# The applicability of slug tests in fractured-rock formations

**GJ van Tonder* and PD Vermeulen**

*Institute for Groundwater Studies, University of the Free State, Bloemfontein 9300, South Africa*

## Abstract

Currently slug tests in South Africa are used with two objectives in mind:
- To get a first estimate of the yield of a borehole
- To estimate the K-value (or T-value) of the aquifer near the borehole.

The paper shows that the use of currently available slug-test interpretation methods to analyse slug tests in fractured-rock aquifers to estimate a T or K-value is problematic. The estimated value is dependent on the flow thickness (thickness of the part of the aquifer in which flow occurs due to the slug input). If this thickness of flow is known, the estimated T-value is more representative of that of the fracture zone. By using the total thickness of the formation for the estimation of the K-value in slug-test analysis, the estimated K-value (and thus KD-value) does not represent the T-value of the formation.

**Keywords**: slug tests, fractured-rock formations

## Introduction

In performing a slug test, the static water level in a borehole is suddenly lowered or raised. This is usually done by lowering a closed cylinder into a borehole. The cylinder replaces its own volume of water within the borehole, thus increasing the pressure in the borehole. As the equilibrium in the water level is changed, it will recover or stabilise to its initial level. If the rate of recovery or recession of the water level is measured, the transmissivity or hydraulic conductivity of the borehole can be determined (Kruseman and De Ridder, 1994).

In South Africa slug tests are conducted for the following two reasons:
- To estimate the hydraulic conductivity (K) of the aquifer in the vicinity of the borehole
- To get a first estimate of the yield of a borehole (Vivier et al., 1995).

Vivier et al. (1995) performed slug tests on 32 boreholes, of which the maximum yield was known and they then derived empirically the following formula (there is a 93% correlation between the actual yield and the yield estimated with the formula):

$$Q = 117155.08t^{-0.83} \quad (1)$$

where:

Q = yield of the borehole in ℓ/h and

t = recession time of the slug test in seconds (90% recovery).

Usually the Cooper method (Cooper et al., 1967) or the Bouwer and Rice method (1976) is used to estimate the K-value (or T-value in the case of the Cooper method).

* To whom all correspondence should be addressed.
☎+2751 401-2840; fax: +2751 447-3541; e-mail: Gerrit@igs.uovs.ac.za

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***Figure1***
*Map of the RSA*

In the following section slug-test results, as well as pumping and tracer-test results for borehole UO5 on the well-known Campus Site of the University of the Free State, South Africa (Fig. 1) will be discussed to illustrate the problems associated with the interpretation of slug tests in a borehole drilled in a fractured aquifer.

## Borehole UO5 on the Campus Site

The Campus Test Site is underlain by a series of mudstones and sandstones from the Adelaide Subgroup of the Beaufort Group of formations in the Karoo Supergroup (Fig. 2). There are three aquifers present on the site. The first, a phreatic aquifer, occurs within the upper mudstone layers on the site. This aquifer is separated from the second and main aquifer, which occurs in a sandstone layer of between 8 and 10 m thick, by a layer of carbonaceous shale with a thickness of 0.5 to 4 m. The third aquifer occurs in the mudstone layers (more than 100 m thick) that underlie the sandstone unit.

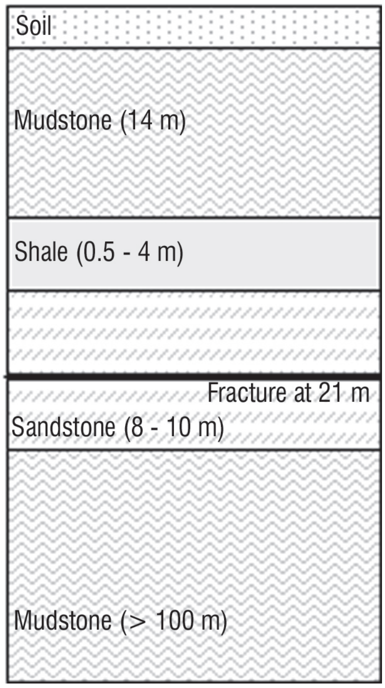


***Figure 2***
*Diagram of the geological formation at the Campus Test Site (relative thickness of the aquifers in brackets)*

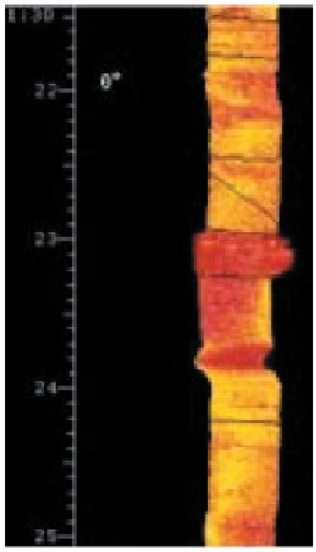

***Figure 3***
*Acoustic scan of borehole UO5 at a depth of 20 m to 25 m below the surface*

A major characteristic of the main aquifer is the presence of a horizontal fracture that coincides approximately with the centre plane of the sandstone layer, and which intersects all 11 boreholes with significant yields on the Site, of which UO5 is one. The remaining 14 boreholes all have very insignificant yields. The fracture zone thickness is approximately 10 mm, but the adjacent 200 mm of sandstone is also highly permeable.

Figure 5 shows a graph of the data from a constant rate test conducted on UO5 at a rate of 1.25 ℓ/s. Measurements were also taken in the observation borehole UO6.

These pumping test data were analysed with a numerical 3D model (Van Tonder et al., 2001), and the following parameters were estimated (Table 1):

**TABLE 1**
**Hydraulic parameters estimated for UO5**

| Parameter | Value |
|---|---|
| T of formation* ($m^2$/d) | 19 |
| K of facture zone (m/d) | 3 600 |
| T of fracture zone ($m^2$/d) | 576 |
| K of matrix (m/d) | 0.17 |
| T of matrix** ($m^2$/d) | 3 |

* Average for fracture + matrix, obtained from Cooper-Jacob fit to late drawdown values.
** For 20 m thickness.

The thickness of the fracture zone was obtained from tracer tests, acoustic scan (Fig. 4) and the borehole video (Fig. 5), and is 0.16 m. The hydraulic parameters given in Table 1 are regarded to be accurate (Van Tonder et al., 2001). It would now be interesting to analyse the data of a slug test (Fig. 6) conducted on borehole UO5 and compare the estimated values with the values given in Table 1.


***Figure 4***
*Borehole video image of the fracture zone in borehole UO5 showing a fracture-zone thickness of about 200 mm*

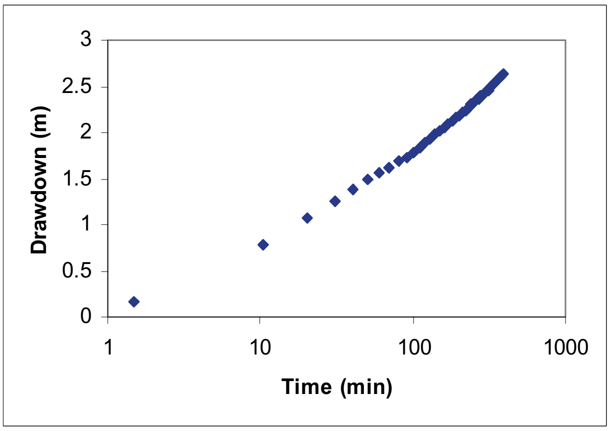


***Figure 5***
*Constant rate pumping test data of UO5*

The 90% recovery occurred after about 9 s, and using Eq. (1) the yield of borehole UO5 is estimated as 5.3 ℓ/s. The tested blow yield of borehole UO5 was 6 ℓ/s during drilling.

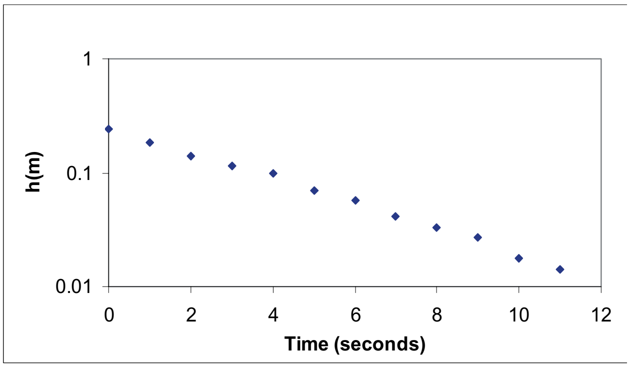


***Figure 6***
*Data collected during a slug test conducted on UO5*

The Bouwer and Rice (1976) method was applied to the data in Fig. 6 . The Bouwer and Rice equation reads:

$$K = \frac{r_c^2 \ln(R_e / r_w)}{2d} \frac{1}{t} \ln \frac{h_0}{h_t} \quad (2)$$

where:

- $r_c$ = radius of the unscreened part of the borehole where the head is rising
- $r_w$ = horizontal distance from the borehole centre to the undisturbed aquifer
- $R_e$ = radial distance over which the difference in head $h_0$ is dissipated in the flow system of the aquifer
- d = length of the borehole screen or open section of the borehole
- $h_0$ = head in the borehole at time=0
- $h_t$ = head in the borehole at time t

The estimated K-value of Bouwer and Rice is dependent on the thickness open to flow, d, and Table 2 shows the different K-value estimates for different flow thicknesses. Note that a flow thickness of 30 m will indicate the depth from the water level to the end of the borehole and that a thickness of 0.16 m is the thickness of the fracture zone in borehole UO5.

**TABLE 2**
**Estimated K-values with the Bouwer and Rice (1976) method for different values of the flow thickness**

| Thickness open to flow (m) | K (m/d) | T ($m^2$/d) |
|---|---|---|
| | | |
| 30 | 12 | 360 |
| 20 | 17 | 340 |
| 10 | 32 | 320 |
| 1 | 231 | 231 |
| 0.16 | 541 | 86 |
| 0.001 | 3 600 | 3.6 |

## Discussion

Comparison of Table 1 and Table 2 shows the following important issues:

- An incorrect K-value is obtained from the slug test if the thickness of the aquifer (total formation) is used as the flow thickness. For a thickness of 30 m, a K-value of 12 m/d (or T=360 $m^2$/d) is estimated from the slug test, which is neither the T-value of the fracture zone nor the T-value of the matrix.
- For a flow thickness of 0.16 m (i.e. the thickness of the fracture zone), a K-value of 541 m/d is estimated with the Bouwer and Rice (1976) slug-test method. This estimated K-value is more representative of the K-value of the fracture zone.
- The average T-value of the formation, which is important for management purposes, was estimated as 19 $m^2$/d from the constant rate pump test. It is impossible to estimate the T- or K-value of the aquifer formation via a slug test.

## Conclusions

The use of the currently available slug-test interpretation methods to analyse a slug test in a fractured-rock aquifer to estimate a T- or K-value is problematic. The estimated value is dependent on the flow thickness (thickness of the part of the aquifer in which flow occurs due to the slug input). If this thickness of flow is known, the estimated K-value is more representative of that of the fracture zone. By using the total thickness of the formation for the estimation of the K-value in slug-test analysis, the estimated K-value (and thus KD-value) does not represent the T-value of the formation.

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