Hydrol. Earth Syst. Sci. Discuss.,
https://doi.org/10.5194/hess-2019-215-AC1, 2019

Hydrology and Earth System Sciences Discussions

HESSD

Interactive comment

Interactive comment on "An extended trajectory-mechanics approach for calculating the path of a pressure transient: Hydraulic tomographic imaging" *by* Donald W. Vasco et al.

Donald W. Vasco et al.

dwvasco@lbl.gov

Received and published: 21 June 2019

While there are things that we do agree with in this review, as a general comment we feel that much of the criticism is not directed at the limitations of the new method, rather the remarks point out limitations on the model assessment and the drawbacks of crosswell slug tests. To answer the issues in order:

It is not clear how the title invokes the Eikonal equation (the term is not mentioned), other than we use a trajectory-based approach for tomography. Simply put, the paper is concerned with a semi-analytic approach to pressure arrival time tomography.

1. Is the math solid? Yes, we have developed trajectory-based imaging approaches for tracer and transient pressure data over many years. However, this paper is concerned with a new approach that overcomes well-known limitations of previous asymptotic methods and should be judged on it's own merits. The work hardly belongs in a math journal, as it's basis comes from developments in physics and the physics of wave propagation (Wyatt 2005).

2. Does this paper present a complete approach for inverse modeling? We are not trying to present a complete approach for inverse modeling. Instead, we present a new approach for working with cross-well slug tests. These tests are quite common and have been shown to yield important additional information that can be combined with core analysis, borehole logging and any other available data.

(a) Uncertainty Quantification. We do discuss model parameter resolution and uncertainty at the bottom of page 8 and provide several references (Vasco et al. 1997; Bohling, 2009; Paradis et al. 2016), noting how the linearized expression (25) facilitates such computations, so the reviewers comments are both unfair and inaccurate. We agree that an important part of the solution to the inverse problem is model assessment and we will revise the paper to include such an assessment. However, as discussed in the current paper and as we will show in our revision, the trajectory-based approach does not preclude the calculation of model parameter resolution and uncertainty but rather facilitates such computations.

(b) Regression/Optimization. Any model is a simplification of reality. However, models are very helpful e.g. for flow and transport modeling, e.g. for prediction of arrival of a tracer or pollutant. The approach does recover the main anomalies present in the reference model, even though they are roughly an order of magnitude larger then the values in the uniform initial or starting model. The resulting model both fits the synthetic pressure arrival times and the validation arrival times. As such, the model derived from the inversion could serve as the starting point for a complete matching of the transient pressure data. (c) Data Integration. The approach that we are describing can easily be

Printer-friendly version

Discussion paper

used as part of an integrated inversion scheme in which many data types are included. Nothing in the methodology prevents that. Therefore, to say that the trajectory-based approach does not provide a way to integrate different types of information is simply incorrect. We merely chose to focus solely on the inversion of pressure arrival times in order to keep the presentation simple and direct and not obscure the comparison with an eikonal-based approach for inverting arrival times.

(d) Spatial Coverage. There are limitations in the crosswell geometry and in slug tests for imaging properties between wells. These limitations are well known. But that is not an issue associated with the new approach that we are illustrating. As the approach that we are describing is applicable to any test where a simulator can be used to compute the transient pressure response at an observation point. In fact, as illustrated in Vasco et al. (2000), the travel time approach can be used for wells 100 m apart when a constant rate test is considered. In that case the peak of the slope of the transient pressure curve is used to define an arrival time. In addition, fully three-dimensional imaging is also possible if such well configurations and data are available. The new technique is not limited to any specific geometry, such as the two-dimensional plane dictated by our crosswell experiment. We merely used data that were available to illustrate the approach. Given three-dimensional crosswell constraints provided by a suite of wells, we could apply the method in three-dimensions.

(e) The use of penalty terms and linearization. We can include some discussion on the influence of the regularization. We use an iterative approach to solve the non-linear inverse problem involving incremental linearized updates. We do not linearize the problem. This is a very common approach for solving non-linear problems in geophysics and hydrology and one of the few practical approaches for very large problems.

(f) Conclusion. The goal of the paper was to compare a new trajectory-based technique for pressure travel time tomography to a conventional approach. This conventional approach, based upon transient pressure travel times has provided the basis for many 'acceptable inverse modeling' studies that we cite in the Introduction. We believe that we have shown that the new approach is somewhat better at imaging rapid variations in properties, as the theory predicts.

3. Is the case study presented appropriate? And what can we learn from it?

(a) Again, we chose to illustrate the approach with data that we had already collected, that was fairly well understood, and that had already been analyzed. The wells are closely spaced as the tests were designed to understand river hydrology. Slug tests, which propagate a transient pulse, cannot be spaced too far due to the decay of the pulse with distance. We do provide a comparison between the new approach using just transient pressure arrival times and an integrated approach that combines geophysical data and pressure data. In the field application the new approach does seem to recover larger variations in permeability (Figure 11), variations that are of the same order as those obtained by a more comprehensive joint inversion (Figure 13). Furthermore, the new approach does seem to have more detailed structure than does the joint inversion. The amount of well core data was limited, and it can be difficult to extract undisturbed core samples from soft sediment environments. However, there are some cores and we can include these observations in a revision.

(b) Crosswell tests in general are limited to imaging within the plane between the two wells. This is just a characteristic of crosswell imaging. One can and does model the pressure propagation in three-dimensions but cannot resolve structure that is far outside of the plane between the wells.

(c) Crosswell tests are generally conducted in regions where the structure is thought to be largely planar with relatively smooth lateral variations and possibly rapid depth variations, is in the field area considered in this paper. The tests were conducted in a sedimentary environment and the wells are close. As such, it is thought that the most rapid spatial changes would be vertical variations in properties. As noted above, nothing in the approach precludes its application in a fully three-dimensional setting, with data from multiple wells. We hope to conduct such studies in the future as we acquire more complete three-dimensional data sets. However, the goals of this paper were limited and reflect the characteristics of our field observations.

(d) By general porous media we mean any porous medium that can be modeled using a numerical reservoir simulator. The factual basis for the statement is that the computations only rely on quantities output by the simulators, it does not invoke any additional assumptions about the medium. On page 2 it is stated that 'previous trajectory-based formulations...relied upon an asymptotic approach that assumes smoothly-varying properties'. Furthermore, we go on to state 'Here we apply a newly developed trajectory-based technique for travel time tomography that dispenses with the assumption of smoothly-varying properties, enlarging its range of validity to any model that may be treated with a numerical simulator.' I am not sure that I understand how the referee reached their conclusions, the statements seem clear.

(e) To simply say 'The case study is not adequate', is not constructive and provides no guidance on possible improvements.

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-215, 2019.