Interpretation and analysis of aquifer tests in fractured - karstified carbonate limestone

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Abstract: This paper presents a method to interpret drawdown and residual drawdown data of pumping tests in fractured (karstified) limestone on the basis of the double-porosity concept. With Kazemi's *et al. (*1969) straight line method, the aquifer characteristics of transmissivity and storativity of both pumping and recovery stage are mathematically formulated without any correction or additional assumption. An actual case is shown to illustrate the proposed method. The methodology presented in this paper can be extended to various situations where the concept of double porosity is applicable.

The method we present here is based on the double-porosity theory, which conceptualizes the fractured rocks as a composition of two media: the fractures of high permeability and low storage capacity, and the matrix blocks of low permeability and high storage capacity. Pumping tests in the fractured rocks often exhibit drawdown curve of three distinct phases, that is:

(1) Early pumping time, when most of the groundwater flows from storage in the fractures, and the drawdown is described in 2D 'depth averaged ' conditions by the Theis's equation (Theis 1935)

$$s_1 = \frac{Q}{4\pi T} W\left(\frac{S_f r^2}{4Tt} \right) \qquad (1)$$

where s is the drawdown observed at a distance r, Q is the pumping rate, $W()$ is the Theis well function, S_f is the storage coefficient or storativity mostly of the fracture network, T is the aquifer transmissivity.

(2) Medium pumping time, a transition period during which a relative stabilization of the drawdown is observed due to the increasing drainage of the groundwater coming from the porosity of the matrix blocks. In a drawdown versus log time diagram, this phase is characterized by an inflection point and sometimes a nearly constant drawdown for certain time interval.

(3) Late pumping time, when it can be considered that the pumped water comes from storage in both the fractures and the matrix blocks

$$s_3 = \frac{Q}{4\pi T} W\left(\frac{(S_f + S_m) r^2}{4Tt} \right) \qquad (2)$$

where S_m is the storativity of the matrix blocks. Given small values of r^2/t, Eq. (1) and (2) can be replaced by the Cooper-Jacob approximation (Cooper *et al.* 1946) as

$$s_1 \approx \frac{2.3Q}{4\pi T} \log\left(\frac{2.25Tt}{S_f r^2} \right)$$

$$\text{and} \qquad s_3 \approx \frac{2.3Q}{4\pi T} \log\left(\frac{2.25Tt}{(S_f + S_m) r^2} \right) \qquad (3)$$

which can be used to compute T, S_f and S_m with the standard procedure outlined for the Kazemi *et al.'s* straight-line method (Kazemi *et al.* 1969; Kruseman and de Ridder 1994).

As the pumping stops, the recovery starts. Given the pumping test has progressed sufficiently far in the 3rd phase the recovery will also exhibit three distinct phases. In the first phase, the fractures are quickly recovering and the drawdown can be calculated on the basis of superposition principle as follows

$$s_1' = \frac{Q}{4\pi T} W\left(\frac{(S_f + S_m) r^2}{4Tt} \right) - \frac{Q}{4\pi T'} W\left(\frac{S_f' r^2}{4T' t'} \right) \qquad (4)$$

where the superscript ' corresponds to the characteristics of recovery stage and t' is elapsed time since the pumping ceases. The second phase is again a transition period when also gradually the pore matrix is recovering. In the 3rd phase both the fracture network and the matrix blocks are recovering, which can be calculated by

$$s_3' = \frac{Q}{4\pi T} W\left(\frac{(S_f + S_m) r^2}{4Tt} \right) - \frac{Q}{4\pi T'} W\left(\frac{(S_f' + S_m') r^2}{4T' t'} \right) \qquad (5)$$

The Cooper-Jacob approximation for Eq. (4) and (5) when $T \approx T'$ is expressed as follow:

$$s_1' \approx \frac{2.3Q}{4\pi T} \log \frac{S_f' t}{(S_f + S_m) t'}$$

$$\text{and} \qquad s_3' \approx \frac{2.3Q}{4\pi T} \log \frac{(S_f' + S_m') t}{(S_f + S_m) t'} \qquad (6)$$

For hard rock, the pumping does not create a mechanical consolidation of the aquifer, but it can modifies slightly its compressibility during loading (pumping) and unloading (recovery), which results in $S_f' \neq S_f$ (and $S_m' \neq S_m$). More important, the obtained transmissivity values in pumping and recovery conditions can be quite different due to a number of factors. For instance, if the borehole was not entirely cleaned before the pumping test is carried out, the pumping has possibly removed most of the muddy materials present in the fractures facilitating the groundwater flow towards the well in the further recovery stage (i.e., T increases). When $T \neq T'$, an estimation of T', S_f' and S_m' is still possible using the Cooper-Jacob approximation for Eq. (4) and (5) as follow

$$s_3^* - s_1' \approx \frac{2.3Q}{4\pi T'} log \frac{2.25T' t'}{S_f' r^2}$$

$$\text{and} \qquad s_3^* - s_3' \approx \frac{2.3Q}{4\pi T'} log \frac{2.25T' t'}{(S_f' + S_m') r^2} \qquad (7)$$

where * corresponds to the pumping drawdown extended with Eq. (3) for $t > t_p$ where t_p is the time since the pumping was stopped (Fig.1). It is worth noting that the extrapolated values of the pumping drawdown depend on the quality of the value of T obtained with Eq. (3). Consequently, any inaccuracy or error in the drawdown is carried over into the estimation of the characteristics of the recovery stage.

An example of the proposed method is presented here with an application of a pumping test that is carried out in fractured and karstified carbonate rocks in the Northwest of Vietnam. The drawdown data are measured in the pumped well. Therefore, the storativity (in both pumping and recovery stages) cannot be accurately evaluated. The pumping stopped at $t_p = 1320$ min. The drawdown record starts at time $t = 15$ min, therefore, evaluation of the 1st phase of pumping stage was unfortunately not possible. The transmissivity, T, estimated during the pumping stage is evaluated to 10.5 m^2/d. The straight line of the 3rd phase is extended which enables to compute quantity $s - s'$ for recovery duration. Finally, the transmissivity, T', evaluated during the recovery stage is 25.8 m^2/d.

In conclusion, the proposed interpretation methods of pumping and recovery drawdown allow, when used jointly, to estimate explicitly the transmissivity and storativity for both pumping stage and recovery stage. In the application of the methods, attention must be paid to the extension of the pumping drawdown for the interval after the pumping stops.

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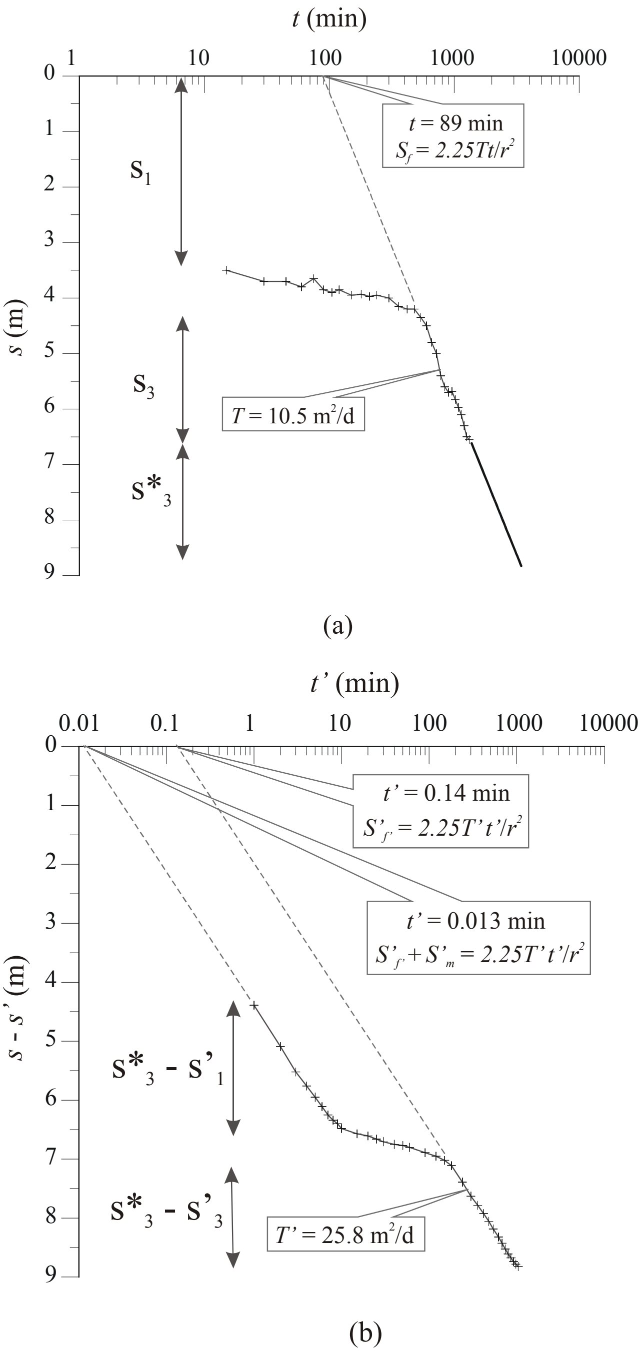

Figure 1. Semi-log plot of (a) pumping drawdown vs. pumping time and (b) s - s' vs. recovery time