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Low velocity non-Darcian flow to a well fully penetrating a confined aquifer in the first kind of leaky aquifer system

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SUMMARY

In this study, we use a finite difference method to solve low velocity non-Darcian flow to a well in the first kind of leaky aquifer system. Flow in the confined aquifer is assumed to be Darcian and horizontal, whereas flow in the aquitard is assumed to be non-Darcian and vertical. The threshold hydraulic gradient existence of non-Darcian flow in low permeability porous media is employed to describe the non-Darcian flow in the aquitard. A numerical solution has been obtained by using a finite difference method. This solution is compared with the previous solution for Darcian flow case in leaky aquifer system. The error has been analyzed. The comparison of this study and Darcian flow case (Hantush and Jacob, 1955) in leaky aquifer system indicates that the error is very small and can be neglected. However, the hydrogeological parameter calculation of leaky aquifer system is remarkably influenced by low velocity non-Darcian flow in aquitard. For the inflection point method (Hantush, 1956), the absolute values of estimated errors for coefficient of transmissibility of confined aquifer and vertical hydraulic conductivity of aquitard show negative relationship with the pumping rate. For the type curve-fitting method (Walton, 1962), the estimated errors for coefficient of transmissibility and elastic drainable porosity of confined aquifer are very small under small pumping rate. In general, the estimated errors for coefficient of transmissibility and elastic drainable porosity of confined aquifer can be controlled under certain level through adjusting pumping rate. The estimated error of vertical hydraulic conductivity of aquitard is quite large no matter which method is used, even up to nearly 300%.

1. Introduction

Because of the common existence of multi-aquifer systems, the aquifer may have hydraulic connection to adjacent aquifers through aquitard. Therefore many researches on groundwater hydraulics in leaky aquifers have been done for decades (Hantush and Jacob, 1955; Hantush, 1959, 1960; Neuman and Witherspoon, 1969; Perina and Lee, 2006; Zhan and Bian, 2006; Li, 2007; Li and Neuman, 2007; Malama et al., 2007). In 1955, Hantush and Jacob (1955) established the first mathematical model for flow to a well in leaky aquifers. That study was based on a series of assumptions, e.g. vertical flow in aquitard, constant pumping rate of well, negligible storage of aquitard, etc, and an analytical solution for transient flow to a well in leaky aquifers was obtained. Then, this solution was extended to consider flow to a constant-head pumping well (Hantush, 1959) and the storage of aquitard (Hantush, 1960). During the last ten years, the theory of groundwater hydraulics in leaky aquifer system has been applied to estimate the relationship between surface water and leaky aquifer system (Singh and Shakya, 2006; Bakker, 2007; Butler et al., 2007; Zlotnik and Tartakovsky, 2008; Chapuis and Saucier, 2013; Ward and Falle, 2013) and the corresponding parameters estimation method has been proposed (Singh, 2008; Yeh et al., 2007; Li and Qian, 2013; Li et al., 2014). For instance, Ward and Falle (2013) obtained semi-analytic formulas for flow to a well screened in a leaky aquifer that was overlain by an aquitard and phreatic aquifer and underlain by a second aquitard and leaky aquifer. The phreatic aquifer is hydraulically connected to a rectilinear stream. Li and Qian (2013) used global curve-fitting for determining the hydrogeological parameters of leaky confined aquifers by transient flow pumping test. All these studies mentioned above are based on the assumption that flow is Darcian. However, under some circumstances, flow in the porous media can be non-Darcian.

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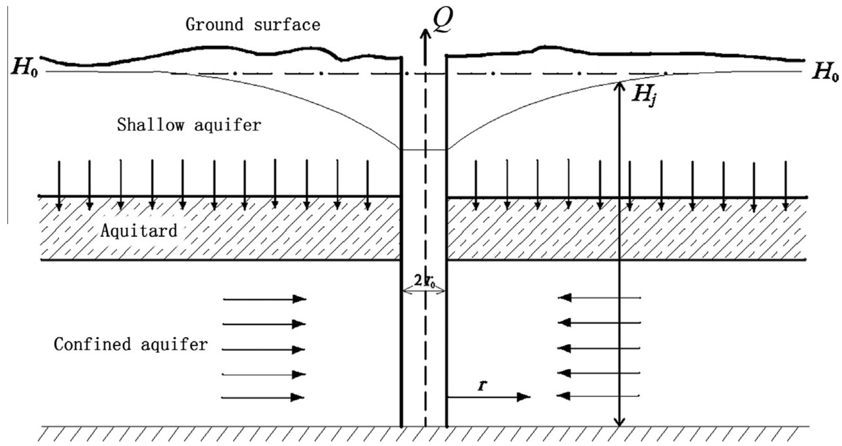

Fig. 1. Schematic of a single confined aquifer pumping well shown in vertical profile.

Table 1
Parameters in the leaky aquifer system.

Parameter	k' (m/d)	T (m^2/d)	S	Q (m^3/d)
Value	0.0001	200	0.0001	500

The non-Darcian flow can be divided into two categories: high velocity non-Darcian flow and low velocity non-Darcian flow.

High velocity non-Darcian flow often occurs near the pumping well when the pumping rate is sufficiently large (Sen, 2000). There are two commonly used formulae to describe the relationship between the hydraulic gradient and the high velocity of non-Darcian flow. One is the Forchheimer equation (Forchheimer, 1901), which states that the hydraulic gradient is a second-order polynomial function of the velocity of water flow. The other is the Izbash equation (Izbash, 1931), which states that the hydraulic gradient is a power function of the velocity of water flow. Both analytical and numerical methods can be employed to solve the non-Darcian flow problems. For analytical methods, the Boltzmann transform has been widely used to solve such non-Darcian flow problems (Sen, 1987, 1988a,b, 1989, 1990; Wen et al., 2006, 2008a). But this method has the shortcoming of non-rigorous mathematical derivation (Butler et al., 1991; Camacho and Vasquez, 1992). In order to overcome this shortcoming, Wen et al. (2008b,c) developed a linearization procedure and obtained some approximate analytical solutions for non-Darcian flow to a well in a confined aquifer. The numerical methods can be divided into the finite difference method and the finite element method. For instance, Mathias et al. (2008) developed a finite difference solution for non-Darcian flow to a well in a confined aquifer based on the Forchheimer equation. Wen et al. (2009) obtained a numerical solution for non-Darcian flow in porous media on the basis of the Izbash equation. As far as leaky aquifer is concerned, Sen (2000) has done the research on non-Darcian flow to a well with the Izbash equation by using a volumetric approach. This method was extended to solve a similar problem with the Forchheimer equation by Birpinar and Sen (2004).

Water flow becomes low velocity non-Darcian flow in low-permeability media (such as clay media) (Liu et al., 2012). This evidence of non-Darcian flow has been reported by Hansbo (1960), Li (1963), Miller and Low (1963), Olsen (1965, 1966), Kraft and Yaakobi (1966), and other scholars from experimental results. For example, Miller and Low (1963) found the existence of a hydraulic gradient below which water is essentially immobile. Hansbo (2001) reported that water flux in low permeability clay is proportional to a power function of the hydraulic gradient when the gradient is less than a critical value, whereupon the relationship between water flux and gradient becomes linear for large gradient values. He explained this behavior by positing that a certain hydraulic gradient is required to overcome the maximum binding energy of mobile pore water. Recently, Xu et al. (2007) experimentally investigated the relationship between the flux of deionized water and hydraulic gradient in individual microtubes with diameters ranging from 2 to 30 μm. They demonstrated that water flow in microtubes with diameters of larger than 16 μm is consistent with Darcy's law, but not for smaller diameters. In the latter cases, the relationship between water flux and hydraulic gradient becomes non-linear. As this low velocity non-Darcian flow is the key issue related to geological disposal of high-level nuclear waste in clay/shale formations (Liu, 2014), Liu and Birkholzer (2012) proposed a new relationship between water flux and hydraulic gradient for both unsaturated and saturated clay by generalizing the currently existing relationships. The relationship is practically useful because it can reduce the number of parameters whose values need to be determined from experiment data in order to model non-Darcian behavior.

To the best of our knowledge, few studies about low velocity non-Darcian flow in leaky aquifer system have been conducted. Because of the existence of aquitard composed by clay, low velocity non-Darcian flow is likely to be an intrinsic behavior in aquitard. And this kind of non-Darcian flow may have significant influence on the distribution of confined groundwater head and the calculation of hydrogeological parameters. In this paper, we establish groundwater flow model in leaky aquifer system considering low velocity non-Darcian flow in aquitard. A finite difference method is employed to solve the model and the result is compared with that of Darcian flow. Then the relative errors of hydrogeological parameters obtained by Darcian flow are analyzed.

2. General statement of problem

The leaky aquifer system investigated is schematically shown in Fig. 1. The assumptions in this study are similar to those used in Hantush and Jacob (1955): the leaky aquifer system is homogenous and laterally infinite; the storage capacity of the aquitard is ignored; flow in the aquifer is horizontal, and assumed to be Darcian in the confined aquifer, the pumping well fully penetrates the aquifer and has a constant pumping rate; the system is hydrostatic before the pumping starts. Flow in the aquitard is vertical and assumed to be non-Darcian; the concept of a threshold gradient