Reply to Reviewer 2

Review of: “Analysis of Groundwater Response to Oscillatory Pumping Test in Unconfined Aquifers: Consider the Effects of Initial Condition and Wellbore Storage” By Ching-Sheng Huang, Ya-Hsin Tsai, Hun-Der Yeh, and Tao Yang

Review by: Michael Cardiff

This paper is not acceptable in its present format for at least a few reasons. My primary reason is this: the authors have claimed to have used data from oscillatory pumping tests (data collected at the Boise Hydrogeophysical Research Site (BHRS), by myself and colleagues). Looking at the data they claim to fit, I can guarantee it is not raw data from any of the tests we collected. As far as I am aware, the authors of this paper did not contact any of the primary collectors of this data in an effort to understand it, nor did they apply an analysis strategy that is appropriate. Publishing data that is suspect under the name of the workers from the BHRS (and using a flawed analysis to do so) negatively impacts those who have worked so hard to collect the high quality data available from this site.

Response: One of the authors, Ya-Hsin Tsai (email: yahsinamlaiy4433@gmail.com), did ask four authors of Rabinovich et al. (2015) including the reviewer by email for the BHRS data. The first email was sent on 2016/10/26 to Avinoam Rabinovich (avinoam_r@yahoo.com) who suggested us asking Warren Barrash (wbarrash@cgiss.boisestate.edu). We then sent emails to Warren Barrash on the same date, Michael Cardiff (cardiff@wisc.edu) on 2016/12/09, and Tania Bakhos (tbakhos@bcamath.org) on 2016/12/09, but unfortunately did not receive any response from them. Until now we still keep the letters of those emails.

The data presented in Fig. 8 of our paper was read from Fig. 4(a) of Rabinovich et al. (2015) using the Grapher digitize function. We will appreciate it if the raw data can be provided from one of the authors and let us redo the analysis.

The current paper claims to develop a novel method for analyzing fully-penetrating oscillatory tests in which wellbore storage and the water table are taken into account. Applying this model to our data from the BHRS is completely nonsensical because: 1) While the wellbore we pumped from was indeed fully penetrating, the wellbore was packed off above and below our “oscillation zone”, meaning that only a 1m interval (partially penetrating) zone served as the pumping interval. This does not fit with the model that has been developed in this paper; also 2) There is no need to consider wellbore storage for the tests performed at Boise because we used a piston to generate the signal within the well (i.e., the oscillating zone was under confined conditions, and we forced water into / out of the formation via piston). For both these reasons, the model the authors have developed is inappropriate for analyzing our data. The authors may have found this out earlier had they bothered to contact any of the field workers who spent such time and effort collecting this data.

Response: Thanks for the comment on the use of partially packed screen. The inner boundary condition describing flux across the screen of a fully penetrating well is therefore changed to

$$2\pi r_w K_r l \frac{\partial h}{\partial r} - \pi r_c^2 \frac{\partial h}{\partial t} = \begin{cases} Q\sin(\omega t) & \text{for } \ z_l \le z \le z_u \\ 0 & \text{outside screen interval} \end{cases} \quad \text{at} \quad r{=}r_w \qquad \text{(R1)}$$

where h is hydraulic head, r is radial distance from the centerline of the pumping well, z is elevation, t is time, K_r is radial hydraulic conductivity, r_c and r_w are respectively inner and outer radiuses of the well, z_l and z_u are respectively lower and upper elevations of screen interval, and $l = z_u - z_l$ is screen length. Eq. (R1) considers the well radius and avoids using the assumption of infinitesimal radius as adopted in some articles (e.g., Black and Kipp, 1981; Rasmussen et al., 2003; Dagan and Rabinovich, 2014). A new solution applicable to a well with partial penetration based on Eq. (R1) is presented in the revised manuscript. This new solution can reduce to the special case of no wellbore effect if letting $r_c = 0$. We add a new section in the revised manuscript to present the special case and others for different scenarios.

We agree that the wellbore storage effect might be very small and negligible in the oscillatory piston pumping test (OPPT). The aim of our work, however, is to present a general analytical solution for the cases with various types of oscillatory pumping test (OPT) including the OPPT. Curve fitting to the data will be reconducted using the present solution with and without considering the wellbore storage effect. The associated text will be rewritten to accommodate all the comments.

With regards to the scientific merit / value of the model itself – I also question whether this model is necessary or useful, and whether it is being considered for reasonable ranges of the given parameters. Consider Figure 5 – Figure 5(b) shows somewhat of a difference from the Dagan and Rabinovich solution at a distance of $\bar{r}$ = 16. Given the non-dimensionalization used, this means it is at a distance of 16 well radii. A standard well radius is about 5 cm, meaning that this effect is being observed only at a distance of less than 0.8m from the pumping location. I have never in my life seen wells spaced 80cm apart. A very big well might be 20 cm, for which the effect would apparently decay after only 3.2m.

Response: The difference in the hydraulic heads predicted by our solution and the Dagan and Rabinovich solution in Fig. 5(b) is arisen from the assumption of infinitesimal radius. The difference is negligible if the distance r from the pumping well to the observation well exceeds 16 times radius r_w of the pumping well. (i.e., $r/r_w \geq 16$). We believe the finding of $r/r_w \geq 16$ can serve as a useful criterion for those who can be aware of the deviation in the results when applying finite difference scheme that treats a pumping well as a nodal point with infinitesimal radius. On the other hand, large-diameter wells with radius ranging from 0.5 m to 2 m are commonly installed in many countries to meet a large demand for domestic and irrigation water uses (Yeh and Chang, 2013). With considering a large-diameter well as a pumping well, the well distance should exceed 8 m for r_w = 0.5 m and 32 m for the extreme case of r_w = 2 m.

The authors seem to have chosen parameters that are unrealistic for most aquifers. For example, they use a specific yield value of S_y = 0.1. Specific yield values in aquifer pumping tests have almost never been measured to be this high (due to delayed drainage), and in the special case of oscillator tests where saturation changes rapidly, it is unlikely even partial drainage will occur. Similarly, many of the other choices in the plots are suspect. Looking at the definition of $\alpha = \frac{r_c^2}{2r_w^2 S_s b}$, for example, I find it hard to understand why the authors have focused on cases such as α = 1 and below in Figure 5. Given that Ss is generally in the range of $10^{-5}m^{-1}$ to $10^{-6}m^{-1}$ for any natural material, and that reasonable aquifers may be 10-1000m thick, can one imagine any realistic solutions where α < 1?

Response: Thanks for the comment on the magnitude of specific yield S_y. Freeze and Cherry (1979, p. 61) mentioned that the usual range of S_y is 0.01 – 0.3. Todd and May (2005, p. 51) provided a table showing representative specific yields ranging from 0.06 to 0.44 for various geologic materials. With $S_y = 10^{-4}$, the program for the present solution is rerun; all the figures are replotted; some discussions are revised. Regarding the magnitude of α, exploring how wellbore storage affects head fluctuation due to OPT was recommended by Prof. John L. Wilson, a 2006 AGU fellow, at 2014 AGU Fall Meeting. The finding is that wellbore storage effect can be ignored for $\alpha \le 10^{-1}$ and is significant for the practical range of α > 1. We believe the finding herein is useful for both OPPT without the wellbore storage effect and other types of OPT which might be subject to significant wellbore storage effect. The associated text is rewritten to accommodate the viewpoint above.

It is also notable that in Figure 8, the confined solution appears to fit the data perfectly well (using the same K and Ss parameters as the unconfined solution, if I am reading correctly) almost exactly as well as the more complex model. This would indicate to me that the details considered in this more complex model matter not one bit, and the water table can simply be considered as a no-flux boundary practically in these tests.

Response: The case of confined flow for curve fitting in Fig. 8 has been removed for avoiding confusion that the water table can be regarded as no-flow boundary. The associated text will be rewritten to accommodate all the comments.

Similarly, Figure 5(a) represents head at the edge of the wellbore itself, which is unlikely to be used in real field scenarios because measurements at the pumping location are subject to numerous nuisance factors (for example, wellbore "skin", non-darcian flow conditions near the wellbore, inertial effects, etc. So I see no practical reason to consider the variability in this result.

Response: We would like to mention that the radius of the pumping well is not negligible in spite of no wellbore storage effect as indicated in the figure when the head is measured at the rim of the well. Literature review reveals there are many scenarios where time-depending head data were measured at the rim of a pumping well (e.g., Pacheco, 2002; Mohamed and Rushton, 2006; Rabinovich et al., 2015).

While it is mathematically interesting to derive new PDE solutions, I fail to see the practical application of these much more complex solutions, given that they are still invoking many assumptions / approximations. For example, the authors do not deal with the fact that they are using only an approximation for the water table response (the linearized free surface condition of Neumann), and that realistically oscillatory tests are likely to be subject to delayed drainage and differing yields as a function of frequency. For all of these reasons I cannot recommend that this paper be published.

Response: The manuscript is largely revised for accommodating the comments above. A more general analytical solution of hydraulic head for OPT is derived when the original inner boundary condition is replaced by Eq. (R1) and the linearized free surface equation is replaced by

$$K_z \frac{\partial h}{\partial z} = -\varepsilon\, S_y \int_0^t \frac{\partial h}{\partial t'} \exp(-\varepsilon(t - t'))\, \mathrm{d}t' \quad \text{at} \quad z = b \tag{R2}$$

where K_z is vertical aquifer hydraulic conductivity, b is aquifer thickness, ε is an empirical constant, and the term on the right-hand side accounts for the effect of delayed gravity drainage (Moench, 1995). New results are discussed and new conclusions are drawn based on the new solution. To conclude our new results, our solution has the following advantages:

(1) The new transient or pseudo-steady sate solution can reduce to seven special cases classified according to aquifer type (i.e., confined or unconfined), well penetration (i.e., full or partial), and with or without wellbore storage effect.

(2) It can be a handy tool to design the OPT or to estimate hydraulic parameters when coupled with an optimization approach because of its simplicity and considerations of well radius, wellbore storage and delayed yield.

(3) It can find a transient head directly at any time *t*. With a small time step for obtaining accurate results, numerical methods such as finite difference and finite element methods should compute the heads at each time step until reaching the end of timeframe, leading to a large amount of computing time.

(4) It allows us to find a head solution at any specific location (*r*, *z*) without going through the entire marching process of finding heads at all nodal points, as one does in finding the numerical solutions using the finite difference or finite element method.

(5) It is stable, efficient, and easier to implement in solution evaluations.

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