Reply to Reviewer 1

Dear Graham:

I have reviewed manuscript hess-2018-199, “Analysis of Groundwater Response to Oscillatory Pumping Test in Unconfined Aquifers: Consider the Effects of Initial Condition and Wellbore Storage" by Ching-Sheng Huanga, Ya-Hsin Tsai, Hund-Der Yeh and Tao Yang. The paper offers another analytical solution for simulating oscillatory pumping, which allegedly will make this a viable aquifer-testing approach. Oscillatory pumping is limited more by complicated field equipment when compared to slug tests. Results from oscillatory pumping would need to be significantly better than slug-test results for me to suffer the additional logistical burden. This paper, like several others, does not demonstrate an advantage of oscillatory pumping to functionally similar slug tests, so slug tests are compared to oscillatory pumping in this review and found superior. Hydrologists really do not need this paper or any others about oscillatory pumping.

Response: Over the past few decades, a considerable number of studies have been made on the oscillatory pumping test (OPT) (e.g., Black and Kipp, 1981; Cardiff et al., 2013; Dagan and Rabinovich, 2014; Rabinovich et al., 2015). The OPT has at least following two advantages (Bakhos et al., 2014) over the slug test:

(1) The hydraulic head is sensitive to external changes, such as changes in the level of rivers adjacent to the field area, pumping or irrigation near observation wells, tidal effect, barometric pressure, changes in overburden. Noise from these sources may affect results in a variety of ways (Spane and Mackley, 2011). Therefore, an important merit of OPT is the ability to extract the signal from a variety of different types of noise, even when the signal is much smaller than the level of noise, provided the duration of OPT is long enough.

(2) Pseudo-steady state models for OPT reduce computational cost as mentioned in the comment.

Oscillatory-pumping, aquifer tests have practical limitations such as small volumes of displaced water and complex methods of displacement. Small volumes clearly limit the volume of aquifer investigated, which practically limits the method to single-well tests. Small pumping volumes also significantly increase the uncertainty of flow across the well screen. This is because wellbore storage in the pumping well is similar to the volume of water pumped. Oscillatory pumping, like slug tests, remain sensitive to unknown entry losses from wellbore damage.

Response: We agree to the comment on the limitations of OPT. However, the OPT has its abovementioned advantages that traditional pumping tests cannot achieve. Oscillatory piston pumping test (OPPT) can significantly diminish wellbore storage effect as addressed by reviewer #2 so that the radius of influence from the pumping well can largely extend.

Oscillatory pumping and slug tests are investigated and compared with a two-dimensional, radial flow model of a shallow, unconfined aquifer that was simulated with MODFLOW (Harbaugh, 2005). The model extended vertically from 0 to 30 ft above the base of the aquifer, where the upper row of the model was the water table, and the 30-ft thickness was divided into uniform, 1-ft thick layers. Temporal changes in the saturated thickness of the aquifer were not simulated because the maximum drawdown near the water table was small relative to total thickness. The model grid was divided into 30 rows of 49 columns that were centered on the pumping well and extended away 37,500 ft. Horizontal hydraulic conductivities (Kx) of 0.1, 3, and 100 ft/d for the aquifer were simulated. Horizontal-to-vertical anisotropy, specific storage, and specific yield of 10 d’less, 2.E-6 1/ft, and 0.1 d’less, respectively, were assigned.

Oscillatory pumping from a 3-in diameter well in a 6-in borehole with wellbore storage and wellbore damage was simulated. Oscillatory pumping was approximated by 1-second stress periods during a 24-second cycle, where the peak flow rate was 0.92 gpm (5.8E-05 m^3/s). Twelve cycles were simulated and water-level changes from the last two cycles were presented (Figure 1KJH). The pumping well was simulated with the first column as 10 ft of cells with very high hydraulic conductivities, a specific yield of 1, and specific storages of 0. Gravel pack of the annular space between well screen and formation was simulated with the second column and extended from 5 to 10 ft below the water table. Hydraulic conductivity of the gravel pack (Kann) ranged from 0.1 ft/d for significant wellbore damage to 100 ft/d for a fully developed well.

Horizontal hydraulic conductivities between 1 and 300 ft/d could reasonably be estimated with oscillatory pumping. Water-level changes for Kx = 3 ft/d were best suited to analysis with the initial displacement largely dissipated and wellbore damage minimally affecting estimates (Figure 1KJH). Water-level changes for Kx = 100 ft/d were sensitive to wellbore damage, which causes Kx to be underestimated. Measurements of water-level changes approach inherent noise in a pumped well as Kx exceeds 300 ft/d. Slug tests are limited equally by wellbore damage and an upper threshold for estimating Kx. Water-level changes for Kx = 0.1 ft/d show a greater sensitivity to dissipating the initial displacement than amplitude of water-level changes. Amplitude was 0.31 ft for both Kx of 0.1 and 3 ft/d (Figure 1KJH), which suggests the oscillatory signal is insensitive to Kx < 1 ft/d. Slug tests are more appropriate for small hydraulic conductivities because recovery time is the limiting factor. About 100 minutes is the 90-% recovery time for a slug test in the example with Kx = 0.1 ft/d. Reasonable variations in well construction and peak pumping rates will not alter these conclusions.

Response: Our response to the comments is as follows:

(1) We presented not only transient solution considering the initial condition of static groundwater for OPT but also pseudo-steady sate solution assuming head fluctuation as a simple harmonic motion (SHM). The former solution is applicable to the case of K_x = 0.1 ft/d with significant initial displacement as discussed in section 3.1 of the manuscript. We believe the comment *"Amplitude was 0.31 ft for both Kx of 0.1 and 3 ft/d (Figure 1KJH), which suggests the oscillatory signal is insensitive to Kx < 1 ft/d."* is true for pseudo-steady sate models rather than transient models.

(2) A key advantage of OPT as mentioned above is its ability to extract the signal from a variety of different types of noise, even when the signal is much smaller than the level of noise, provided the duration of OPT is long enough (Bakhos et al., 2014). Despite such a finding, we agree to the difficult identification of water-level fluctuation for a large hydraulic conductivity because the practical duration of OPT is always limited.

Slug tests investigate significantly larger volumes of aquifer than oscillatory pumping (Figure 2KJH). An initial displacement of 3 ft (1.1 gallons in a 3-in well) simulated a slug test where Kx = 3 ft/d. Water levels were displaced at least 0.02 ft through the thickness of aquifer and about 50 ft away from the slug test. Maximum displacements greater than 0.01 ft from oscillatory pumping mapped where amplitudes exceeded 0.02 ft and were comparable to maximum extents for slug tests. Oscillatory pumping influenced about 2 percent of the aquifer that was influenced by a typical slug test (Figure 2KJH).

Response: We agree that for this case wellbore storage effect diminishes the radius of influence (RI) from the pumping well for OPT and the slug test induces a wider RI due to no wellbore storage effect. However, the OPPT is a good alternative because of using piston pumping to prevent the effect. If this case adopts the OPPT with 50-second cycle, the RI at which the amplitude is 0.02 ft extends to about 50 ft predicted by the present solution. The associated text is revised to accommodate the comment.

The need for oscillatory pumping as an aquifer-testing method seems limited, which has greatly dampened my enthusiasm for reviewing anymore articles about oscillatory pumping.

Sincerely, Keith J Halford

Response: The OPT has its advantages over other tests as mentioned above. The OPT was adopted for field experiments with success in the past. It may be a feasible alternative in the case that the field test condition is not favorable to other tests.

References

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Rabinovich, A., Barrash, W., Cardiff, M., Hochstetler, D., Bakhos, T., Dagan, G., and Kitanidis, P. K.: Frequency dependent hydraulic properties estimated from oscillatory pumping tests in an unconfined aquifer, J. Hydrol., 531, 2–16, 2015.

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Figures

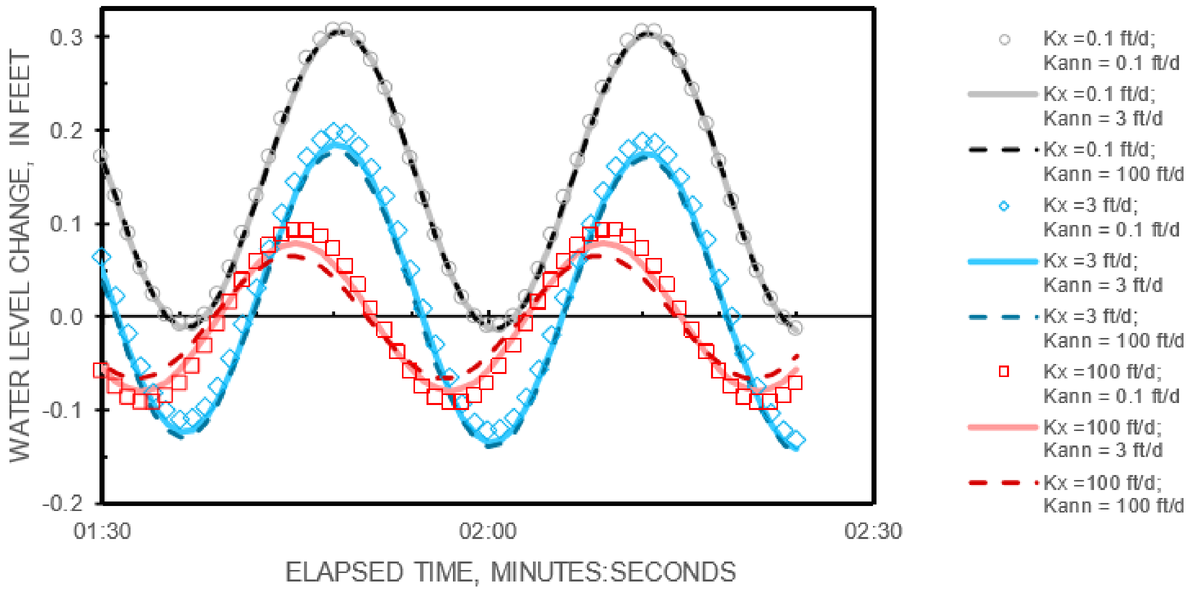

Figure 1KJH.—Water-level changes in an oscillatory pumping well for horizontal hydraulic conductivities (Kx) of 0.1, 3, and 100 ft/d and annular hydraulic conductivities (Kann) of 0.1, 3, and 100 ft/d.

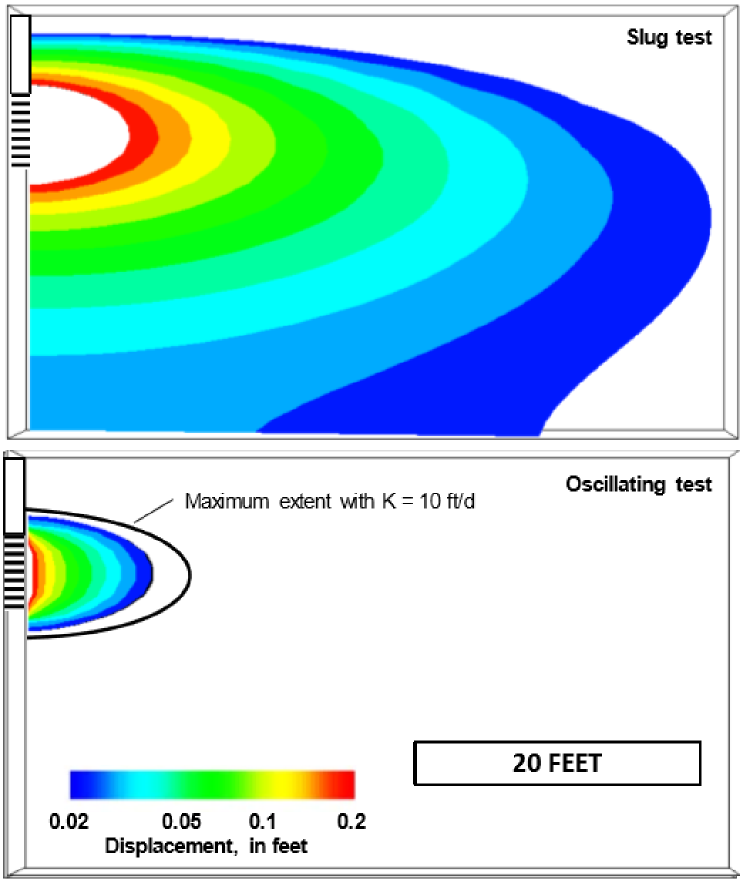

Figure 2KJH.—Maximum extent of water-level displacement from a slug test with 3 ft (1.1 gal) of initial displacement and oscillatory pumping with a peak rate of 0.92 gpm, where Kx = 3ft/d and Kann = 100 ft/d.