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Research papers

Characterization of horizontal transmissivity anisotropy using cross-hole slug tests

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ABSTRACT

Traditional methods for characterizing horizontally anisotropic aquifers are all based on pumping tests. In this paper, we present a new method for the identification of horizontal anisotropy using cross-hole slug tests, which is much more easily accessible comparing to pumping tests. Through scaler transform, an anisotropic medium was converted into an equivalent isotropic medium. When applying the analytical solutions derived for isotropic media to interpret cross-hole slug tests performed in anisotropic media, the estimated transmissivity is the geometrical mean of the anisotropic transmissivity tensor, regardless of sampling direction. However, the apparent storativity calculated from different observation wells, is equal to the true storativity scaled by a factor defined by the formation anisotropy. Thus, anisotropy can be resolved through apparent storativity that bears directional information. The proposed method was first validated by a numerical experiment and then applied to field data. It was found that the tensor results obtained by this new method with cross-hole slug tests are consistent with that obtained by applying the classical Papadopulos' method with cross-hole pumping tests conducted in the same wells. When applied to heterogeneous media, tensor results produced by the new method may be subject to considerable errors. This is because the results are strongly sensitive to the connectivity between measurement boreholes and the formation medium. To reduce the error level, responses from a large number of observation wells located in various directions around the source well are needed. In addition to the adopted KGS solution for confined aquifers, the proposed methodology can be applied to incorporate other analytical methods for a variety of aquifer types, as long as the characteristic relationship between the measure scale and the aquifer storativity can be established.

1. Introduction

Conventional single-well hydraulic methods for the determination of aquifer transmissivity are based on a common assumption of homogeneous and isotropic formations. However, natural aquifers are often highly anisotropic because the formation of sedimentary aquifers is often driven by many highly directional processes such as streaming, wind and faulting. Characterizations of groundwater flow patterns in natural systems maybe significantly in error if the aquifer anisotropy is not considered in the conceptual models.

In the middle 1960s, analytical methods for estimating horizontal aquifer anisotropy using multiple observation wells were developed for confined aquifers (Papadopulos, 1965; Hantush, 1966a,b) and leaky aquifers (Hantush and Thomas, 1966). These methods rely on the joint interpretation of time-drawdown responses to a pumping recorded in at least three observational wells that are not radially aligned. The restriction on total number of pumping-observation pairs is possible to reduce through using a sequential pumping scheme (Neuman et al., 1984). The methods were then extended to estimate three-dimensional (3D) transmissivity components (Way and McKee, 1982; Hsieh and Neuman, 1985).

Another way for determining the horizontal anisotropic transmissivities is through the scaler transformation technique (Bear, 1972; Freeze and Cherry, 1979). In this method, the scale of the flow region in the directions of maximum and minimum principle transmissivities is firstly transformed (reduced and increased, respectively) by a factor defined by the anisotropy ratio, such that the anisotropic medium is converted to an equivalent isotropic one. The traditional analytical solutions, derived based on isotropic medium assumption, can then be applied. Once the equivalent hydraulic parameters are determined, an

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inverse transformation is then applied to calculate the true anisotropic parameters. Based on this principle, Mutch (2005) has developed a distance-drawdown method where the classical Cooper-Jacob method was applied to determine the components of anisotropic transmissivity tensor.

All of the above mentioned developments are based on idealized assumptions of homogeneous formations and of noise-free data collection. When significant heterogeneity occurs or when the recorded hydraulic data are subject to significant noise, the use of three (or less) observation wells in different directions to define the principle transmissivities may not always yield a physically plausible solution (Neuman et al., 1984). To solve this problem, least square optimizations can be applied in conjunction with the Papadopulos' method, such that drawdown responses from a large number of observation wells can be integrated to balance the effects of aquifer heterogeneity and imperfect data sampling (Maslia and Randolph, 1987).

According to our best knowledge, existing analytical methods for determining anisotropic transmissivity tensor are all based on pumping tests. Hydraulic responses to slug tests that are much more easily accessible have not yet been used. Comparing to pumping tests, slug tests are much easier to perform and the test duration is much shorter. Since there is no water produced during a test, at sites that are potentially contaminated slug tests have become a primary method for determining aquifer transmissivity. With modern equipment, larger and sharper perturbations can be generated such that stronger signals can be accurately detected at observational locations far away from the source well (Paradis et al., 2016). The cross-well response data can provide extra information regarding inter-well hydraulic connections that are very helpful in characterizing preferential flow directions. These important advantages of slug tests have motivated us to devise a new interpretation method for evaluating transmissivity tensors in anisotropic aquifers using cross-hole slug test data. Here, we focus only on the detection of the horizontal transmissivity anisotropy based on a two-dimensional depth-integrated model configuration. However, it should be noted that the presented model can be extended to three-dimensional and to include the vertical anisotropy when interference signals are collected from multilevel slug tests with packer installations (Freeze and Cherry, 1979; Paradis and Lefebvre, 2013).

The theoretical feasibility of using cross-hole slug test for estimating transmissivity tensors stems from its close relation to pumping tests. It has been demonstrated that slug tests can be represented as a specialized form of constant-rate pumping tests (Novakowski, 1989, Peres et al. 1989). Spane (1996) and Spane et al. (1996) has applied the method of Peres et al. (1989) to convert slug test data collected from an unconfined aquifer to equivalent constant-rate drawdown responses. The converted responses were compared to real pumping test data collected from the same well. A good match between the two sets of response was found, and similar estimated values of transmissivity and storativity were calculated using the two types of data. On the other hand, recent studies have performed resolution analyses of tomographic (i.e. sequential cross-hole) slug test data numerical simulations (Paradis et al., 2015; Paradis et al., 2016). Results have shown that, comparing to tomographic pumping test data, the tomographic slug test data hold the equivalent potential of conveying important information regarding resolving coarse-scale heterogeneity and anisotropy of aquifer transmissivity. Moreover, inversions of cross-hole slug test data have also been successfully performed in recent field investigations (Brauchler et al., 2010; Paradis et al., 2016). In short, results from theoretical, numerical and field studies have demonstrated the strong relevance of using cross-hole slug test to determine aquifer anisotropy.

Depending on the type of aquifers being tests, a number of analytical and semi-analytical models for interpreting cross-hole slug tests have been presented in the literature (e.g. Karasaki et al., 1988; Novakowski, 1989; Hyder et al., 1994; Butler and Zhan, 2004; Malama et al., 2016). Among others, the solution of Hyder et al. (1994), also known as the KGS model, is widely used in the hydrogeological community (Belitz and Dripps, 1999). In this work, we also choose to use this solution due to the representativeness of the conceptual model related to the KGS method for the specific hydrogeological configuration of our field site. The complete KGS solution includes a wide variety of parameters, such as the aquifer transmissivity, storativity, vertical-to-horizontal transmissivity ratio, finite-radius of source well, wellbore skin, as well as upper and lower boundaries (Hyder et al., 1994). Although it is possible to consider all the parameters in the proposed methodology, for the sake of brevity here we will only focus on the effect of aquifer transmissivity and storativity. We first demonstrate the validity of the method using numerical simulations, and then apply it to a field example. Justifications for validity of the adopted simplification for our field analysis are detailed in Sections 4.1 and 4.2. Discussions on the effect of aquifer heterogeneity, measurement scale and on the emergent transmissivity tensors are presented in Section 5.

2. Theory

The diffusion process of groundwater flow in response to an instantaneous change in water level obeys the basic law of mass conservation. This is reflected by the characteristic relationship between a scale measure, for instance the slug-observation well distance d_{ow}, and the aquifer storativity S, the only scaler term appears in the diffusivity equation, as given by:

$$d_{ow}^2 S = \text{const.} \quad (1)$$

If the finite radius of the source well, r_s, is taken into account, the following relationship also holds:

$$d_{ow}/r_s = \text{const.} \quad (2)$$

Eqs. (1) and (2) imply that, the displacement (i.e. water level change) predicted by the cross-hole slug test solution remain unchanged if d_{ow} and r_s is doubled and S quartered, or if d_{ow} and r_s is halved and S quadrupled. This characteristic relationship is validated using the KGS model (Fig. 1) using the hydraulic parameters presented in Table 1.

In anisotropic aquifers, the relations shown by Eqs. (3) and (4) may be defined in a certain radial direction, but is not applicable for all other directions. This is because in anisotropic media, the direction of hydraulic gradient does not coincide with the direction of discharge. Thereby, the transmissivity is defined as a second-rank tensor in two-dimension, which can be understood as a linear transformation relating the two directions (Marcus, 1962). In an arbitrary r direction, the directional transmissivity is given by Bear (1972):

$$T_r = T_g/[\sqrt{T_{min}/T_{max}}\cos^2\theta + \sqrt{T_{max}/T_{min}}\sin^2\theta], \quad (3)$$

where T_{max} and T_{min} are maximum and minimum transmissivities, respectively; θ represents the angle between the direction of T_{max} and that

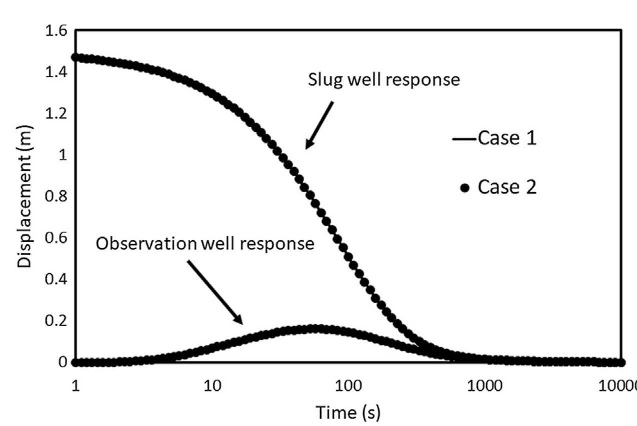

Fig. 1. Validation of the characteristic relationship associated with the KGS method.