Journal of Hydrology 542 (2016) 756–771

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Depth-discrete specific storage in fractured sedimentary rock using steady-state and transient single-hole hydraulic tests

Patryk M. Quinn *, John A. Cherry, Beth L. Parker

School of Engineering, University of Guelph, 50 Stone Road East, Guelph, Ontario N1G 2W1, Canada

ARTICLE INFO

Article history:
Received 13 June 2016
Received in revised form 16 August 2016
Accepted 19 September 2016
Available online 21 September 2016
This manuscript was handled by P. Kitanidis, Editor-in-Chief, with the assistance of Todd C. Rasmussen, Associate Editor

Keywords:
Specific storage
Storativity
Fractured rock
Packer testing
Pumping test

ABSTRACT

A method is presented for obtaining depth-discrete values of specific storage (*Ss*) from single-hole hydraulic tests in fractured rock boreholes using straddle packers (1.5–17 m test intervals). Low flow constant head (CH) step tests analyzed using the Thiem method provide transmissivity (*T*) values free from non-Darcian error. Short-term, constant-rate pumping tests (0.5–2 h) analyzed using the Cooper-Jacob approximation of the Theis method provide *S* from the hydraulic diffusivity using the Darcian T value from the CH step test. This synergistic use of two types of hydraulic tests avoids the common source of error when pumping tests (injection or withdrawal) are conducted at higher flow rates and thereby induce non-Darcian flow resulting in the underestimation of T. Other errors, such as well bore storage and leakage, can also substantially influence *S* by causing a shift in the time axis of the Cooper-Jacob semi-log plot. In this approach, the Darcian *T* values from the CH step tests are used in the analysis of the transient pumping test data for calculating *S* throughout the pumping test using the Cooper-Jacob approximation to minimize all of the aforementioned errors, resulting in more representative *S* values. The effect of these non-idealities on the measured drawdown is illustrated using the Theis equation with the Darcian *T* and *S* values to calculate drawdown for comparison to measured data. The *Ss* values for tests in sandstone obtained from this approach are more consistent with confined aquifer conditions than values derived from the traditional Cooper-Jacob method, and are within the range of field and lab values presented from a compilation of literature values for fractured sandstone. (10^{-7}–10^{-5} m^{-1}) This method for obtaining Ss values from short-interval, straddle packer tests improves the estimation of both K and Ss and provides opportunity to study their spatial distribution in fractured rock.

1. Introduction

Storativity (*S*) and its more fundamental expression, specific storage (*Ss*), where specific storage is storativity divided by aquifer thickness, are important properties of permeable geologic media but it is not well understood why calculated storage values are occasionally anomalous based on data analysis using traditional methods developed for homogeneous porous granular aquifers (i.e., Theis, Cooper-Jacob). This paper concerns *S* and *Ss* of fractured rock, a more complex, relatively stiff, heterogeneous media, where there has been little attention directed at assessment of storage values despite fractured rock aquifers being an important source of water supply. When water is injected or withdrawn from a confined hydrogeologic unit in fractured rock, the propagation of the pressure response is rapid relative to that of confined granular aquifers. This rapid response is commonly due to the small value of *S*; when the medium is more rigid, *S* is small, which results in less dampening of the pressure response propagation. *T* and *S* are the bulk parameters obtained from a hydraulic test, but hydraulic conductivity (*K*) and *Ss* expressed for a unit volume of rock are more suitable for comparing results from different studies or when determining spatial distributions and relationships between formation properties and fractured rock characteristics.

Specific storage derived from *S* is defined as the volume of water released from storage per volume of rock from a unit change in head, and is a bulk property of the volume of rock. A hydraulic test initially provides a value for hydraulic diffusivity (*T/S*), and *S* must be separated from transmissivity (*T*) using a type curve analysis such as the Theis method (1935) or the straight line semi-log plot method introduced by Cooper and Jacob (1946). However, when both parameters are obtained from the same hydraulic test, the influence of the model assumptions regarding *T* cannot be assessed. This is common for pumping tests, where the error in *T* leads to error in *S*.

* Corresponding author.
E-mail addresses: pquinn@uoguelph.ca (P.M. Quinn), cherryja@uoguelph.ca (J.A. Cherry), bparker@uoguelph.ca (B.L. Parker).

http://dx.doi.org/10.1016/j.jhydrol.2016.09.046
0022-1694/

The literature values reported for S or Ss of fractured rock are primarily derived from hydraulic tests, and nearly all come from the analysis of drawdown in observation wells at some distance from a well pumped at constant rate. This was the situation considered by Theis (1935) and Jacob (1940) in their development of the storativity concept. The S values obtained from observation well responses are large-scale, bulk average values pertaining to the permeable geologic medium between the pumping well and the observation well. These bulk values are limited in their usefulness for assessment of spatial variability. However, for location specific values, S can also be obtained from analysis of drawdown measured in the pumping well (e.g., Jacob and Lohman, 1952; Rushton, 1978; van Tonder et al., 2001). These are referred to as single-well S values, and are the focus of this paper. S values obtained from single-well tests pertain to the properties of the geologic medium close to the well, or close to the borehole if the test is done in rock using straddle packers. Such values are rare in the literature, especially for fractured rock, likely because of the difficulty in obtaining suitable test data. The premise of this paper is that a valid method for measuring Ss in single boreholes in fractured rock from hydraulic tests in short borehole segments isolated using straddle packers is needed for determining the spatial distribution of Ss. Only with such a method will it be possible to assess relations of Ss to local-scale hydrogeology. This paper presents a method aimed at improvement of the estimation of S from straddle packer tests by assessment of the inherent assumptions in the Theis equation, most notably Darcian flow and horizontal radial flow. Ss values determined for fractured rock may ultimately give insight about the nature of the fractures and fracture network because fracture compressibility is likely a major contributor of storage (e.g., Kazemi et al., 1969; Bourdet and Gringarten, 1980; Rutqvist et al., 1998; Svenson et al., 2007). The storage characteristics of fractured rock likely relate to the same fracture network and rock matrix characteristics that influence contaminant behavior. Reliable Ss values might support estimations of fracture porosity (ϕ_f) for determining average linear groundwater velocities in fractured rock. However, no studies providing S values have been reported for fractured sedimentary rock in which the hydraulic test involves small volumes of rock (i.e., 1–5 m test intervals). The few studies that reported S values for sandstone that tested moderate volumes of rock used open holes 8–15 m long (e.g., Rushton, 1978; Crouch, 1991; van Tonder et al., 2001; Castagna et al., 2011). In contrast, hydromechanical studies conducted in igneous rock determined S from high pressure injection tests in short borehole intervals (e.g., 0.65–3 m) in single holes (e.g., Rutqvist et al., 1998; Svenson et al., 2007; Schweisinger et al., 2009). Overall, information concerning the small-scale nature of Ss and relationships to the characteristics of fractured sedimentary rock is lacking.

Three approaches are commonly used to obtain S values in fractured rock: (1) hydraulic tests where S is obtained within the diffusivity concept using analytical or numerical models, with the rock treated as an equivalent porous medium (e.g., Cooper and Jacob, 1946; Theis, 1935; Rushton, 1978; Rutqvist et al., 1998; Tiedeman and Hsieh, 2001; Van Tonder et al., 2001; Doan et al., 2006); (2) measurement of fracture contraction or dilation during a hydraulic test using an down-hole extensiometer, where S is attributed only to fracture elasticity (Robson and Banta, 1990; Svenson et al., 2007; Schweisinger et al., 2009); and (3) analysis of hydrographs from single holes under ambient conditions using earth tide data and/or barometric efficiency methods (van der Kamp and Gale, 1983; Burbey, 2010; Smith et al., 2013; Allègre et al., 2016).

The determination of T and S in all types of media using hydraulic tests typically involves matching the drawdown data with a type curve based on the Theis equation. These S values are prone to large error or uncertainty, mostly due to non-uniqueness problems caused by deviations from the type curve at early times [e.g., well bore storage] and late times [e.g., boundary effects] (Barker and Black, 1983; Chapuis, 1992; Chow, 1952; De Marsily, 1986; Papadopulos and Cooper, 1967; van Tonder et al., 2001).

This paper has two goals. The first is to present a method for obtaining S values based on the synergistic use of the results of two types of low flow, hydraulic tests conducted in short borehole segments isolated by straddle packers in fractured sandstone with an emphasis on assessing the model assumptions regarding non-idealities in an attempt to minimize errors in the Ss values. The second goal is to present a compilation of literature-derived values of Ss for sandstone and an assessment of uncertainties or bias in Ss values reported in the literature for sandstone.

2. Development of the storativity concept

Given the paucity of information in the literature on the nature of storativity in fractured rock, examination of the evolution of the storage parameter for analysis of transient hydraulic tests in granular aquifers is the necessary starting point. Theis (1935) introduced the transient solution to the groundwater flow equation based on a lumped parameter he called the "coefficient of diffusivity". Theis described the coefficient of diffusivity as analogous to T divided by specific yield (i.e., drainable porosity); he also discussed the error using this equation for unconfined aquifers because of the time lag required for gravity drainage, but surmised that this error would lessen as the pumping time increased. To obtain the mathematical solution to the groundwater flow equation, Theis used heat conduction as the analog for hydraulic behavior, where a specific amount of heat is lost simultaneously as the temperature decreases. The application of this concept to a saturated elastic artesian aquifer is that a specific volume of water is instantaneously released from storage as the pressure decreases. A few years later, Theis (1938) referenced Meinzer (1928), for recognizing that substantial quantities of water must come from storage in confined aquifers. Theis referred to this storage parameter in confined aquifers as the "storage coefficient". Jacob (1940) followed these landmark papers by deriving the fundamental differential equation governing flow in an elastic artesian aquifer and, as part of this derivation, he established the physical parameters that constitute the "storage coefficient" described by Theis. For confined granular media, Jacob neglected the compressibility of the mineral or rock grains, and indicated that the release of water from storage caused by decreasing the water pressure is accompanied by compression of the aquifer skeleton and the expansion of water:

$$S = \rho g b(\alpha + \varphi \beta_w), \quad S = bS_S, \quad S_s = \rho g(\alpha + \varphi \beta_w), \tag{1}$$

where S is the storativity [–], ρ is the density of water [M/L^3], g is the acceleration of gravity [L/T^2], b is the aquifer thickness [L], α is the compressibility of the aquifer skeleton [LT^2/M], φ is the porosity [–], β_w is the compressibility of water [LT^2/M], and Ss is the specific storage [1/L]. In general, the compressibility of water is small (4.4×10^{-10} Pa^{-1} at 25 °C) relative to the aquifer skeleton compressibility (α) and, therefore, is typically neglected at shallow depths. The concept of specific storage, which is related to the storativity of an aquifer in the same way that K is related to T, was only implied by Jacob and it took another 20 years before Hantush (1960) called this parameter "specific storage", and introduced the definition in use today.

For pumping tests in granular aquifers, the skeleton compressibility results from the rearrangement and compaction of the individual grains due to an increase in the effective stress caused by a decrease in the pore water pressure (e.g., Jacob, 1940; Terzaghi, 1943). Domenico and Mifflin (1965) presented typical Ss values