Assessing the Impact of Bentonite-CMC Drill-In Fluids on Slug Tests in High-Permeability Aquifers

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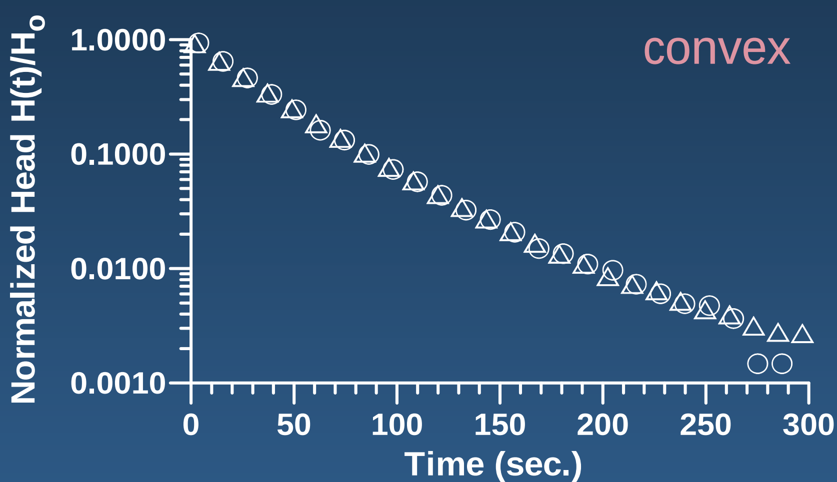
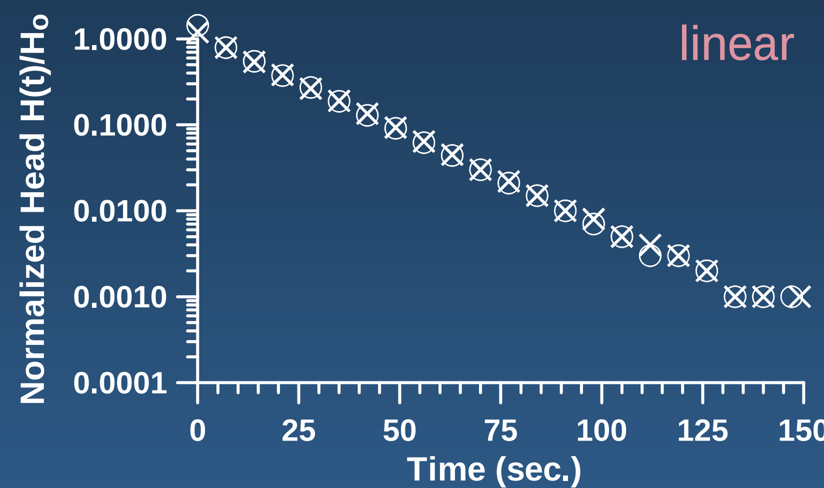
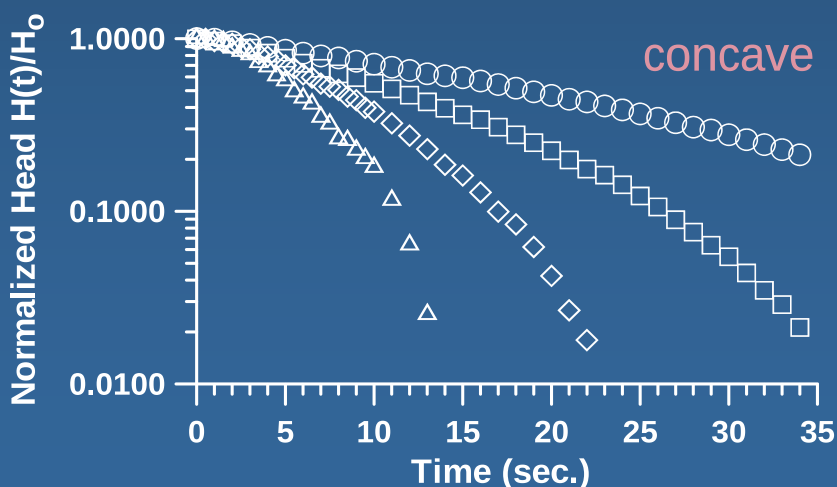
- What do overdamped slug tests tell us about?
  About Aquifer Parameters or about Flow Processes?
- Classical Hvorslev-Style Slug Test Analysis for Well 7354
- Well Performance Testing at Well 7354
- Slug Test Analyses Acknowledging Formation Damage
- Summary

What do overdamped slug tests tell us about?





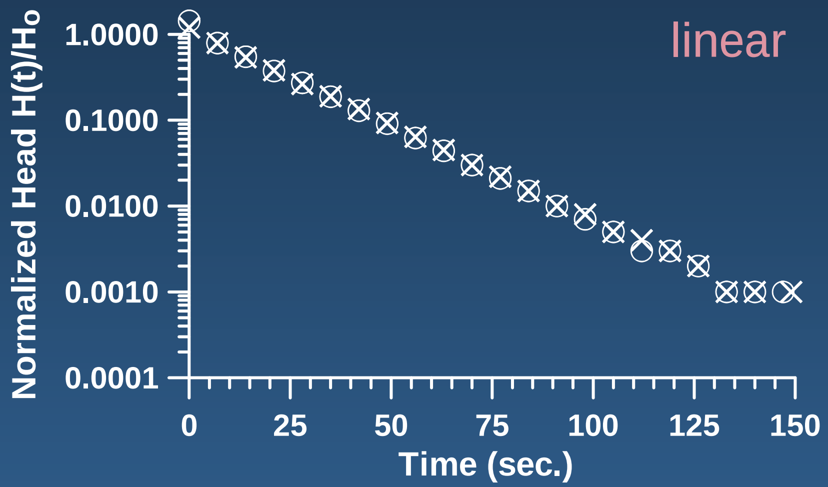


Subsequently, this characteristic is looked at in more detail.

Classical Hvorslev-Style Slug Test Analysis for Well 7354

The Classical Model of Hvorslev (1951)

$$H(t) = H_0 \cdot e^{\left(-\pi r_c^2 \, t / F k_r\right)}$$



- The head response is exponentially decaying in time (head data shown are from direct-mud rotary drilled well 7354, Berlin).
- The aquifer hydraulic conductivity is determined from the slope of a semi-logarithmic Hvorslev-style plot.

Classical Hvorslev-Style Slug Test Analysis for Well 7354

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A Hvorslev-Style Analysis Yields:

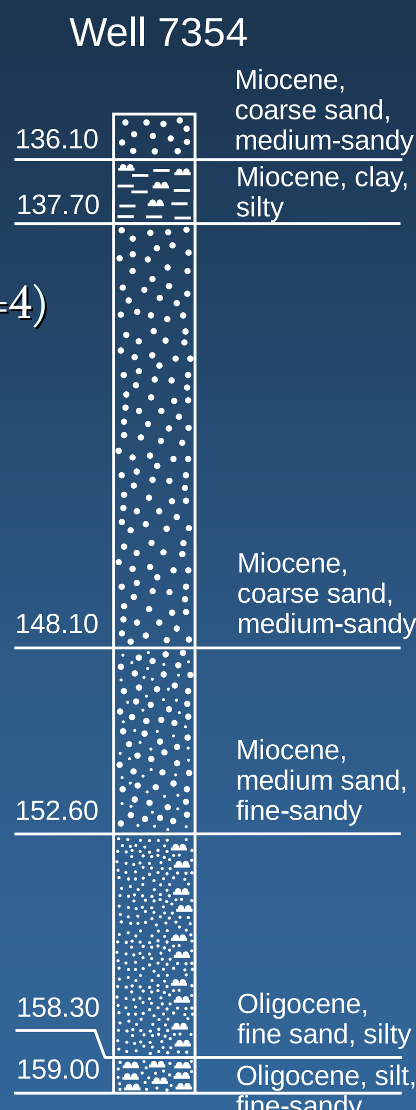
-> $k_r = 9.3 \cdot 10^{-5}$ m/sec.
(Hvorslev's case no. 8 with B=4.0 m, k_r/k_z=4)

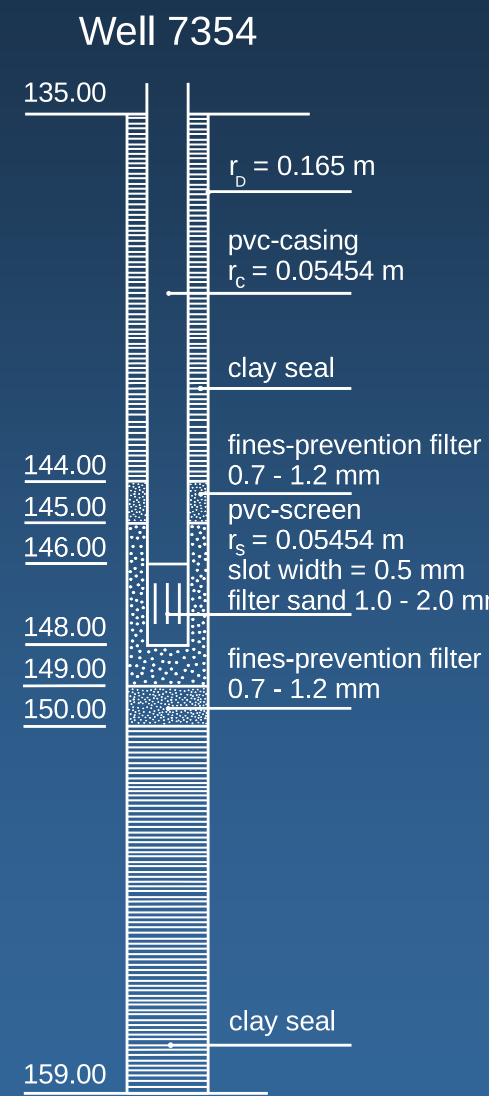
-> $k_r = 2.7 \cdot 10^{-5}$ m/sec.
(Hvorslev's case no. 9 with M=B=14.9 m)

-> The hydraulic conductivity is too small for coarse/medium sand!

-> Is there a better way of analyzing the data?

-> Let's look at skin effects first!





Well Performance Testing at Well 7354

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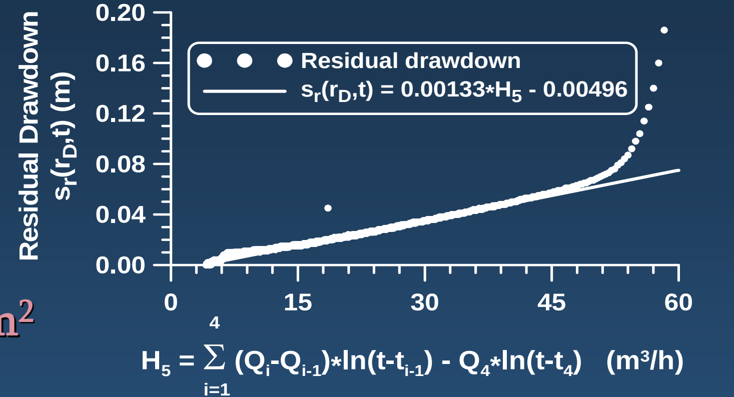
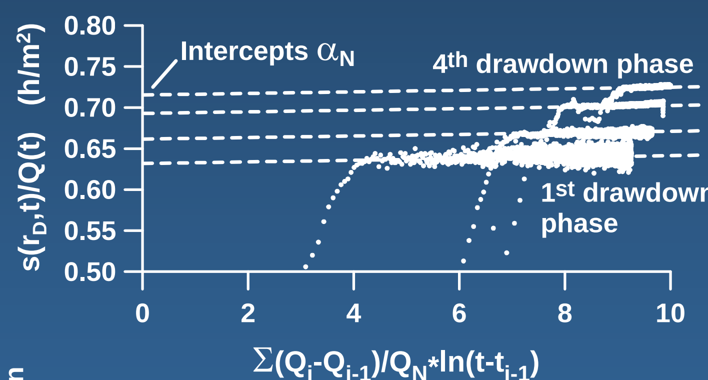
A Well Performance Test Analysis Yields:

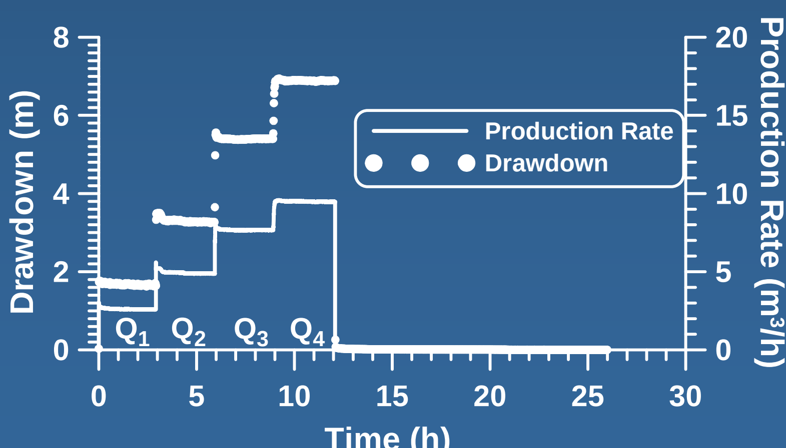
-> k_r = 1.14*10^{-3} m/sec. (assumed: k_r/k_z=4, S = 2*10^{-4})
(from superposition recovery plot)

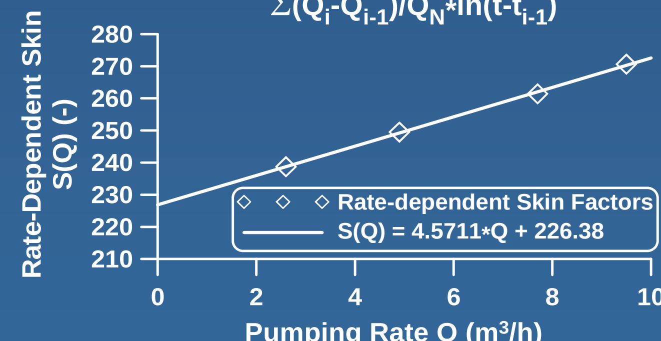
-> Estimated linear well loss coefficient: B_2 = 2119 sec./m^2
Respective mechanical skin factor: S_w = 58.6
(from superposition drawdown plot)

-> The bentonite-cmc drill-in fluid in conjunction with the employed direct-mud rotary drilling technique has likely caused this formation damage

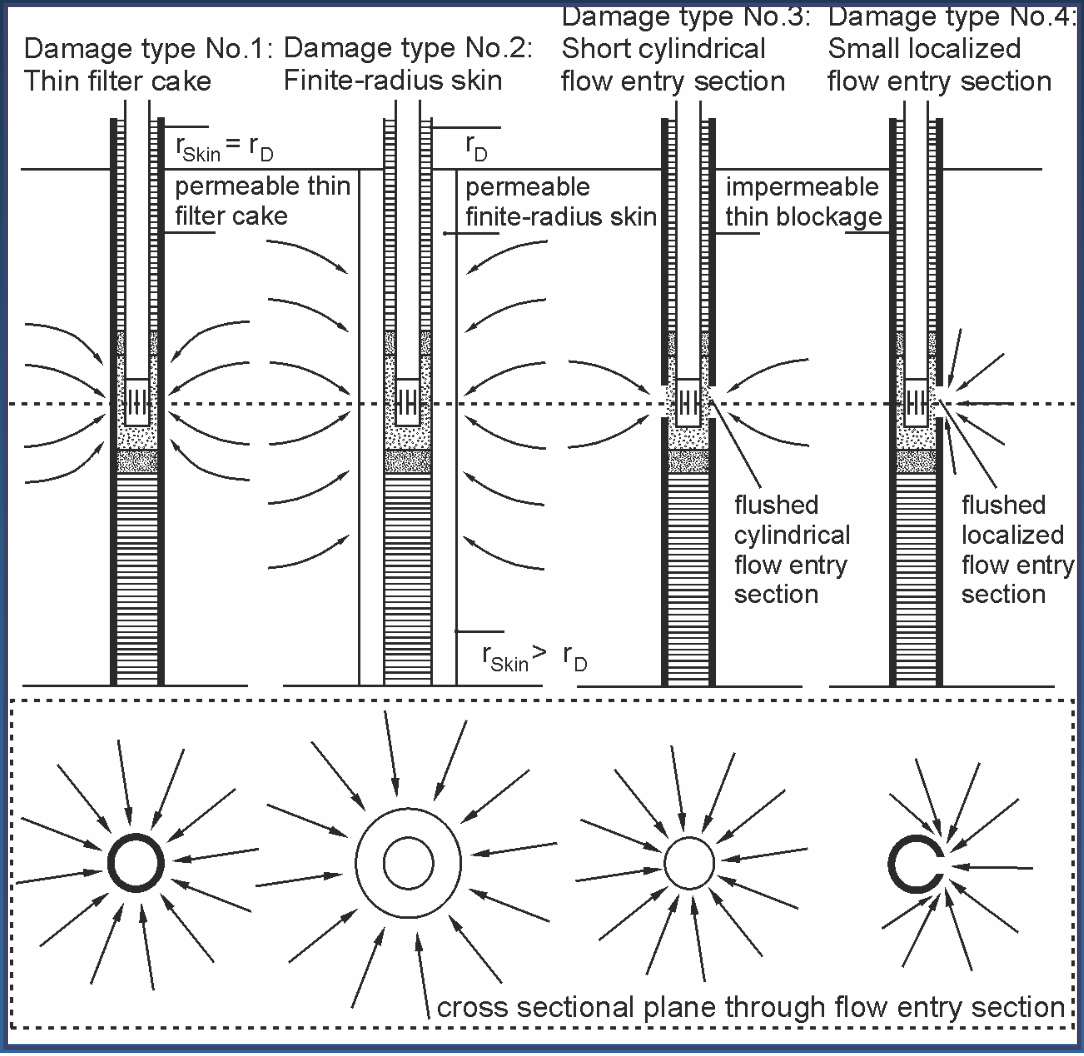








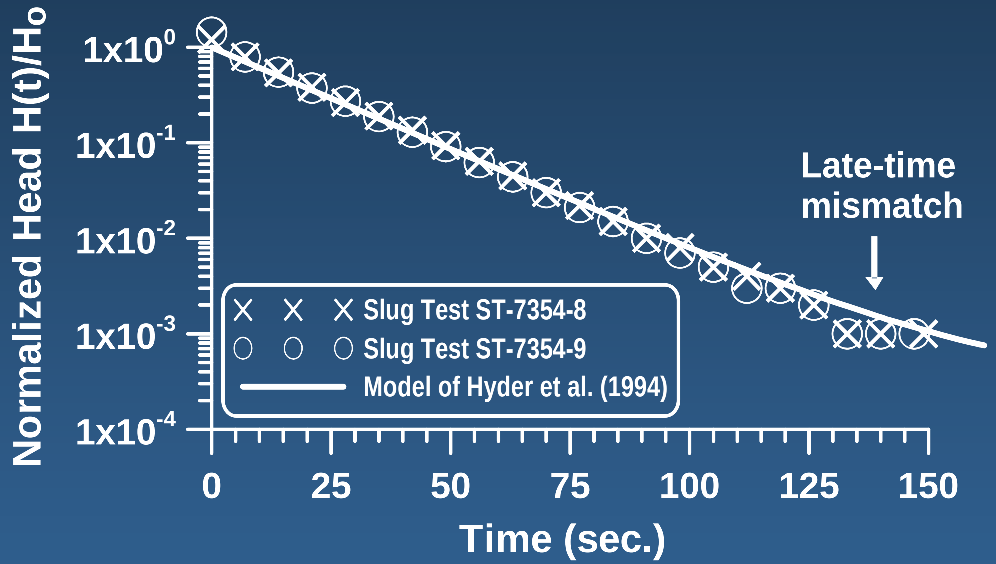
Conceptualization of Formation Damage for Slug Test Analysis



- Damage types #1, #2, and #3 represent cylindrically convergent flow.
- Damage type #4 represents spherically convergent flow.

-> Can the hydraulic parameters from well performance testing be used to verify formation damage by slug test analyses?

Radial Flow Model of Hyder et al. (1994)



- Assuming $k_r = 1.14 {*} 10^{-3}$ m/sec., $k_r/k_z=4$, and $S = 2{*}10^{-4}$ simulations of slug tests can be made to collapse onto the shown response curve for damage types #1, #2, and #3 using realistic skin permeabilities, respectively!

-> Can the slight late-time misfit be removed by application of alternate models?

Slug Test Analyses Acknowledging Formation Damage

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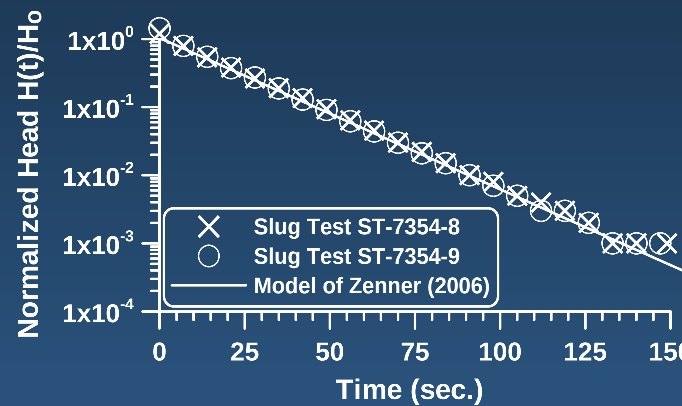
Nonlinear Hvorslev-Style Model of Zenner (2006)

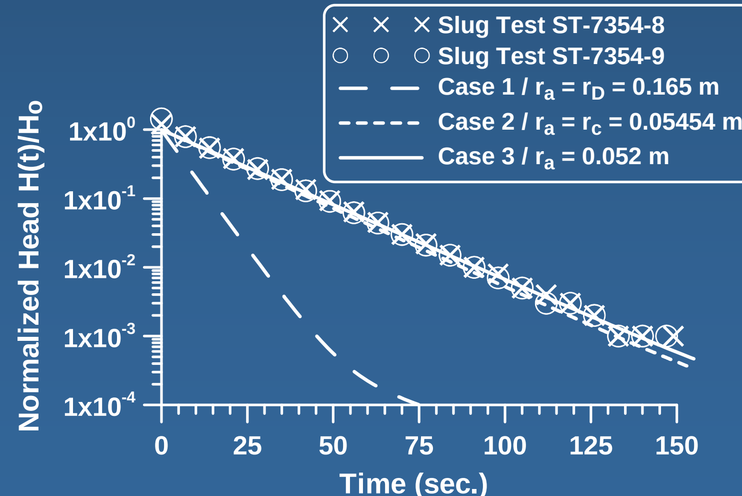
$$-\alpha(H)\frac{d^2H}{dt^2}+\beta\left(H,\frac{dH}{dt}\right)\left(\frac{dH}{dt}\right)^2-g\left(\pi r_c^2 B_2+\frac{\pi r_c^2}{F k_r}\right)\frac{dH}{dt}-gH=0$$



Simulation shown for Hvorslev's case no. 9 and:
$k_r = 1.14 \cdot 10^{-3}$ m/sec., $B_2 = 2119$ sec./m^2, B = 14.9 m

Spherical Flow Model of Barker (1988)

$$H(t)=H_0 t_c \mathrm{L}_s^{-1}\left\{\left[st_c+q(1+S_w q)^{-1}\right]^{-1}\right\}$$



Estimated spherical screen radius: $r_a = 0.052$ m
($k_{spherical} = (k_r^2 k_z)^{1/3} = 0.718 \times 10^{-3}$ m/sec., $S = 2 \cdot 10^{-4}$)

-> For sufficiently small r_a, the head decays exponentially in time, even if S is large!

Summary and Take-Home Messages

- Slug testing tells us about aquifer parameters and governing flow processes!

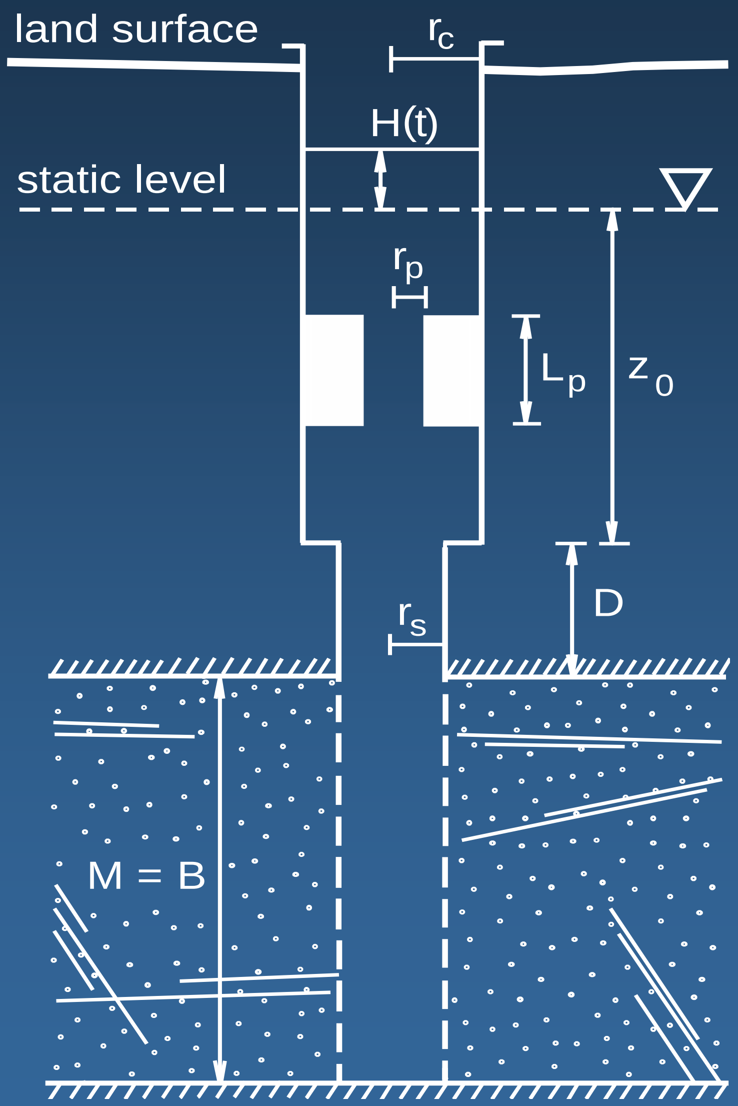
- A linear head decay in a Hvorslev-style plot indicates Darcian flow:
  - negligible aquifer storage
  - significant formation damage / spherical flow entry into the well (/6/, /15/)
  - -> favor air-lift drilling over direct-mud rotary drilling when installing water wells

- A convex head decay in a Hvorslev-style plot indicates Darcian flow:
  - significant aquifer storage
  - an imperfectly sealed well / rising background head trends -> static level in the well may not represent piezometric level in the aquifer (/2/, /3/, /4/, /11/)

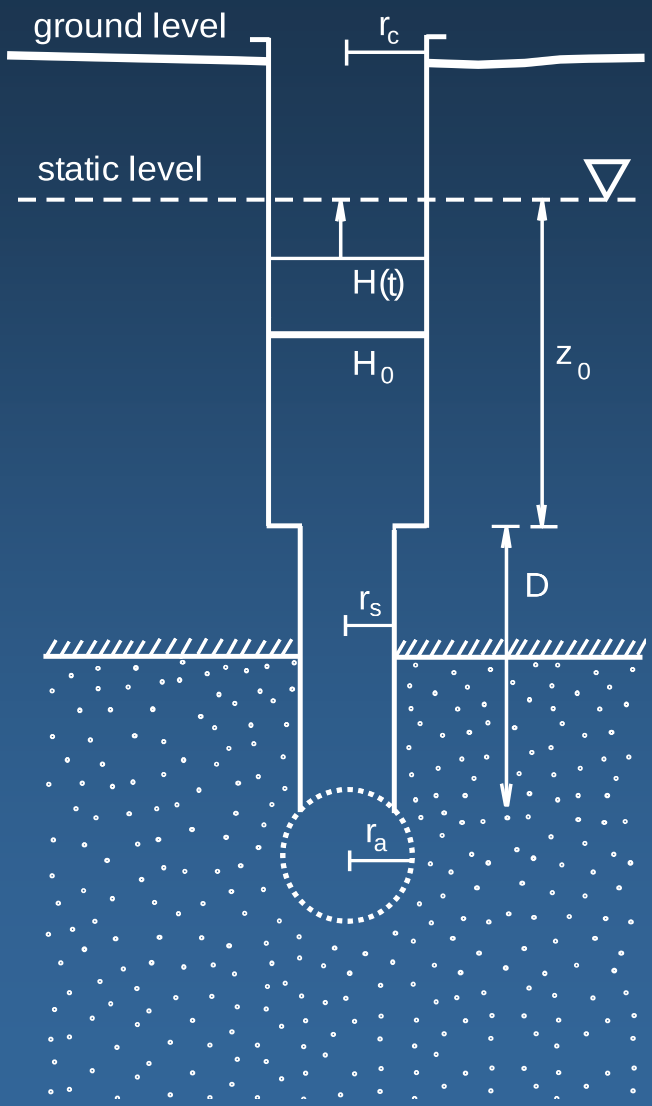
- A concave head decay in a Hvorslev-style plot may indicate non-Darcian flow:
  - dominant nonlinear flow (/9/, /10/, /13/, /14/).
  - an imperfectly sealed well / falling background head trends -> static level in the well may not represent piezometric level in the aquifer (/2/, /3/, /4/, /11/)

--- Backup ---

Schematic of a Slugged Fully Penetrating Well



Schematic of a Slugged Well with Spherical Screen



Cooper-Bredehoeft-Papadopulos (CBP) Model (1967):

$$\frac{H(t)}{H_0} = \frac{8 r_s^2 S}{\pi^2 r_c^2} \cdot \int_0^\infty \frac{1}{u \cdot \Delta u} \exp\left\{ - \frac{T t u^2}{r_s^2 S} \right\} du$$

The right-hand side is independent of H_0!
The head response is convex in a Hvorslev-style semi-logarithmic format with response curves collapsing onto a unique curve for increasing magnitude of the initial displacement H_0.

A Nonlinear Hvorslev-style Model Variant (Zenner, 2006):

$$-\left(H + z_0 + \left[\frac{r_c^2}{r_p^2} - 1\right] L_p + \left[\frac{3}{8}B + D\right]\frac{r_c^2}{r_s^2}\right)\frac{d^2H}{dt^2} - g\pi r_c^2 \left(B_2 + \frac{1}{Fk_r} + C\left(\pi r_c^2\right)^{p-1}\left|\frac{dH}{dt}\right|^{p-1}\right)\frac{dH}{dt}$$

$$+\frac{1}{2}\left[\left(\frac{r_c^2}{2r_sB}\right)^2 - 1 + \xi_{\text{loss}} - \left(f_p\frac{L_p r_c^4}{2r_p^5} + f_s\frac{Dr_c^4}{2r_s^5} + f_c\frac{z_0 - L_p + H}{2r_c}\right) sign\left(\frac{dH}{dt}\right)\right]\left(\frac{dH}{dt}\right)^2$$

$$-gH = 0$$

The head response is concave or linear in a Hvorslev-style semi-logarithmic format with response curves potentially shifted toward larger times for increasing magnitude of the initial displacement H_0.

A Transient Nonlinear Slug Test Model (Zenner, 2008):

$$-\left(H+z_0+\left[\frac{r_c^2}{r_p^2}-1\right]L_p+\left[\frac{3}{8}B+D\right]\frac{r_c^2}{r_s^2}\right)\frac{d^2H}{dt^2}-g\pi r_c^2\left(B_2+C\left(\pi r_c^2\right)^{p-1}\left|\frac{dH}{dt}\right|^{p-1}\right)\frac{dH}{dt}$$

$$+\frac{1}{2}\left[\left(\frac{r_c^2}{2r_sB}\right)^2-1+\xi_{\text{loss}}-\left(f_p\frac{L_p r_c^4}{2r_p^5}+f_s\frac{Dr_c^4}{2r_s^5}+f_c\frac{z_0-L_p+H}{2r_c}\right)\text{sign}\left(\frac{dH}{dt}\right)\right]\left(\frac{dH}{dt}\right)^2$$

$$-gH-\frac{gr_c^2}{2\pi^2T}\int_0^t\frac{\partial^2H}{\partial\tau^2}\int_0^\infty\frac{1-e^{-\frac{4T(t-\tau)x^2}{Sr_D^2}}}{x^3\left[J_1^2(2x)+Y_1^2(2x)\right]}dx\,d\tau=0$$

This slug test model for finite-diameter fully penetrating wells covers the entire range of underdamped to overdamped head responses with response curves potentially shifted toward larger times for increasing magnitude of the initial displacement H_0.

The Spherical Flow Slug Test Model of Barker (1988) and Its Implications

The Model of Barker (1988):

$$\frac{H(t)}{H_0} = t_c \, \mathcal{L}_s^{-1}\left\{\left[st_c + q(1+S_w q)^{-1}\right]^{-1}\right\}$$

$$q = 1 + \sqrt{st_a} \qquad t_a = \frac{S_s r_a^2}{k_{spherical}} \qquad t_c = \frac{r_c^2}{4k_{spherical}\, r_a}$$

s = Laplace variable

The right-hand side is independent of H_0!
The head response is convex or linear in a Hvorslev-style semi-logarithmic format with response curves collapsing onto a unique curve for increasing magnitude of the initial displacement H_0.

For small t, S_s, r_a or large $k_{spherical}$, S_w:

$$\frac{H(t)}{H_0} \approx \exp\left(-\frac{t}{t_c(1+S_w)}\right)$$

⟹ If r_a is sufficiently small the head is exponentially decaying, even if the aquifer storage capacity is significant!

Determination of Skin Effects from Superposition

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Superposition Recovery Data Yield k_r:

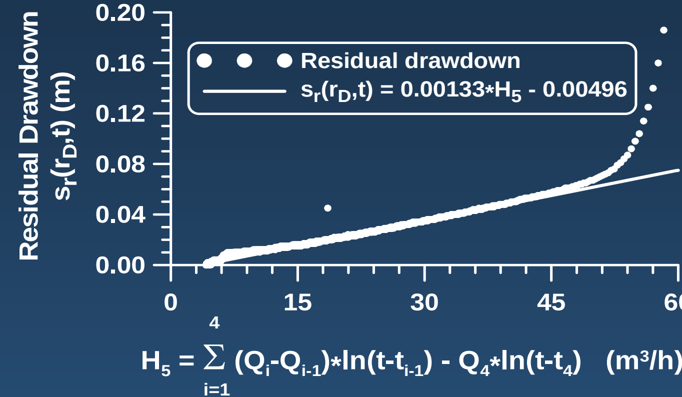
$$s_r(r_D,t) = \frac{\left(\sum_{i=1}^{4}(Q_i - Q_{i-1})\ln(t - t_{i-1}) - Q_4 \ln(t - t_4)\right)}{4\pi k_r M}$$

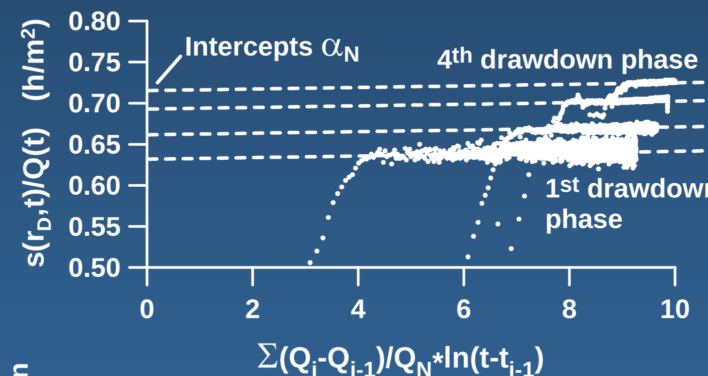
Superposition Drawdown Data Yield S_w:

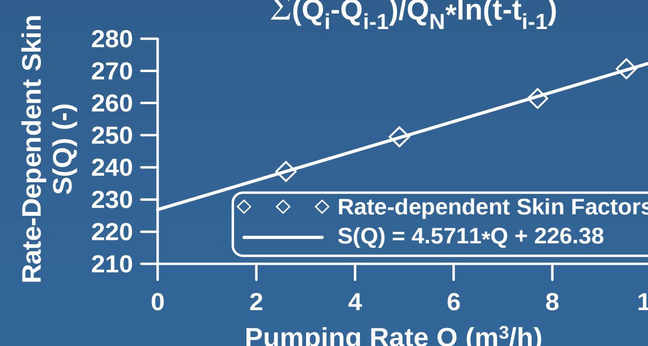
$$\frac{s(r_D,t)}{Q_N} = \frac{1}{4\pi k_r M}\sum_{i=1}^{N}\frac{Q_i - Q_{i-1}}{Q_N}\ln(t - t_{i-1}) + \frac{1}{4\pi k_r M}\ln\frac{2.25 k_r M}{S r_D^2} + \frac{S_t + D|Q_N|}{2\pi k_r M}$$

-> $$S(Q_N) = S_t + D|Q_N| = 2\pi k_r M \left.\frac{s(r_D,t)}{Q_N}\right|_0 - \ln\left(\sqrt{\frac{2.25 k_r M}{S r_D^2}}\right)$$

-> $$S_t = \frac{M}{B}\times S_w + S_p \qquad B_2 = \frac{S_t}{2\pi k_r M}$$







The Pseudo-Skin Factor S_p due to Partial Well Completion

$$S_p = \frac{2M^2}{\pi^2 B^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \left(\sin\left[n\pi \frac{l}{M} \right] - \sin\left[n\pi \frac{d}{M} \right] \right)^2 K_0\left(n\pi \frac{r_s \sqrt{k_z / k_r}}{M} \right)$$

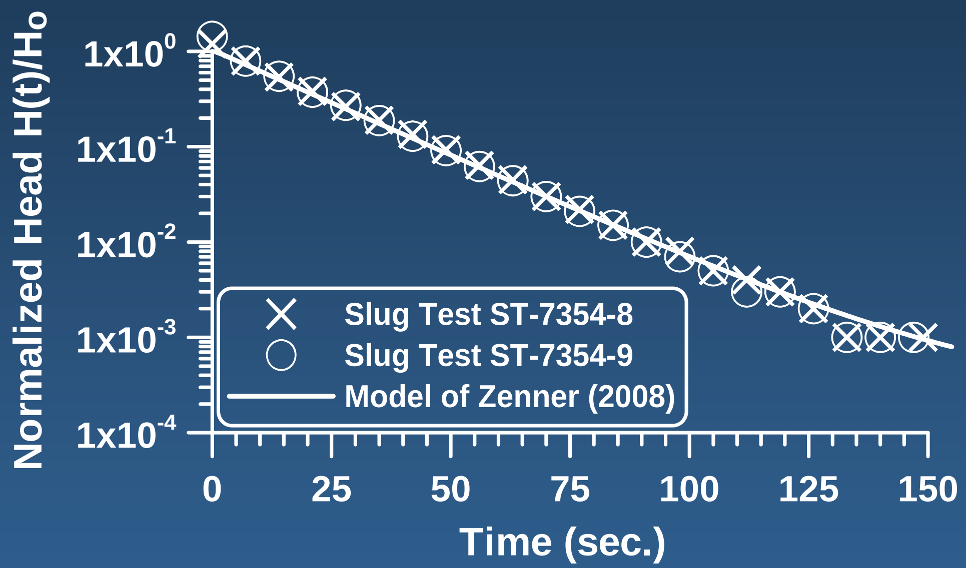
Flow concentration at a partially penetrating screen can be represented by an additional dimensionless and time-independent head loss $2S_p$ as soon as the formation starts to respond over the entire aquifer thickness.

Total rate-independent skin factor S_t, mechanical skin factor S_w, pseudo-skin factor S_p, and linear well loss coefficient B_2 are related by:

$$S_t = \frac{M}{B} \times S_w + S_p \qquad B_2 = \frac{S_t}{2\pi k_r M}$$

The linear well loss coefficient B_2 aggregates mechanical skin and pseudo-skin head losses.

Simulation by the Model of Zenner (2008) (page 15):



Simulation shown for:

$k_r = 1.14 * 10^{-3}$ m/sec., $S = 2 * 10^{-4}$, $C = 0$, $B_2 = 2119$ sec./m², $B = 14.9$ m

-> Accomodation of formation damage and partial penetration effects by the total rate-independent skin factor S_t yields good simulation results for the current slug test example.

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