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NO.1839

An Investigation on the Reciprocity Theory with In-Situ Test at The Heterogeneous Saturated Soil

Abstract

In this study, the pumping test of reciprocity between wells is developed for 11 wells located on campus of NYUST. The reciprocity analysis is conducted with the heterogeneous hydrogeological parameters distributions of the site. The mathematical theory of reciprocity implies that choose one as stimulation point and the other as observed response point in two known points at the same random field. Repeat the above action, the response behavior should have the reciprocity between the two points. However, the lack of literature with the in-situ experiment to prove that reciprocity principle. Therefore, this study is expected to investigate the reciprocity of drawdown with the sequential pumping test which will have heterogeneous hydrogeological parameters distributions obtained by inverse method. In general, there are two ways to investigate the reciprocity of pumping tests of two sequential wells. One way is to evaluate the drawdown reciprocity of two sequential wells. From the evaluation the reciprocity of the drawdown behavior during the sequential pumping wells, the reciprocity of the drawdown behavior is investigated. The other one is to estimate cross-correlation between the drawdown behavior of the sequential pumping wells and heterogeneous hydrogeological parameters distributions. The reciprocity of between the drawdown and the heterogeneous parameters distributions is therefore can be investigated. This study proved the reciprocity of drawdown with the sequential pumping test and heterogeneous hydrogeological parameters distributions obtained by inverse method. Meanwhile, we proved the reciprocity is existed during the pumping test in the aquifer.

Keywords: *Stimulation, Response, Reciprocity, Cross-correlation*

Study Motivation

Bruggeman [1972], Hariga et al. [2010], and Delay et al. [2011, 2012] proved the reciprocity exists between pumping well and observation well by mathematical in unconfined Aquifer. No study proves the reciprocity exists at field studies in a confined aquifers.

Study Purpose

Using field data prove the reciprocity of pressure head(h) between any two well sets. Viewing the reciprocity whether exists in the distributions of correlation between the heterogeneous hydrogeological parameters and h from any two well sets during pumping test in a confined aquifers.

Description of the Field Site

1. Area about 100 m2
2. 11 boreholes (BH01 through BH11)
3. Confined Aquifer
4. A detailed description of the field site and geology is given in Wen et al. [2010]

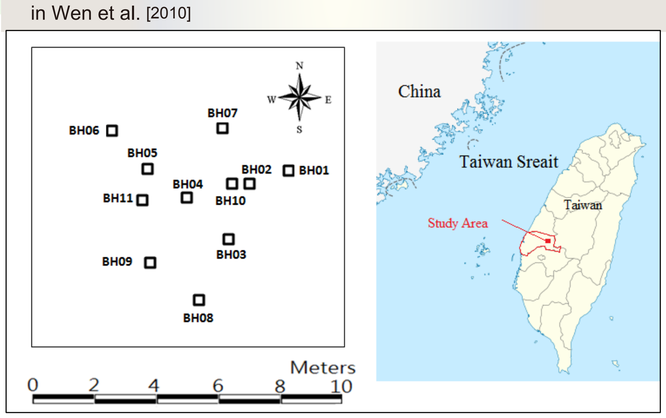

Fig 1. Well locations on campus site of NYUST.

Reciprocity Pumping Test

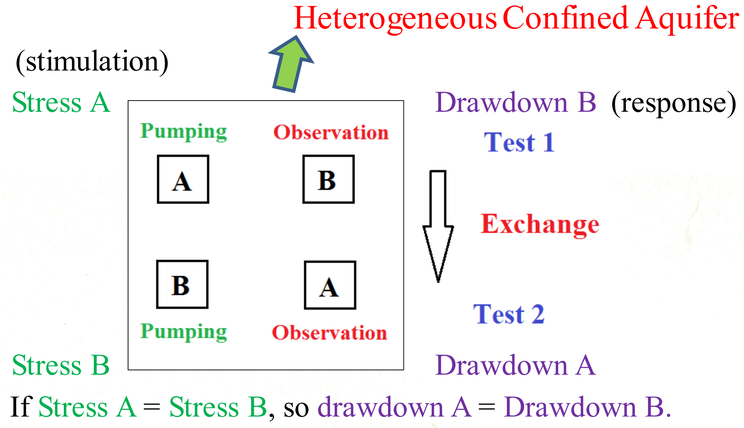

Fig 2. Reciprocity conceptual diagram.

Reciprocity of Observed Drawdowns during Pumping Test at Field Site

The equation (1) from Delay et al. [2011] used in viewing the reciprocity of drawdown during pumping test in unconfined Aquifer.

$$\frac{h^2(0)-h^2_{A,B}(t)}{Q_B}=\frac{h^2(0)-h^2_{B,A}(t)}{Q_A} \quad \cdots\cdots (1)$$

The equation (1) from Delay et al. [2011] used in viewing the reciprocity of drawdown during pumping test in unconfined Aquifer. According Bear [1979] mentioned the characteristic of h of continuous equation is linear in a confined aquifers. Therefore, we defined the equation (2) viewing the reciprocity of h from pumping test in heterogeneous confined aquifer whether exist. If left side equal right side from equation (2), we can decide the reciprocity is exist.

$$s_{A,B}(t)=h(0)-h_{A,B}(t) \qquad s^*_{A,B}(t)=\frac{s_{A,B}(t)}{Q_B}, s^*_{B,A}(t)=\frac{s_{B,A}(t)}{Q_A}(A,B=1,2,3,...,11)$$

$$s^*_{A,B}(t)=s^*_{B,A}(t) \quad \cdots\cdots (2)$$

Where $h_{A,B}(t)$ is the pressure head at location A while pumping in B, and $h_{A,B}(t)$ is the pressure head at location B while pumping in A, and $h(0)$ being the initial head, and is drawdown.

Cross-correlation Analysis with Numerical Simulation

The total 110 distributions of heterogeneous hydrogeological parameters (Transmissivity (T) and Storativity (S)) were inversed with unsteady h from 11 pumping tests by Transient Hydraulic Tomography (THT). The flowchart as Fig 3.

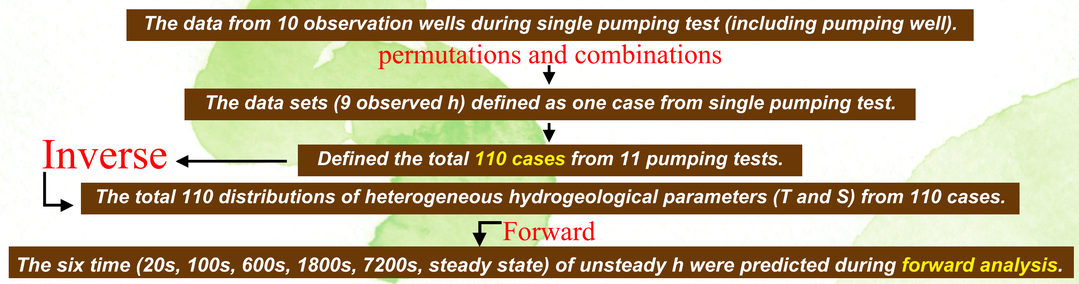

Fig 3. Flowchart for numerical simulation.

All predicted h and the hydrogeological parameters (T and S) used in cross-correlation analysis, we call the result are $\rho_{h,T}$ and $\rho_{h,S}$. The distribution of hydrogeological parameters are 441 grids (21 m × 21 m) in 2-D hydrogeological modeling (as Fig 4 shown). We choose the predicted h of observation well BH05 at same time with pumping well BH04 from 110 cases during forward analysis. Then, the correlation coefficient is calculated with the 110 predicted h of observation well BH05 at same time and the 110 hydrogeological parameters value of each grid. Therefore, the contour map were produced by correlation coefficients of 441 grid.

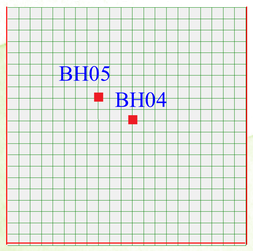

Fig 4. The 2-D hydrogeological modeling.(Total 441 grids)

Reciprocity of two wells

The results of reciprocity is exist, but the reciprocity not hold in BH02, BH04, and BH10 are shown in Fig.5.

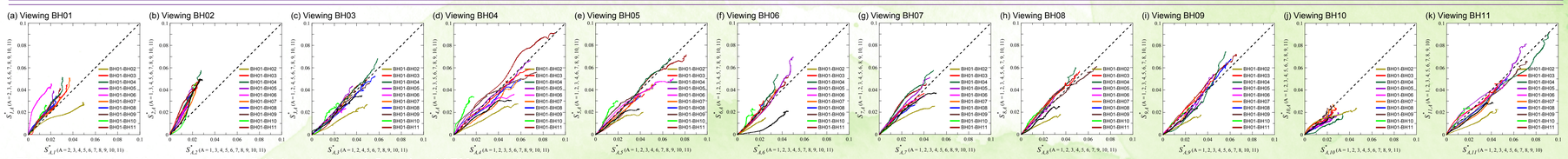

Fig 5. Comparison of the reciprocity from field data. (note: each figure has 14,700 data set)

Cross-correlation h and T, $\rho_{h,T}$

1. Viewing the correlation of $\rho_{h,T}$ between BH04 and BH05.
2. The results of correlation between the predicted h and T field are lower at early time as Fig 6(a)-1, (b)-1, (a)-2, and (b)-2 shown.
3. The statistic errors are lower at early time, but it became higher at medium time as Fig 6(c)-3.
4. The results of correlation between the predicted h and T field are higher at medium time and late time as Fig 6 (d)-1,(e)-1, (f)-1, (d)-2, (e)-2, and (f)-2 shown.
5. The statistic error reach steady state at late time as Fig 6(f)-3.
6. The result suggest that the same pattern between Fig 6(a)-1 to (f)-1 and Fig 6(a)-2 to (f)-2, it means have the reciprocity exists at the field site.

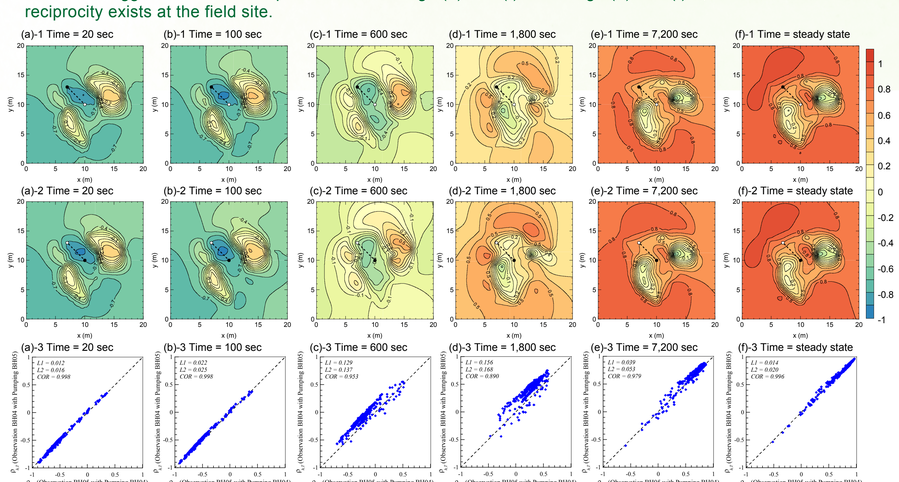

Fig 6. The results of the cross-correlations between the predicted h and T field at time = (a) 20 (b) 100 (c) 600 (d) 1,800 (e) 7,200 (f) steady state (1. Pumping BH04; 2. Pumping BH05; 3. 45 degree line diagram).

Cross-correlation h and S, $\rho_{h,S}$

1. Viewing the correlation of $\rho_{h,S}$ between BH04 and BH05.
2. The results of correlation between the predicted h and S field are lower at early time as Fig 7(a)-1, (b)-1, (a)-2, and (b)-2 shown.
3. The statistic errors are average distribution at early time, but it became higher at medium time as Fig 7(c)-3.
4. The results of correlation between the predicted h and S field are higher at 1,800 sec as Fig 7(d) shown, but became lower at late time as Fig 7(e)-1, (f), (e)-2 and (f)-2 shown.
5. The statistic error reach steady state at 1,800 sec as Fig 7(f)-3.
6. The result suggest that the same pattern between Fig 7(a)-1 to (f)-1 and Fig 6(a)-2 to (f)-2, it means have the reciprocity still exists at the field site.

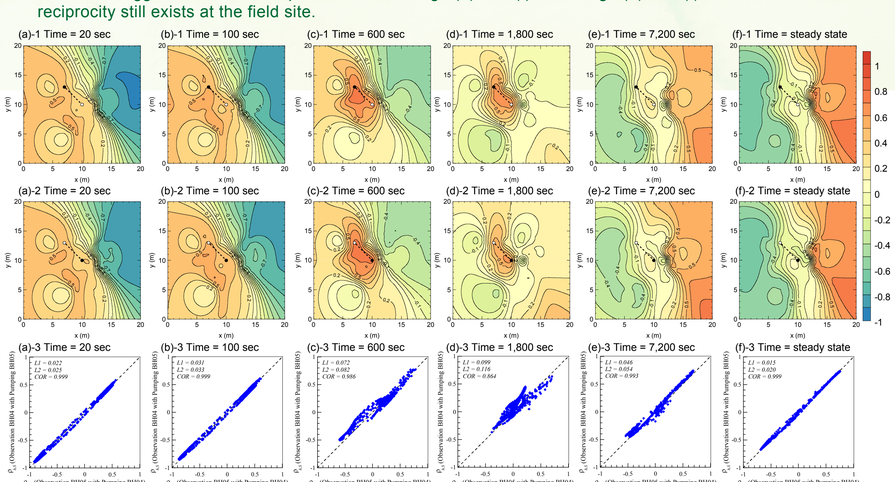

Fig 7. The results of the cross-correlations between the predicted h and S field at time = (a) 20 (b) 100 (c) 600 (d) 1,800 (e) 7,200 (f) steady state (1. Pumping BH04; 2. Pumping BH05; 3. 45 degree line diagram).

Acknowledgements

The authors express gratitude to the Ministry of Science and Technology for the funding through grants **NSC 102-2221-E-224 -050.**

Conclusion

In this study, we have confirmed,

1. The reciprocity exist during the pumping test in a confined aquifers.
2. The reciprocity exists between the heterogeneous hydrogeological parameters and pressure head by Cross-correlation analysis in a confined aquifers.
3. Furthermore, we can utilize the field data to prove the reproducibility of reciprocity.