A Simple Data Analysis Method for a Pumping Test with the Skin and Wellbore Storage Effects

Reporter: Chuan-Gui Lan

Professor: Chia-Shyun Chen

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Introduction

• The pumping test is commonly conducted using a pumping well and at least one nearby observation well.

• Analyzing the time-drawdown variation in the observation well $h(r,t)$ with an appropriate well hydraulics model allows the evaluation of the relevant aquifer parameters; transmissivity $T$ and the storage coefficient $S$. 
Theis [1935] model

• For a confined homogeneous and isotropic aquifer,

\[ h(r,t) = \frac{Q}{4\pi T} W \left( \frac{r^2 S}{4Tt} \right) \]

• The radii of the pumping well, \( r_w \), and the observation well, \( r_o \), are not involved because they are assumed to be infinitesimally small.
Wellbore storage effect, $\alpha_w$

- In the pumping well, wellbore storage may take place at early times when water withdrawn is not derived from the surrounding aquifer materials but from the water volume originally stored in the well casing [Papadopulos and Cooper, 1967].

- When it occurs, the early-time drawdown data from the pumping well, $h_w(t)$, is characteristic of a 45° straight line on a logarithmic plot [Streltsova, 1988; Papadopulos and Cooper, 1967; Fenske, 1977].
Skin effect, $s_k$

- The skin effect is caused by drilling mud invasion into surrounding formations and creates a damaged zone of reduced permeability surrounding the borehole.

- This damaged zone induces an extra head loss to the groundwater flow.

- The skin effect is proportional to the groundwater velocity across the wellbore surface.

- The larger the $s_k$ is the more head loss is.
[Chen and Chang, 2006]
Both skin and wellbore storage effect

- Such a combined effect can influence drawdown variation in nearby observation wells [Agarwal et al., 1970; Chu et al., 1980; Park and Zhan, 2002 and 2003; Chen and Chang, 2006].

- Neglecting it could result in serious overestimate of $S$ and underestimate of $T$ [Agarwal et al., 1970; Jargon, 1976].
The drawdown solution of the pumping well

- For a confined, homogeneous and isotropic aquifer, the dimensionless drawdown solution of a fully penetrating pumping well subject to both wellbore storage and well skin is [Agarwal et al., 1970; Kabala, 2001]

\[
h_{wD}(\tau) = L^{-1} \left\{ \frac{K_0(\sqrt{p}) + S_k \sqrt{p} K_1(\sqrt{p})}{p\left\{ \frac{p}{2\alpha_w} \left[ K_0(\sqrt{p}) + S_k \sqrt{p} K_1(\sqrt{p}) \right] + \sqrt{p} K_1(\sqrt{p}) \right\}} \right\}
\]

where \( \alpha_w = S(r_w/r_{wc})^2 \) the wellbore storage coefficient of the pumping well
The drawdown solution of the observation well

- The drawdown in the observation well is subject to wellbore storage of its own as well as the combined effect of well skin and wellbore storage in the nearby pumping well [Moench, 1997]

\[
h_{oD}(\rho, \tau) = L^{-1} \left\{ \frac{K_0(\rho \sqrt{p})/[1 + W_D p]}{p\left\{ \frac{p}{2\alpha_w} [K_0(\sqrt{p}) + S_\kappa \sqrt{p K_1(\sqrt{p})}] + \sqrt{p K_1(\sqrt{p})} \right\}} \right\}
\]

where \( W_D = 2.65 (r_{oc}^2/r_w^2 S) \) is a dimensionless coefficient reflecting the wellbore storage effect of the observation well.
5 unknown \textit{a priori} parameters

• T, S, S_k, W_D, and \( \alpha_w \).

• How to estimate them?

• Using a trial-and-error procedure!!! X

• Graphic method. ✓
The pumping test

- Located from 70 m to 94 m below the ground surface \((b = 24 \text{ m})\), this aquifer comprises very fine sand and silt from 70 m to 86 m and fine sand with traces of silty mud from 90 m to 94 m.

- \(r_w = r_{wc} = 7.62 \text{ cm}\)

- \(r_o = r_{oc} = 7.62 \text{ cm}\)

- \(r = 4.65 \text{ m}\)

- \(Q = 87 \text{ L/min and run } 1,277 \text{ minutes}\)
The occurrence of wellbore storage in the pumping well

Only the late-time data of $h(r, t)$ are to match with the Theis curve. Thus the Cooper-Jacob [1946] method is appropriate for the determination of $T$ and $S$. 
semi-logarithmic plot

- O: field data of $h_w(t)$
- ▽: field data of $h(r,t)$

- $h_w(1) = 2.26$ m
- $\Delta s_w = 0.35$ m
- $t_v = 0.0342$ min
- $\Delta s = 0.323$ m
The Cooper-Jacob [1946] method

- Transmissivity

\[ T = \frac{0.183Q}{\Delta s} = 4.93 \times 10^{-2} \text{ m}^2 / \text{min} \]

\[ K = \frac{T}{b} = 1.9 \times 10^{-3} \text{ m/min}, \text{ which corresponds to } K \text{ of very sandy silt [Schwartz and Zhang, 2003; p.79].} \]

- Storage coefficient

\[ S = \frac{2.25Tt_0}{\mu^2} = 1.76 \times 10^{-4} \]

The estimate of S is in the typical range of \( 10^{-5} \leq S \leq 10^{-3} \) for unconsolidated materials [e.g., Schwartz and Zhang, 2003].
Determine $\alpha_w$ and $W_D$

- Once $S$ is known,

\[
\alpha_w = S\left(\frac{r_w}{r_{wc}}\right)^2 = 1.76 \times 10^{-4}
\]

\[
W_D = 2.65\left(\frac{r_{oc}^2}{r_w^2S}\right) = 1.51 \times 10^4
\]
semilogarithmic plot

- $h_w(1) = 2.26$m
- $t_0 = 0.0342$ min
- $\Delta s = 0.323$m
- $\Delta s_w = 0.35$m
Determine $S_k$

- Streltsova [1988] gives a graphic method for the determination of $S_k$ using the late-time drawdown data of $h_w(t)$ as

$$S_k = 1.1513 \left[ \frac{h_w(1)}{\Delta s_w} - \log \frac{2.246 T_w}{S r_w^2} \right] = 1.68$$
Method Validation

\[ T = 4.93 \times 10^{-2} \text{ m}^2/\text{min} \]
\[ S = \alpha_w = 1.76 \times 10^{-4} \]
\[ W_D = 1.51 \times 10^4 \]
\[ T_w = 4.55 \times 10^{-2} \text{ m}^2/\text{min} \]
\[ S_k = 1.68 \]
Conclusion

• A simple data analysis method is developed, which takes advantage of the late-time characteristics of drawdown data and the late-time asymptotic behavior of the appropriate well hydraulics solutions.

• In order to apply this simple data analysis method, the pumping test should run long enough such that $h_w(t)$ and $h(r,t)$ can fully develop into straight lines on the semi-logarithmic plot.

• In this regard, it worthy mentioning that “cutting the pumping duration short for the economic reason is not justifiable because the cost of running the pumping test a few extra hours is low compared with the total costs of the test [Kruseman and de Ridder, 1991]”.

Work to be down

- 21 hr pumping test
- 24 hr pumping test

\[ T = 4.9 \times 10^{-2} \text{ (m}^2\text{/min)}, S = \alpha_w = 1.744 \times 10^{-4} \]
\[ S_{k21} = 2.35, S_{k24} = 2.82 \]
\[ S_{k21} = S_{k24} = 0 \]
Thanks