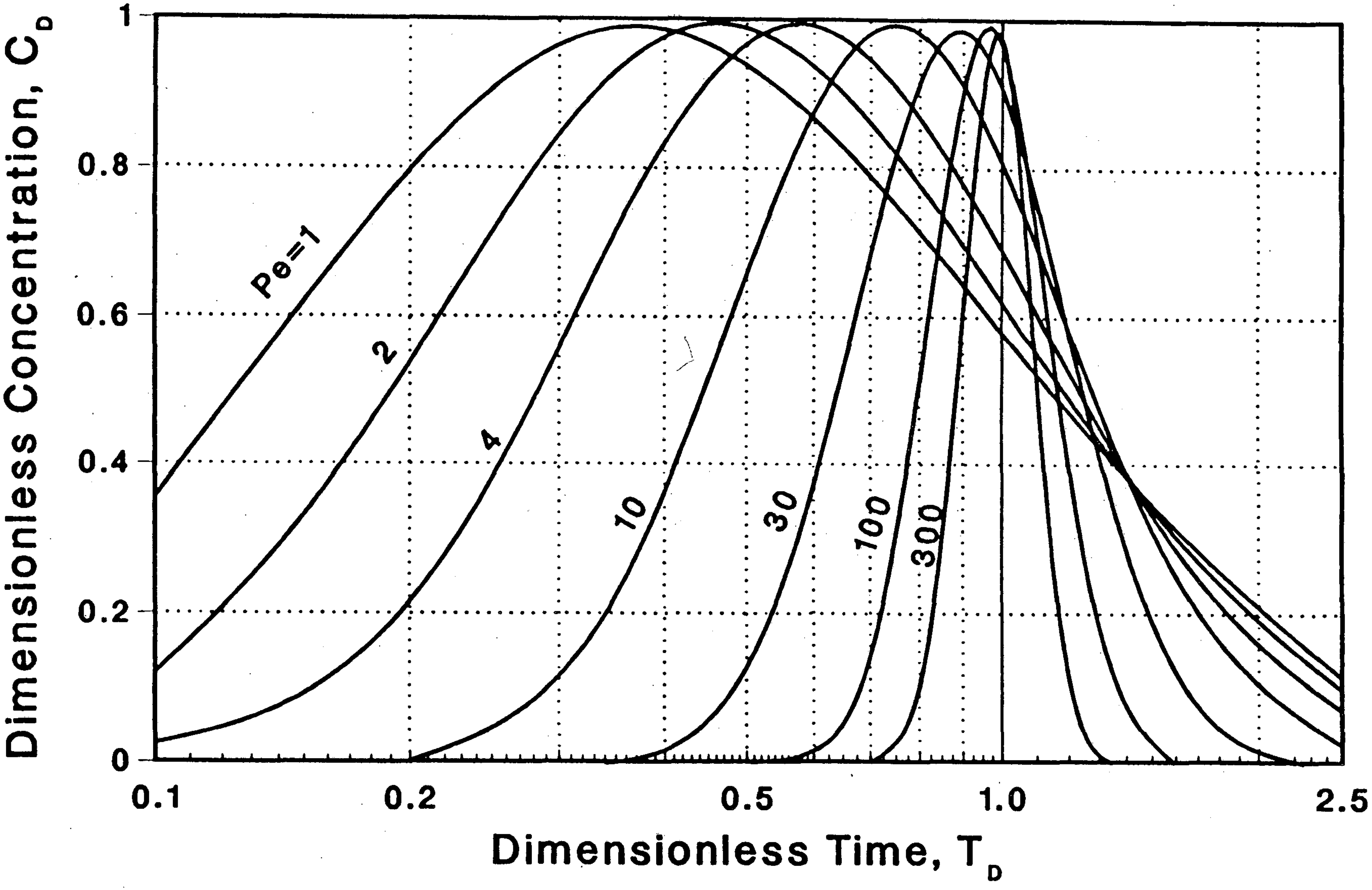

Figure 6. Type curves for instantaneous tracer injection in a radially convergence flow field (modified from Sauty 1980).

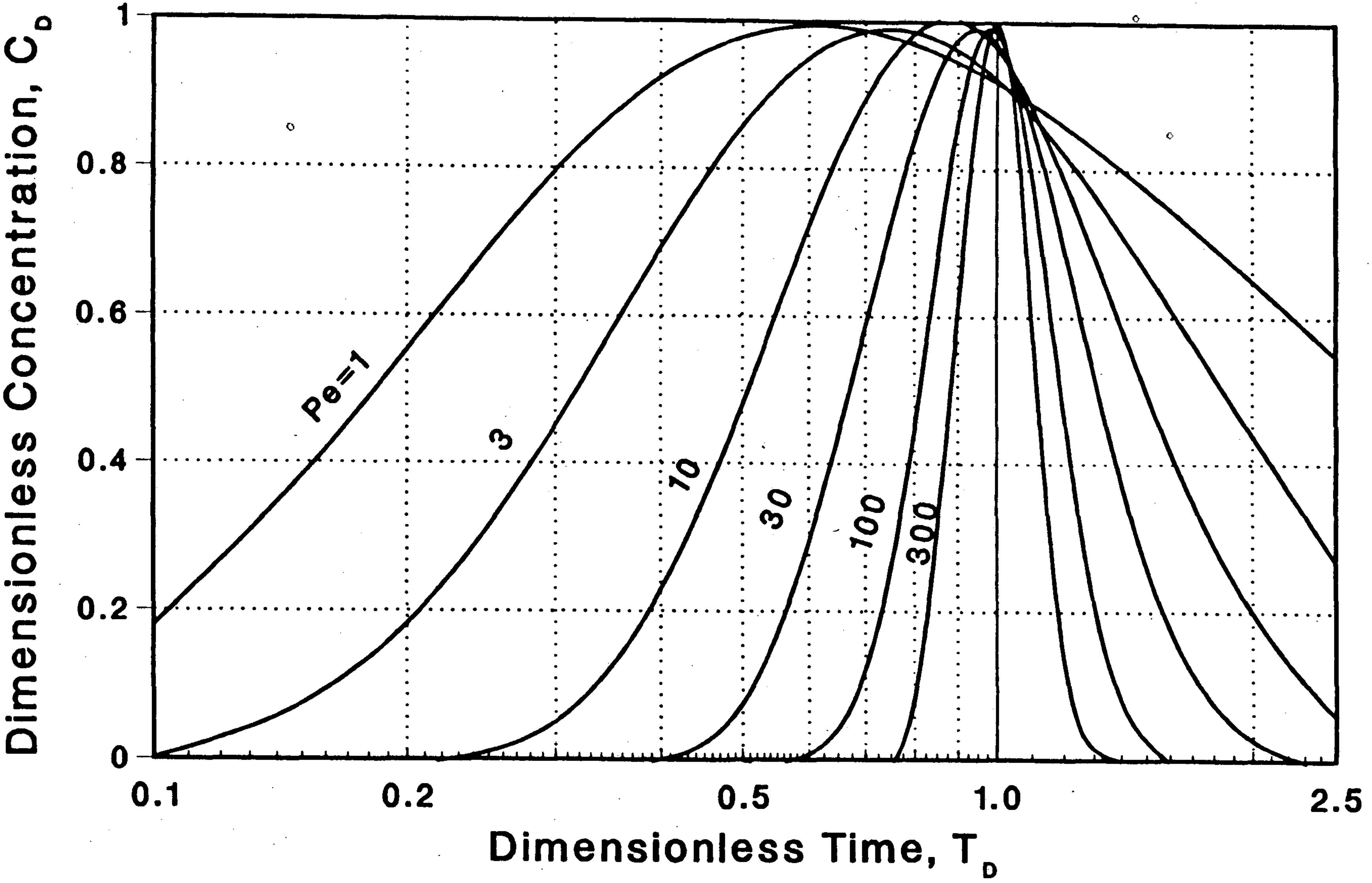

Figure 7. Type curves for instantaneous tracer injection in a radially diverging flow field (modified from Sauty, 1980).

Furthermore, for a given testing configuration, the error will increase with the regional flow velocity.

Two Well Recirculating Tracer Method

In this test, water is pumped from a well, and, after being labeled with an appropriate tracer, is injected in another well in the vicinity of the pumping well. In so doing, the maximum possible hydraulic gradient is developed between the two wells and the time required to run the test is minimized. Here again, a tracer may be introduced either in slug form or continuously for a relatively long period of time. Leonhart et al. (1985) used the two well tracer test with a pulse input to determine the effective porosity of deep basalt flow at Hanford, Washington. Interpretation of their results was based on the type curves developed by Gelhar (1982). Benson (1988) used this technique to characterize hydrologic and transport properties of the shallow aquifer under Kesterson Reservoir in California. Grove and Beetem (1971)) have described a tracer technique for obtaining porosity and dispersivity. Their approach is a generalized form of the method proposed by Webster et al. (1970). Grove and Beetem (1971) and Claassen and Cordes (1975) employed this method using tritium as a tracer to determine the porosity and dispersivity of highly conductive fractured carbonate aquifers in New Mexico and Nevada, respectively. The following is a brief description of the method proposed by Grove and Beetem (1971).

Theory and Procedure

Consider two wells which completely penetrate and are open to the total thickness of the formation to be investigated. The distance between these two wells depends on the hydraulic conductivity of the formation. Distances from 50 m to 120 m have been selected for very permeable aquifers. Smaller distances should be used in aquifers having smaller hydraulic conductivities.

Water should be pumped from one of the wells and transferred to be injected into the other well until a steady state condition is reached. The rate of pumping Q should be measured at the steady condition. Water samples are taken to measure the background concentration.

A certain volume of tracer is mixed with the water to be injected over a finite period of time. Samples of water should be collected from the discharging well and analyzed for the concentration of the tracer C. This process should continue until the tracer concentration becomes almost constant.

If we ignore the regional flow field, the pattern of streamlines developed by such a system, after a steady state condition has been reached, may be shown on Fig. 8. The length of each of the streamlines connecting the two wells may be given by

$$L = \frac{2a\theta}{\sin\theta} \tag{15}$$

where

a = half the distance between wells

θ = $\pi(1 + \frac{2\psi}{q})$ which varies between 0 to π

q = pumping rate per unit aquifer thickness

ψ = stream function which is equal to $\frac{q}{2\pi}\tan^{-1}\frac{2ay}{a^2-x^2-y^2}$, where (x, y) are the coordinates of the point through which the streamline passes.

The time T for a water particle to travel along a particular streamline between two wells may be given by

$$T = \frac{4\pi\phi a^2}{q\sin^2\theta}[\theta\cot\theta - 1] \tag{16}$$

where

ϕ = effective porosity

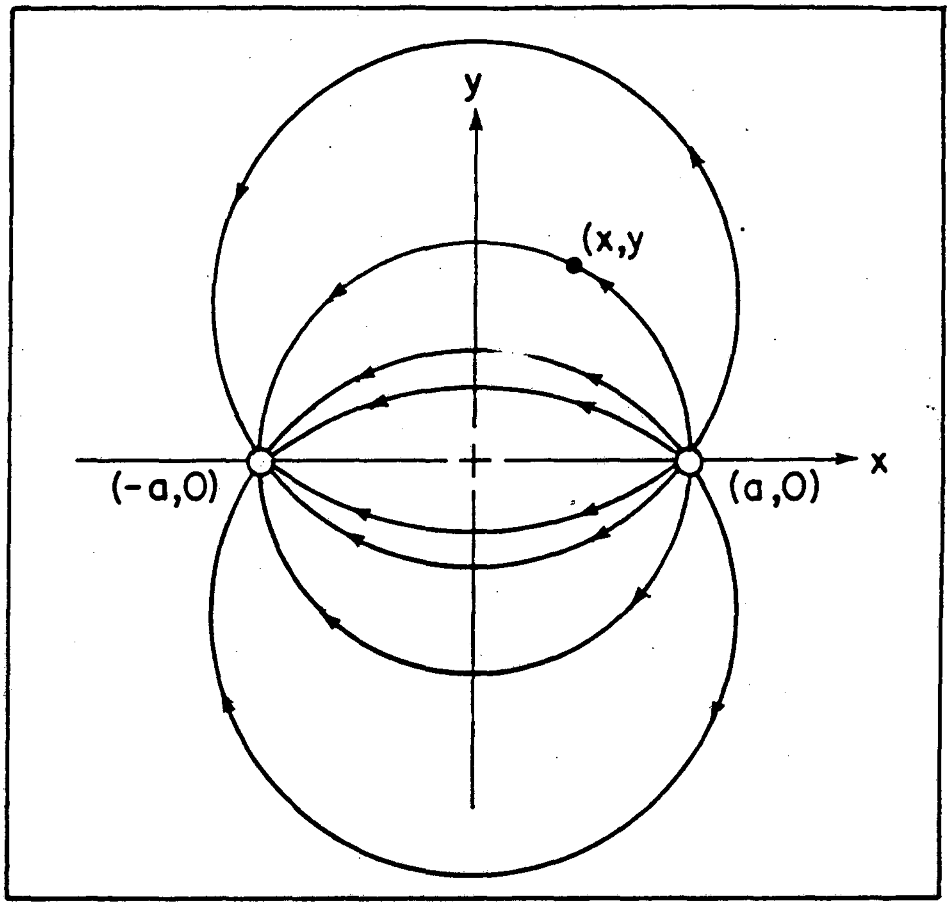

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Figure 8. Pattern of streamlines formed by a recharging-discharging well pair.

If the tracer concentration at the recharge point of any of the flow channels shown on Fig. 8 is C_O, the value of the dimensionless concentration C/C_O as a function of time at the other end of the channel may be given by

$$\frac{C}{C_O} = 1 - \exp[P_e(2-t_D)] \sum_{n=1}^{\infty} \frac{\lambda_n \sin(2\lambda_n)}{(\lambda_n^2 + p_e^2 + p_e)} \cdot \exp(-\frac{\lambda_n^2 t_D}{p_e}) \qquad (17)$$

where

C = concentration of tracer at the discharge point of the flow channel

$t_D = \frac{t}{T}$ = dimensionless time; t is time since the injection started and T can be obtained from Equation (16).

$P_e = \frac{L}{4\alpha_L}$ = Peclet number; L can be obtained from Equation (15)

α_L = longitudinal dispersivity

λ_n = the nth positive root of $\tan 2\lambda = 2\lambda P_{e/(}\lambda^2 - P_e^2)$

Grove and Beetem (1971) suggest that Equation (17) be used whenever P_e/t_D is less than one, and for P_e/t_D equal or greater than one the following equation is recommended:

$$\frac{C}{C_O} = \tfrac{1}{2}\,\mathrm{erfc}[(P_e/t_D)^{1/2}(1-t_D)] + (4P_e t_D/\pi)^{1/2}[3 + 2P_e(1+t_D)]$$

$$\cdot \exp[-P_e(1-t_D)^2/t_D] - [\tfrac{1}{2}+2P_e(3+4t_D) + 4P_e^2(1+t_D)^2]$$

$$\cdot \exp(4P_e)\,\mathrm{erfc}[(P_e/t_D)^{1/2}(1+t_D)] \qquad (18)$$

where

erfc = complementary error function

Analysis of Field Data

To analyze the field data, a set of type curves for different values of ϕ and α_L should be prepared, as described below.

Divide the flow field to N different flow channels each represented by an arch connecting two wells. Given q and a, calculate L and T for each arc from Equations (15) and (16). Calculate the Péclet number for each arc. Using equation (17) or (18), calculate the values of C/C_O for different values of time since the injection started. For each given time t, find the average value of C/C_O of all flow channels. A plot of C/C_O obtained from summation of all flow channels versus time would give a breakthrough curve for the assumed values of ϕ and α_L and the given q and a of the test. Compare the plot of observed variation of C/C_O versus time with the breakthrough curves prepared for different values of ϕ and α_L until a good match is obtained. The porosity and dispersivity of the formation correspond to that of the type curve which best matches the field data.

Uncertainties

- It is presumed that the flow field between the two wells reaches steady state condition before the tracer is injected. This is a reasonable assumption when we are dealing with a highly permeable formation. However, when hydraulic conductivity is relatively low, achievement of a steady state condition in a reasonable length of time is impossible. The effect of the regional flow system is considered to be negligible. Depending on the magnitude of regional velocity, this assumption may or may not introduce an appreciable error. The whole development is based on two-dimensional, homogenous aquifers.

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