Groundwater velocity determination by single-borehole dilution test

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Abstract. The single-borehole dilution test involves the injection of a tracer into a borehole following by repeated water column profiling to monitor groundwater velocity within the vicinity of the borehole. Based on the concept that a tracer’s concentration decreases as a consequence of the groundwater dilution, the groundwater velocity can be determined by analysing the measured tracer concentration curves over time. The borehole dilution test allows the determination of both horizontal and vertical velocities in a single well. The presence of vertical flow in a borehole may greatly affect the evaluation of horizontal velocity since the decline of tracer concentration is caused by both horizontal and vertical flow simultaneously. Two approaches presented provide the estimation method of horizontal velocity without using packers to prevent vertical flow.

1. Introduction
The estimation of groundwater velocity is a vital requirement in many fields such as dam leakage investigation, ground water resources evaluation, wellhead protection, and ground water contamination prevention and remediation. The principles of single-borehole dilution test (SBDT) have been applied widely [1-5]. In a SBDT, a tracer is introduced into the water column in a borehole and subsequently diluted by groundwater flow. The reduction of the tracer concentration is measured over time and different velocities along the vertical profile can be obtained if several depths are monitored within the borehole.

There were several kinds of material used as tracer to label the groundwater in the development of dilution test. Radioisotope has been selected in the SBDT at the early application of this detection method. With the increasing concerns about the pollution to the environment and human bodies, radioactive material was gradually abandoned and replaced by other tracers. Several new types of tracers have been applied for borehole dilution method, e.g. dye [4], chloride [6, 7], and deionized water [8, 9].

The SBDT can determine both horizontal and vertical groundwater seepage velocity via the dilution of tracer concentrations horizontally at several depths and tracking the movement of the peak tracer concentration respectively. However, these two kinds of velocity are usually detected separately and when there are both horizontal and vertical groundwater movements simultaneously in the
borehole, the determination of horizontal velocity is difficult since the dilution of tracer is caused by not only the horizontal flow but also the vertical flow. The traditional approach to deal with this problem was employing packers to isolate the detection sections and prevent the occurrence of vertical flow, but the application of packer system was inconvenient in the field tests and could not avoid the influence of vertical flow completely. In this study, two data processing methods for determining horizontal flow rate are presented and the measurement of vertical flow velocity is described briefly. Furthermore, two novel methods are discussed to determine horizontal velocity with the presence of vertical flow but without the packer system.

2. Horizontal velocity determined by SBDT

The detection requires that water can freely flow across borehole sidewalls. For cased boreholes, the casing has to be perforated with slots and the velocity detection can be conducted at well screen section. In a SBDT process shown in figure 1, a tracer is injected at a certain section in a borehole with two ends isolated by packers and mixed by a mixer to be evenly distributed. Subsequently a probe is deployed to measure the tracer concentration repeatedly such that concentration profiles are recorded as a function of time to produce a sequential series of breakthrough curves. After being emplaced into the groundwater, the tracer will be diluted by the groundwater flow. The relationship between the tracer dilution rate and the flux of the groundwater flow can be used to estimate the seepage velocity:

\[
V_f = \frac{\pi r}{2\alpha \Delta t} \ln \frac{C_0}{C_i}
\]

where \(V_f\) is the groundwater velocity, \(r\) is the borehole radius, \(C_i, C_0\) is the tracer concentration in the time \(t_i, t_0\) after the tracer injection, respectively, \(\Delta t = t_i - t_0\), and \(\alpha\) is a dimensionless correction factor accounting for the distortion of the natural flow field due to the presence of the borehole; a widely accepted value for \(\alpha\) is 2. Usually, the background value of the tracer should be taken into consideration, e.g., if we use saline water as the tracer, then the measured tracer concentration in equation 1, represented by electrical conductivity, should have the natural electrical conductivity of water detected before the emplacement of the tracer subtracted from it.

Groundwater horizontal velocity can be calculated by equation 1 with two measurements of tracer concentration at two times at a certain depth. The velocity can be approximately regarded as an average value during the time segment between these two measurement times if the groundwater flow is unsteady. When the groundwater flow is steady, only one velocity is obtained all the time. In the situation without vertical flow, the packers may not be used and the tracer can be injected in the entire water column in the borehole. Consequently, the groundwater velocity profile can be obtained from the repeated tracer concentration logging.

Figure 1. Schematic diagram of the SBDM process.

Figure 2. Linear regression to determine horizontal velocity at a certain depth in the borehole.
By using equation 1, the velocity at a certain depth can be obtained if the tracer concentrations have been measured for two times. However, the measurement errors are unavoidable in the field test leading to inaccurate results. In such a circumstance, more data are needed to improve the measurement accuracy. As a first step, the dilution of tracer concentration can be expressed as follows:

\[
\ln(C_i) = -\frac{2\alpha V_f}{\pi r} t_i + \ln(C_0)
\]  

(2)

According to equation 2, the natural logarithm of the ratio of tracer concentration \(C_i\) at any time to the initial concentration \(C_0\) exhibits a linear trend with time \(t_i\). The field data can be plotted and performed regression analysis as illuminated in figure 2. The slope of the regression line \(m\) is proportional to the groundwater velocity \(V_f\):

\[
V_f = m \frac{2\alpha}{\pi r}
\]  

(3)

As a result, the groundwater velocity can be determined since the slope is figured out, noting that such a calculation is valid only when the groundwater flow is steady.

3. Vertical velocity determined by point SBDT

If a borehole intercepts some aquifers with different water heads, then vertical flow may occur. In such a situation, the tracer is point emplaced to a certain depth and the tracer plume will then move up or down from the emplacement point in the borehole. As displayed in figure 3, the vertical flow velocity can be determined by tracking the peaking values of the tracer concentration at different depths and calculated out by the distance of two peaks over the movement time:

\[
V_v = \frac{\Delta H}{\Delta T}
\]  

(4)

where \(V_v\) is the vertical flow velocity, \(\Delta H\) is the distance between the two peaks, and \(\Delta T\) is the time difference of the measured time corresponding to these two peaks, \(\Delta T = t_2 - t_1\).

4. Determination of horizontal velocity with the presence of vertical flow

4.1 General Physical Model of SBDT

There are some other factors impacting the decline of the tracer concentration such as vertical currents, density convection, molecular diffusion, and mixing device, as discussed by [2]. In most cases, the influence of density convection, molecular diffusion, and mixing device is negligible and not
necessary to be considered. Only when the dilution test being applied in some particular situation should some of these factors be taken into account, e.g. the tracer diffusion should be evaluated in a porous, fractured, low-permeability aquifer [10]. However, unlike the other three factors, the vertical flow in the borehole may cause significant errors in the assessment of horizontal velocity, which is the reason why traditional dilution test employed packers to prevent vertical flow from occurring in the borehole. Nevertheless, it was inconvenient to conduct dilution detection with a packer system in the field test. Sometimes the vertical flow may bypass the packer through well screens and gravels filled in the annular space between the casing and the terrain, leading to the failure of the vertical flow being blocked completely.

To eliminate the impact of vertical flow on the determination of horizontal velocity, a general physical model of SBDT was proposed to carry out the test without packer system [11]. The model setup is displayed in figure 4, showing there are both horizontal and vertical flows in the borehole and supposing the vertical flow is downward. The horizontal velocity at the test segment AB can be calculated by:

\[
V_f = \frac{\pi r}{2\alpha} \left[ C(0,t)v_A - C(h,t)v_B \right] - \int_0^h \frac{\partial C(z,t)}{\partial t} \, dz 
\]

where \( C(0,t), C(h,t) \) is the tracer concentration at A, B respectively, \( C(z,t) \) is the tracer concentration distribution in the segment AB, \( v_A, v_B \) is the vertical flow velocity at A, B respectively, \( h \) is the length of AB.

By point SBDT, the vertical flow velocities can be determined at each depth in the borehole. \( C(z,t) \) is a function of depth and time and can be fitted by the measured data. Consequently, the horizontal flow velocity can be approximated by equation 5.

4.2 Simplification method to determine horizontal velocity

In the practical application, a fine fitting process of the term \( C(z,t) \) in equation 5 requires well-designed experiment scheme in the field test, e.g. setting appropriate time intervals between repeatedly measurements of tracer concentration. Moreover, the fitting process may also be impacted largely by the measurement errors at each depth. A simple method is presented here to determine average horizontal velocity within a test section in borehole, which may also provide sufficient information to investigate subsurface seepage for some cases.

Average horizontal velocity can be obtained from a point SBDT, analog to a vertical velocity detection process. As shown in figure 3, the tracer is point emplaced at a certain depth and the entire concentration curve may be acquired by moving a detector to measure up and down. Supposing the vertical flow is downward, the tracer will move downwards carried by vertical flow. At a deeper depth, another concentration curve may also be obtained with low concentration values since the tracer is diluted by horizontal flow constantly during the movement. Noting that the vertical flow will not dilute the tracer, the horizontal velocity can be determined by the decline of the tracer concentration:

\[
V_f = \frac{\pi r}{2\alpha \Delta t} \ln \frac{A_1}{A_2} 
\]

where \( A_1 \) and \( A_2 \) are the integration of shaded area measured at time \( t_1 \) and \( t_2 \) respectively (displayed in figure 3).

In the field test, after the tracer being input at a certain depth, the movement of tracer may be tracked by a detector. As a result, a sequential evolution of tracer concentration curves can be plotted at different depths along the vertical flow direction. The average horizontal flow velocities at different segments in borehole can thus be determined by using equation 6.
5. Conclusion

Single borehole dilution method provides a simple and direct way to determine both horizontal and vertical flow within the vicinity of a monitoring well. In this method, a tracer is evenly introduced into a test section and its decreasing concentration is subsequently monitored over time. If other impact factors can be neglected, the decreasing tracer concentration can be regarded as a dilution induced by groundwater flow. The groundwater horizontal velocity in the aquifer can be determined from the repeatedly measured tracer concentration profiles with packers being used to prevent vertical flow from drifting the tracer vertically. The vertical flow velocity can be detected by a point SBDT. In this study, two approaches to measure horizontal velocity without packers are also presented for the convenient application of SBDT in the field test.

As a whole, SBDT has proved to be a low-cost and efficient alternative to estimate groundwater velocity. The method may serve to complement or supplement traditional methods based on measurement of hydraulic head and hydraulic conductivity.

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