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Constant-head test in a leaky aquifer with a finite-thickness skin

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SUMMARY

Constant-head test is a commonly used aquifer testing method in groundwater hydrology. A mathematical model for constant-head test in a leaky aquifer with a finite-thickness skin was developed in this study. Three different aquifer–aquitard systems were considered and the Laplace-domain solutions were obtained and then inverted numerically with the Stehfest method to yield the time-domain solutions. The well discharges for different cases were computed and a sensitivity analysis of the well discharge on different parameters was performed. The results indicated that the dimensionless transmissivity of the aquitard had little effect on the well discharge at early times while a larger transmissivity of the aquitard leaded to a larger well discharge at late times. The well discharge for the positive skin was smaller than that without the skin while the well discharge for the negative skin was larger than that without the skin, where positive and negative skins refer to the cases in which the permeability values of the skin zones are less and greater than that of the formation zone, respectively. A thicker skin resulted in a smaller well discharge for the positive skin case but leaded to a larger well discharge for the negative skin case at late times. We also found that the drawdown for the positive skin case was less than that for the negative skin case at the same time, and a positive skin might result in delayed response of the aquifer to pumping. The sensitivity analysis indicated that the well discharge was sensitive to the properties of the skin zone, but not sensitive to the properties of the aquitards for the aquifer–aquitard system presented in this study.

1. Introduction

Constant-head test is a technique commonly used to estimate the aquifer parameters such as the storage coefficient and the hydraulic conductivity (Chen and Chang, 2002). For a constant-head test, the hydraulic head or the drawdown in the test well remains constant and the well discharge is measured as a function of time. The measured well discharge versus time data can be used to evaluate the aquifer parameters using an appropriate flow theory. For instance, Jacob and Lohman (1952) obtained an analytical solution of the well discharge for a constant-head test in a confined aquifer and developed a method to estimate the storage coefficient and the transmissivity. Hantush (1964) obtained a similar solution for a constant-head test in leaky aquifers. In addition, many researchers studied the constant-head test problem (e.g., Hantush, 1959; Mishra and Guyonnet, 1992; Hiller and Levy, 1994; Murdoch and Franco, 1994; Chen and Chang, 2002; Chang and Chen, 2002). Jones et al. (1992) and Jones (1993) pointed out that the constant-head test was particularly useful when the transmissivity of the aquifer was relatively small. Constant-head test was also performed in boreholes or piezometers to determine the hydraulic conductivity of the clays (Wilkinson, 1968; Tavenas et al., 1990).

A problem that needs to be considered for a constant-head test is the well skin. The well skin is a small region surrounding the well and its permeability is different from that of the formation zone. This skin zone can be caused by the drilling mud and/or the formation damage during the well drilling and installation procedure (Chen and Chang, 2006). The well skin is generally classified into two types: a positive skin and a negative skin. If the permeability of the skin zone is less than that of the formation zone, the skin is called positive; while if the permeability of the skin zone is greater than that of the formation zone, the skin is called negative. The well skin has been studied extensively in hydrological sciences and petroleum engineering (e.g., Hurst, 1953; Hurst et al., 1969; Motz, 2002; Park and Zhan, 2002; Yang and Yeh, 2002, 2005; Chen and Chang, 2006; Walton, 2007; Pasandi et al., 2008).

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For instance, Hurst et al. (1969) presented the concept of the effective well radius to deal with a negative skin. Pasandi et al. (2008) investigated the flow to a partially penetrating well in a phreatic aquifer considering a finite-thickness skin. Motz (2002) obtained an analytical solution for one-dimensional flow in a leaky aquifer considering the effect of a low-permeability skin. Chen and Chang (2006) investigated a more realistic skin problem by proposing a mathematical model for non-uniform skin effect on the aquifer response due to the constant-rate pumping. Yang and Yeh (2005) obtained the Laplace-domain solutions for a constant-head test conducted in a partially penetrating well with a finite-thickness skin. It is probably worthwhile to mention that most studies of well skin are referred to vertical wells. However, the well skin also exists around a horizontal well (Park and Zhan, 2002, 2003). Park and Zhan (2002) investigated the flow to a finite-diameter horizontal well considering a skin with an infinitesimal thickness.

Although the well skin was commonly assumed to be infinitesimal (e.g., Hurst, 1953; Dougherty and Babu, 1984; Kabala and Cassiani, 1997; Park and Zhan, 2002, 2003), the thickness of the skin might vary from nearly zero to a few meters (Barker and Herbert, 1982). For a finite-thickness skin, the problem should be considered as a composite aquifer system. Up to now, many studies have been devoted to study the finite-thickness skin (e.g., Moench and Hsieh, 1985; Yang and Yeh, 2005, 2006, 2009; Chiu et al., 2007; Yeh and Yang, 2006; Yeh et al., 2008). For instance, Yang and Yeh (2006) obtained an analytical solution for a constant-head test considering a finite-thickness skin. Chiu et al. (2007) developed a mathematical model for a constant-rate test in a partially penetrating well with a finite-thickness skin in a confined aquifer. Yeh and Yang (2006) investigated the slug test conducted in a well with a finite-thickness skin in a confined aquifer. Yang and Yeh (2009) investigated the finite-thickness skin effect on the constant-rate test in leaky aquifers.

A careful review of the present literatures shows that there are limited researches on the constant-head test in a leaky aquifer with a finite-thickness skin, which will be the purpose of this study. Similar to the study of Hantush (1960), three different aquifer–aquitard systems will be discussed. The well discharge for different cases will be analyzed and a sensitivity analysis will be performed. The results of this investigation are also compared with previous studies to exhibit the new features of the constant-head test in a leaky aquifer with a finite-thickness skin.

2. Problem statement and solutions

2.1. Mathematical model

The schematic diagram of the investigated problem is shown in Fig. 1, the main aquifer is bounded by two aquitards. The coordinate system is set up as follows. The x-axis is horizontal, the z-axis is oriented upward along the axis of the well, and the origin of the

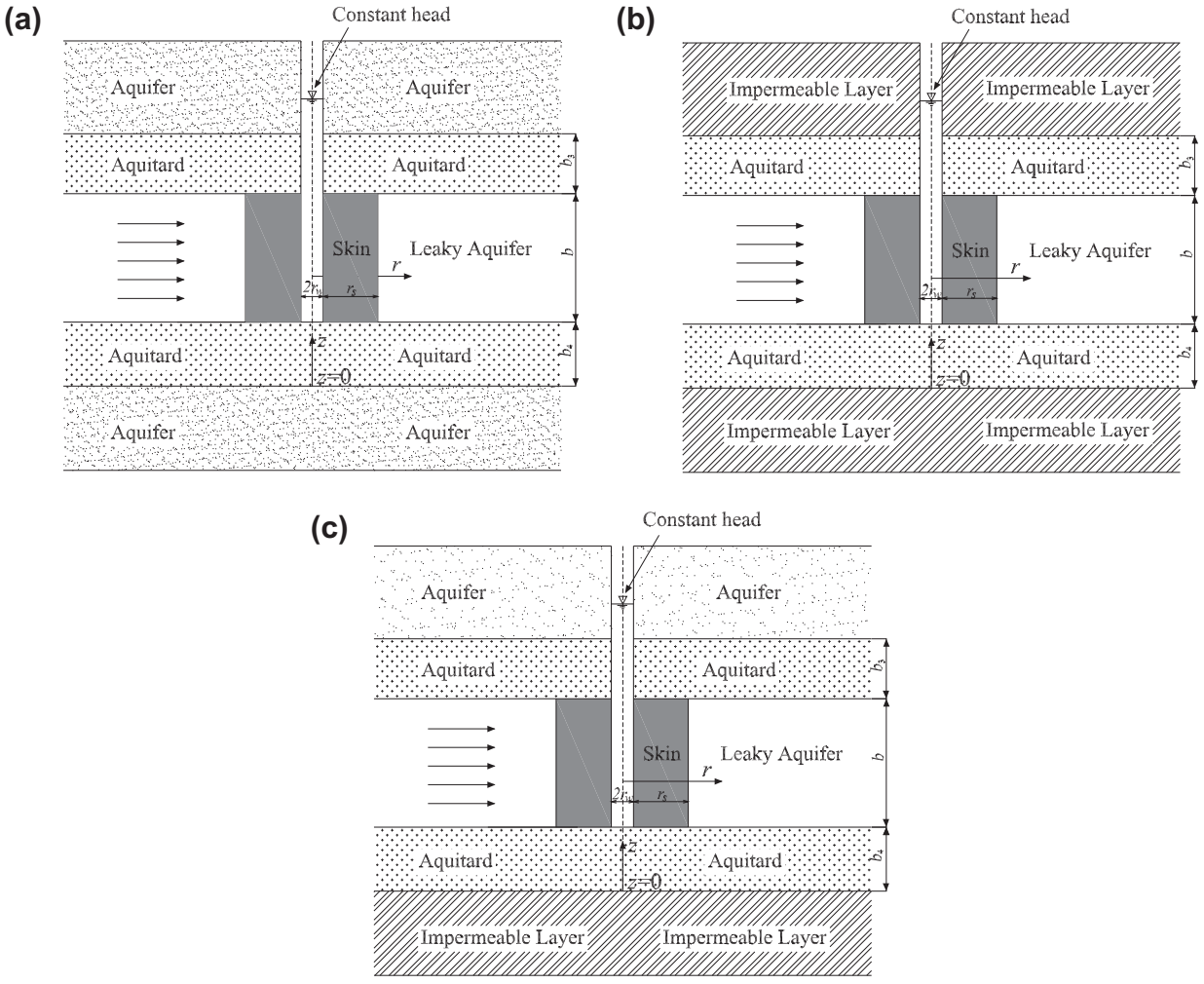

Fig. 1. The schematic diagram of the system: (a) case A: the two aquitards are over- and underlying two aquifers in which the hydraulic heads are constants; (b) case B: the two aquitards are over- and underlying two impermeable layers; (c) case C: one aquitard is bounded by an impermeable layer and the other is bounded by an aquifer in which the hydraulic head is constant.