Groundwater

Methods Note/

Slug Tests in Wells Screened Across the Water Table: Some Additional Considerations

by J.J. Butler Jr.[1,2]

Abstract

The majority of slug tests done at sites of shallow groundwater contamination are performed in wells screened across the water table and are affected by mechanisms beyond those considered in the standard slug-test models. These additional mechanisms give rise to a number of practical issues that are yet to be fully resolved; four of these are addressed here. The wells in which slug tests are performed were rarely installed for that purpose, so the well design can result in problematic (small signal to noise ratio) test data. The suitability of a particular well design should thus always be assessed prior to field testing. In slug tests of short duration, it can be difficult to identify which portion of the test represents filter-pack drainage and which represents formation response; application of a mass balance can help confirm that test phases have been correctly identified. A key parameter required for all slug test models is the casing radius. However, in this setting, the effective casing radius (borehole radius corrected for filter-pack porosity), not the nominal well radius, is required; this effective radius is best estimated directly from test data. Finally, although conventional slug-test models do not consider filter-pack drainage, these models will yield reasonable hydraulic conductivity estimates when applied to the formation-response phase of a test from an appropriately developed well.

Introduction

Slug tests are commonly performed at sites of suspected groundwater contamination to obtain estimates of hydraulic conductivity (K) for risk assessments and design of remediation systems (Butler 1998). The vast majority of tests at sites of shallow groundwater contamination are performed in wells that were originally put in for water sampling; a large percentage of these wells have installed (artificial) filter packs and are screened across the water table. Although slug tests have been performed in wells screened across the water table for decades, there are still a number of unresolved issues concerning such tests. These issues arise because tests in this setting can be affected by mechanisms beyond those that occur in the well-formation configurations of the standard slug-test models (Cooper et al. 1967; Bouwer and Rice 1976).

The most common of these mechanisms is drainage of the gravel or filter pack (henceforth, filter-pack drainage). Figure 1a is a schematic depiction of a well with an installed filter pack immediately after the initiation of a rising-head slug test; the test is assumed to have been initiated rapidly relative to the response of the filter pack or formation (H_0^* is the initial displacement expected from volumetric considerations [casing radius and slug geometry] for tests initiated with solid slugs). The installed filter pack will typically be considerably more permeable than the formation (ASTM 2010), so the first phase of the test is the drainage of the filter pack. The filter pack will drain into the well until the water levels in the well and filter pack are the same (Figure 1b); the water levels will then rise together as a function of the formation response.

Slug tests in wells that have installed filter packs and are screened across the water table typically display a pronounced two-limb (double straight line) form when plotted as the logarithm of normalized head vs. time

[1]Kansas Geological Survey, University of Kansas, Lawrence, KS 66047; 785-864-2116; jbutler@kgs.ku.edu
[2]Group of Hydrogeology, Universitat Politècnica de València, Valencia, Spain.
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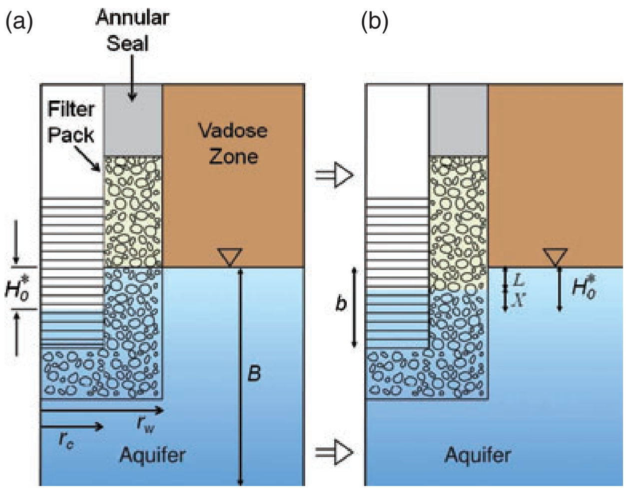

Figure 1. Schematic diagram of a slug test in a well screened across the water table. (a) Situation immediately after initiation of a rising-head slug test with an expected initial displacement of H_0^*; (b) Situation immediately after completion of filter-pack drainage (filter-pack drainage is assumed to be completed prior to any aquifer response; r_c is the radius of the well casing and screen, r_w is the radius of the borehole, b is the effective [submerged] screen length at static conditions, B is the aquifer thickness, L and X are defined in text).

(Figure 2a). The first limb (phase) of the test is a function of the filter-pack drainage, while the second is primarily a function of the hydraulic properties of the formation. The analysis should focus on head changes during the second test phase, as those in the first are not a function of the formation K.

The purpose of this note is to address four unresolved issues for slug tests in wells screened across the water table. Ideally, slug tests should be performed in wells where the second phase of the test occurs above the noise level of the sensor. However, the wells in which slug tests are performed were typically not constructed for that purpose, so the well design may result in problematic test data (small signal-to-noise ratio; i.e., the formation response can be difficult to distinguish from sensor noise). Thus, the first issue to be addressed is that of how to assess the suitability of a particular well design for slug tests.

In formations of moderate to low K, the filter-pack drainage and formation-response phases can be clearly identified (e.g., Figure 2a). However, in more rapidly responding systems, uncertainty may arise about which portion of the test represents filter-pack drainage and which represents the formation response (e.g., Figure 2b). Thus, the second issue to be addressed is that of how to identify the filter-pack drainage phase of a test.

A key well-construction parameter required for all slug test models is the casing radius (casing defined here as the portion of the well in which the water level is changing). However, in a slug test in a well screened across the water table, the nominal casing radius is not appropriate when water levels in the well and the filter pack are behaving as one (e.g., Figures 1b and 2a). Thus,

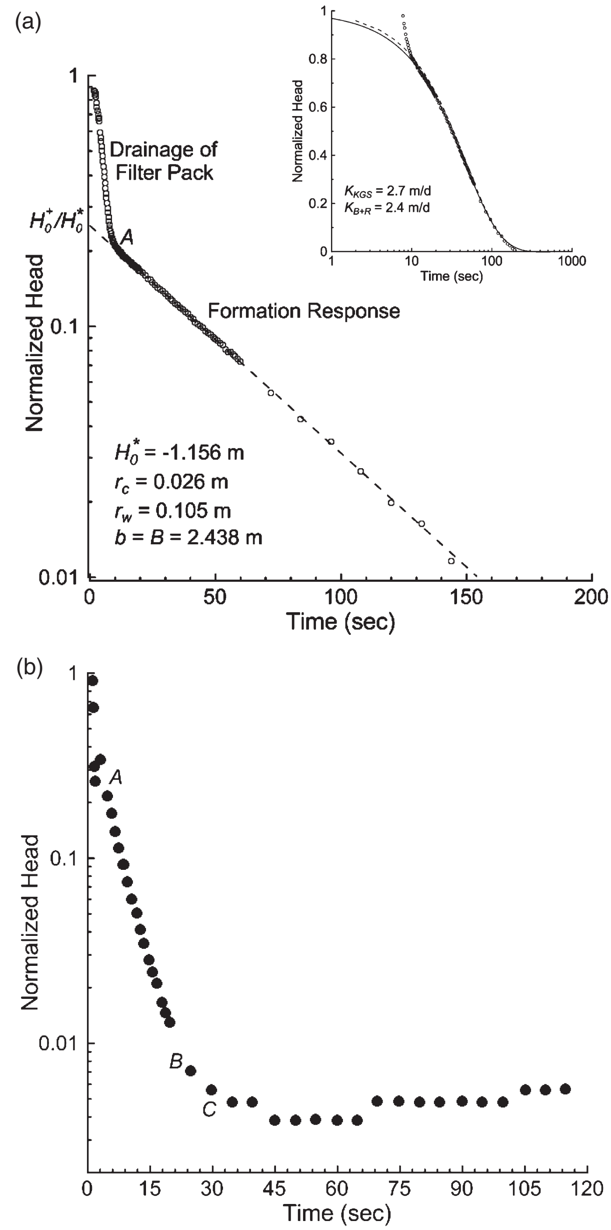

Figure 2. (a) Logarithm of normalized head vs. time since test initiation plot for a slug test in a well screened across the water table in an unconsolidated aquifer in north-central Texas (deviation from static data normalized by the expected initial displacement (H_0^*); dashed line is the Bouwer and Rice model fit; H_0^+/H_0^* is the y-intercept of the dashed line (0.252); A designates the end of filter-pack drainage; other terms are as defined in Figure 1; inset shows the KGS (solid line) and Bouwer and Rice (dashed line) model fits in a normalized head (deviation data normalized by H_0^+) vs. logarithm of time format; data courtesy of G. Zemansky. (b) Logarithm of normalized head vs. time since test initiation plot for a slug test in a well screened across the water table in an unconsolidated aquifer in east-central Kansas (deviation from static data normalized by the expected initial displacement (H_0^*); A, B, and C defined in text).

the third issue to be addressed is that of how to estimate an effective casing radius for wells screened across the water table.

Conventional slug test models do not incorporate the filter-pack drainage mechanism. As a result, uncertainty may arise concerning how to analyze response data from tests in wells screened across the water table. Thus, the final issue to be addressed is that of the most appropriate methods for analysis of tests performed in this setting.

Slug Tests in Wells Screened Across the Water Table: Key Issues

Assessment of Well Suitability

The suitability of a particular well design can be assessed using a simple mass balance. Assuming that the installed filter pack is considerably more permeable than the formation, the volume of water drained from the filter pack must equal the volume of water entering the well casing:

$$\pi r_c^2 X = \pi \left(r_w^2 - r_c^2\right) nL \quad (1)$$

where r_c and r_w are the casing and borehole radii, respectively [L]; X is the water-level rise in the well produced by filter-pack drainage [L]; n is the drainable porosity of the filter pack [-]; and L is the length of the drained filter pack [L] (Figure 1).

Substituting $H_0^* - L$ for X and solving for L yields:

$$L = \frac{H_0^*}{(An - n + 1)} \quad (2)$$

where H_0^* is the expected initial displacement [L] and A is r_w^2/r_c^2.

Both sides of Equation 2 can then be divided by H_0^* to obtain an equation for the normalized head at the completion of filter-pack drainage:

$$\frac{L}{H_0^*} = \frac{1}{(An - n + 1)}. \quad (3)$$

Equation 3 serves as a rapid means to evaluate how much filter-pack drainage should be expected for a particular well design. For example, the test in Figure 2a was performed in a well with a casing radius of 0.026 m (2″ Sch 40 casing) set in a 0.105 m (0.344 feet) radius borehole with an installed filter pack of 10-20 sand (estimated drainable porosity of 0.28). Given these parameters, the filter-pack drainage will be completed at a normalized head of 0.19 according to Equation 3. This is consistent with the response data and should often result in a data set with an acceptable signal-to-noise ratio. However, if a smaller well with a casing radius of 0.013 m (1″ Sch 40 casing) had been set in this same borehole for ease of installation, the filter-pack drainage would be completed at a normalized head of 0.06, which could make the analysis more problematic because of the smaller signal-to-noise ratio. Given that the drainable porosity is often not known, a range of n values should be used in Equation 3 to incorporate the uncertainty in that parameter.

Equation 3 demonstrates that tests performed in a small-diameter well in a relatively large borehole will likely produce response data that are dominated by filter-pack drainage. Although the test in Figure 2a was initiated with a relatively large initial displacement, and thus used here to illustrate the test phases, slug tests should typically be initiated with small initial displacements (a few tenths of a meter) to avoid relatively large changes in the effective (submerged) screen length (b in Figure 1) during the formation-response phase of the test and to avoid inducing non-Darcian head losses and mobilization of near-well fines (Butler 1998). However, if the well has a relatively wide filter pack, the formation response may occur below the sensor noise level for tests initiated with the recommended small displacements. Thus, larger initial displacements, such as that of Figure 2a, should be used when Equation 3 indicates that only the last few centimeters of the response data will be a function of the formation response. Repeat tests should be performed with different initial displacements and then plotted in a normalized format to assess if changes in the submerged screen length and other mechanisms (non-Darcian head losses and mobilization of fines) are affecting the response data; the coincidence of normalized plots indicates that such mechanisms can be ignored. In general, if the formation-response phase of the test (H_0^+ in Figure 2a) is less than about 25% of the submerged screen length at static conditions, the impact of changes in submerged screen length during the test should not be of practical importance. Although use of larger initial displacements will increase the signal-to-noise ratio of the response data, the volume of the aquifer affected by the test will not change (Butler 1998).

Identification of Filter-Pack Drainage

Figure 2b presents data from a test performed in a well with an installed filter pack that is screened across the water table in a relatively permeable unconsolidated aquifer. In this case, there was confusion about which portion of the data represented filter-pack drainage and which represented the formation response. The original analyst had assumed that filter-pack drainage ended just before point B and had used the Bouwer and Rice (1976) method to estimate K from a straight line between B and C. However, as is clear from examination of the plotted data, the recorded changes after point B are far more likely to be the product of sensor noise than formation response. Thus, one can have little confidence in the resulting K estimate.

The original analyst had evidently identified the end of filter-pack drainage from a visual inspection of the data. Apparently, water-level changes in the period before point A were considered to be a product of noise associated with test initiation and those in the A to B interval to be the product of filter-pack drainage. Although r_c is the same as in Figure 2a, r_w, n, and H_0^* were not reported. However, given common practices, the assumption that r_w and n are the same as in Figure 2a is reasonable. Undoubtedly, H_0^* was somewhat larger than 1.09 m (the first reported value at 1.1 s after test initiation), so 1.2 m is used here.

Given these known and assumed parameters, Equation 1 (the two sides should be in balance) or Equation 3 can be used to identify the end of filter-pack drainage. Equation 1 is most convenient for this purpose, so it is used here. If point *A* (normalized head of 0.22) is assumed to mark the end of filter-pack drainage, the two sides of Equation 1 are within 18% of one another. If the end of filter-pack drainage is assumed to occur at a normalized head of 0.01 (shortly before point *B*), the two sides of Equation 1 differ by over a factor of 20. Thus, the mass balance indicates that water-level changes in the period prior to point *A* were likely produced by filter-pack drainage, and those in the *A* to *B* period by the formation response.

Visual identification of the filter-pack drainage phase should always be confirmed in rapidly responding systems by applying Equation 1 to the end point of the apparent drainage period to ensure that the appropriate interval is the focus of the analysis. If the two sides of Equation 1 are in balance to well within a factor of two (factor is based on field experience and incorporates uncertainty in n and the possibility of formation response during filter-pack drainage), one can assume that the drainage phase has been correctly identified.

Estimation of Effective Casing Radius

All slug-test analysis methods require an estimate of the casing radius. For tests in wells that are screened across the water table and affected by filter-pack drainage, the well and the filter pack are behaving as one, so the nominal casing radius is not appropriate. Instead, an effective casing radius ($r_{c_{ef}}$), which is the radius of the borehole corrected for the drainable porosity of the filter pack, is needed. Bouwer (1989) proposed the following equation for the estimation of $r_{c_{ef}}$:

$$r_{c_{ef}} = \left[r_c^2 + n\left(r_w^2 - r_c^2\right)\right]^{0.5}. \quad (4)$$

As Butler (1998) points out, error can be introduced into the resulting $r_{c_{ef}}$ estimate through uncertainty in n and r_w. This error is amplified in the estimation of K because the casing radius appears as a squared term in all analysis methods.

Butler (1998) and Binkhorst and Robbins (1998) proposed somewhat similar mass-balance approaches for estimation of $r_{c_{ef}}$ to avoid the error produced by the uncertainty in n and r_w (Butler 1998) and n (Binkhorst and Robbins 1998). These two approaches differ in their conceptualization of the formation response during filter-pack drainage. The approach of Butler (1998) incorporates the possibility of formation response, while that of Binkhorst and Robbins (1998) does not.

Given its greater flexibility, the approach of Butler (1998) is the focus here. In this method, estimates of n and r_w are not required. Instead, a mass balance is written using the expected initial displacement (H_0^*) and the apparent initial displacement (H_0^+) estimated from the *y* intercept of the straight line fitted to the response data (Figure 2a):

$$H_0^* \pi r_c^2 = H_0^+ \pi \left[r_c^2 + n\left(r_w^2 - r_c^2\right)\right] = H_0^+ \pi r_{c_{ef}}^2. \quad (5a)$$

Rearrangement and solving for $r_{c_{ef}}$ yields:

$$r_{c_{ef}} = r_c \sqrt{H_0^*/H_0^+}. \quad (5b)$$

Note that this approach requires that the data from the formation-response phase of the test plot as a straight line in a logarithm of normalized head vs. time format (i.e., the assumptions underlying the Bouwer and Rice model are appropriate).

For the test of Figure 2a, the estimates of n and r_w appear to have been reasonable as the $r_{c_{ef}}$ values calculated from Equations 4 and 5b are within 13% of one another, 0.060 m and 0.052 m, respectively, which translates into a K difference of about 25%. If r_w is known, then the $r_{c_{ef}}$ value from Equation 5b can be substituted into Equation 4 to calculate n. In this case, an n estimate of 0.20 is obtained, which is within 30% of the assumed value of 0.28. Although the agreement between the two $r_{c_{ef}}$ estimates was reasonable in this example, that may not always be the case. Thus, directly estimating $r_{c_{ef}}$ from the response data (Equation 5b) is recommended when the data plot as a straight line in a logarithm of normalized head vs. time format.

Most Appropriate Analysis Methods

The standard models for the analysis of slug tests performed in unconfined aquifers can also be used to analyze tests in wells screened across the water table. Although one might be tempted to estimate the hydraulic properties of the filter pack with these models, the results will not be defensible because the models do not incorporate the primary mechanisms controlling filter-pack drainage. Thus, the focus of the analysis should be on the formation-response phase of the test.

The most commonly used method for the analysis of tests in wells screened across the water table is that of Bouwer and Rice (Bouwer and Rice 1976; Bouwer 1989). Three major assumptions of the mathematical model underlying this method are that the water table position does not change during the test, changes in the submerged screen length are relatively small, and effects of elastic storage mechanisms can be ignored. This last assumption results in a quasi-steady-state representation of the slug-induced flow (Butler 1998). When this assumption is valid, the formation response during filter-pack drainage will not affect the K estimate as long as the response data used in the analysis are from the period after the completion of the drainage phase. In the Bouwer and Rice method, a straight line is fit to the response data from the second phase of the test (e.g., Figure 2a); the slope of this line, $r_{c_{ef}}$, and a shape factor are then used to estimate the formation K. The shape factors provided by Bouwer and Rice (1976) or the more rigorously derived shape factors of Zlotnik et al. (2010) and others can be used. For the well-formation configurations most common in practice, the difference between K estimates obtained with these various sets of shape factors rarely exceeds 20%.

The Kansas Geological Survey (KGS) model (Butler 1998), which is based on a more rigorous representation of the slug-induced flow system that incorporates elastic storage mechanisms, can also be used to analyze tests in wells screened across the water table. However, as with the Bouwer and Rice method, only data after the period of filter-pack drainage can be used. In the KGS model, the response data are normalized by H_0^+ and a type curve is fit to the response data following the cessation of drainage (e.g., inset in Figure 2a). For tests in wells screened across the water table, the impact of elastic storage mechanisms is typically small, so K estimates from the KGS and Bouwer and Rice models should be in good agreement after appropriate well development. Although the KGS model can help identify the existence of a low-K well skin in many well-formation configurations (close model fit can only be obtained with an implausibly low specific storage value [Butler 1998]), the general insensitivity of slug tests in wells screened across the water table to elastic storage mechanisms limits its use for that purpose in this setting. Thus, the recognition that a test is affected by a low-K well skin can often only be based on a K estimate that is deemed too low for the interpreted hydrostratigraphy. Appropriate well development is clearly a critical step prior to slug tests in wells screened across the water table.

The test shown in Figure 2a was analyzed using the implementations of these two models in the AQTESOLV software package (Duffield 2007). The dashed line on the logarithm of normalized head vs. time plot is the Bouwer and Rice model fit to the data from the formation-response phase of the test. A K estimate of 2.4 m/d was calculated using the slope of this line, the $r_{c_{ef}}$ value of 0.052 m from Equation 5b, and the Bouwer and Rice (1976) shape factors. The inset in Figure 2a shows the KGS (solid line) and Bouwer and Rice (dashed line) model fits in a normalized head vs. logarithm of time format. The K estimate from the KGS model, 2.7 m/d, is about 12% larger than that from the Bouwer and Rice model. A specific storage estimate of $7.6e^{-5}$/m was also calculated with the KGS model. The model fit, however, is insensitive to orders of magnitude decreases in specific storage, an indication that elastic storage mechanisms have little impact on tests in this well-formation configuration.

Summary and Conclusions

Slug tests are commonly performed in wells screened across the water table at sites of groundwater contamination. However, tests in this setting can be affected by mechanisms beyond those that are incorporated into the standard slug test models. These mechanisms give rise to additional issues that must be considered for the design, performance, and analysis of slug tests in wells screened across the water table. The purpose of this note was to address four of these issues.

Slug tests in wells with installed filter packs that are screened across the water table typically display two distinct phases: a first phase that is produced by the drainage of the filter pack into the well and a second phase in which water levels in the well and the filter pack rise together as a function of the formation response. The data from this second phase must be above the noise level of the measurement device to obtain a defensible hydraulic conductivity (K) estimate. A simple equation can be used to assess if this will occur for a particular well design.

In rapidly responding systems, it may be difficult to identify which portion of the test is produced by filter pack drainage and which is produced by the formation response. A mass balance can be applied to the end point of the apparent drainage period to assess if the test phases have been correctly identified.

A key parameter required for the analysis of tests in wells screened across the water table is the effective casing radius ($r_{c_{ef}}$—radius of the borehole [r_w] corrected for the drainable porosity [n] of the filter pack). The common approach for estimation of $r_{c_{ef}}$ requires that n and r_w be known, which may often not be the case. The uncertainty in these parameters can introduce error into the $r_{c_{ef}}$ value, which is then amplified in the K estimate. An approach for directly estimating $r_{c_{ef}}$ from the response data is recommended to avoid the error produced by uncertainty in n and r_w.

Conventional slug test models can be used for the analysis of tests performed in wells screened across the water table. These models, however, do not incorporate the filter pack drainage mechanism, so the analysis should focus on the period following cessation of drainage. The assumptions underlying the commonly used Bouwer and Rice (1976) model appear reasonable for many tests performed in this setting. Thus, that model should produce reasonable K estimates for the well-formation configurations commonly faced in the field when the test well has been appropriately developed.

The above findings are for rising-head slug tests performed in well-formation configurations with installed (artificial) filter packs. The tests should be initiated using initial displacements that are small (<25%) relative to the effective (submerged) screen length at static conditions (b in Figure 1b). The relevant initial displacement parameter in this case is the apparent initial displacement (H_0^+ in Figure 2a). If this quantity is large (>25%) relative to b, then the analysis method of Dagan (1978) may be required (Butler 1998). Additional mechanisms may affect falling-head slug tests in wells screened across the water table, so rising-head tests are preferred in this setting. Repeat tests using different initial displacements should always be performed to help identify if mechanisms beyond those considered in the standard models are affecting the response data. Although most wells that are screened across the water table at sites of groundwater contamination have an installed filter pack, heaving sands and other factors may preclude filter pack installation. In slug tests in such wells, the drainage phase is typically not observed (i.e., there is no abrupt break in slope, data plot as a straight line or as a smooth concave upward curve [Figure 6.7a in Butler 1998] in a logarithm of normalized head vs. time format), so the nominal casing radius (r_c) should be used in the analysis. In extremely permeable settings, slug tests may only last a few to several seconds and the "noise" associated with test initiation (i.e., dynamic pressure effects produced by insertion or removal of a solid slug) can dominate much of the response data. In that case, slug tests can only provide an approximate lower bound on the K of the tested interval. Finally, slug tests performed in settings where light nonaqueous phase liquids are floating on the water table may be affected by mechanisms beyond those considered here (e.g., Huntley 2000; Batu 2012).

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