The Borehole Permeameter Approach for Stormwater Infiltration Testing

AWRA National Conference



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Topics Covered

- Borehole permeameter (BP) equation
- Updating the Pilot Infiltration Test (PIT) approach
- Borehole Infiltration Test Approach
  - Small-scale hand dug holes
  - Vactor explorations
  - Drilled wells
- Predicting performance of infiltration facilities

Thanks to Chris May at Kitsap County and John Phillips at King County for supporting use of these methods on their projects.

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The Most Important Take-Away

- Infiltration rate is not a soil property!
- Infiltration rate depends on:
  - Hydraulic conductivity (K) which is a soil property
  - Hydraulic gradient
  - Facility geometry
  - Stratigraphy
  - Depth to groundwater (sometimes)

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Soil is a 3-D Water Conveyance System

- Hydraulic conductivity (K) is a 3-D vector
- For our purposes, 2-D is sufficient
- Water-deposited soils are layered, so vertical K (Kv) is less than horizontal K (Kh)
- Anisotropy ration: $1 < Kh/Kv < 10$
- Borehole tests weighted towards Kh
- Shallow horizontal test facilities weighted towards Kv
- Use of term “Bulk K” represents our inability to evaluate anisotropy

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Borehole Permeameter (BP) Approach

(Also referred to as Constant Head Well Permeameter Approach, Reynolds, 2008)

$$K = \frac{CQ}{2\pi H^2 + \pi r^2 C + \frac{2\pi H}{\alpha^*}} \quad (Equation\ 1)$$

Hydrostatic Pressure Flow

Vertical Gravity Flow

Capillarity Flow

Where:

K = Field saturated bulk hydraulic conductivity (feet/day)

Q = Steady state flow (cubic feet/day)

H = Steady State head/ponding Depth (feet)

r = Radius of borehole(feet)

α^* = Porous media sorption number (1/feet)

C = Shape factor (dimensionless)

Where: $C = \left[\frac{(H_L/r)}{Z_1 + Z_2(H_L/r)}\right]^{Z_3}$ (Zhang et al., 1998)

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PIT and USBR Equations Compared with BP Equation

BP Equation: $K = \frac{CQ}{2\pi H^2 + \pi r^2 C + \frac{2\pi H}{\alpha^*}}$

USBR Equation: $K = \frac{CQ}{2\pi H^2}$

PIT Equation: $K = \frac{Q}{\pi r_e^2}$

Where:

K = Field saturated bulk hydraulic conductivity (feet/day)

Q = Steady state flow (cubic feet/day)

H = Steady State head/ponding Depth (feet)

r = Radius of borehole(feet)

α^* = Porous Media sorption number (1/feet)

C = Shape factor (dimensionless)

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Capillary and Shape Factor Parameters

Zhang et al, 1998

Soil Type	**α^* (feet^{-1})**	**Z_1**	**Z_2**	**Z_3**
1) Compacted clays	0.3	2.081	0.121	0.672
2) Unstructured fine-grained porous media	1.2	1.992	0.091	0.683
3) Structured fine grained porous media or unstructured fine-medium sandy media	3.7	2.074	0.093	0.754
4) Structured fine-medium sandy porous media and coarse-grained gravelly media	11	2.074	0.093	0.754

Decreasing Capillary Flow Effect

Most porous media of interest for infiltration are Type 3.

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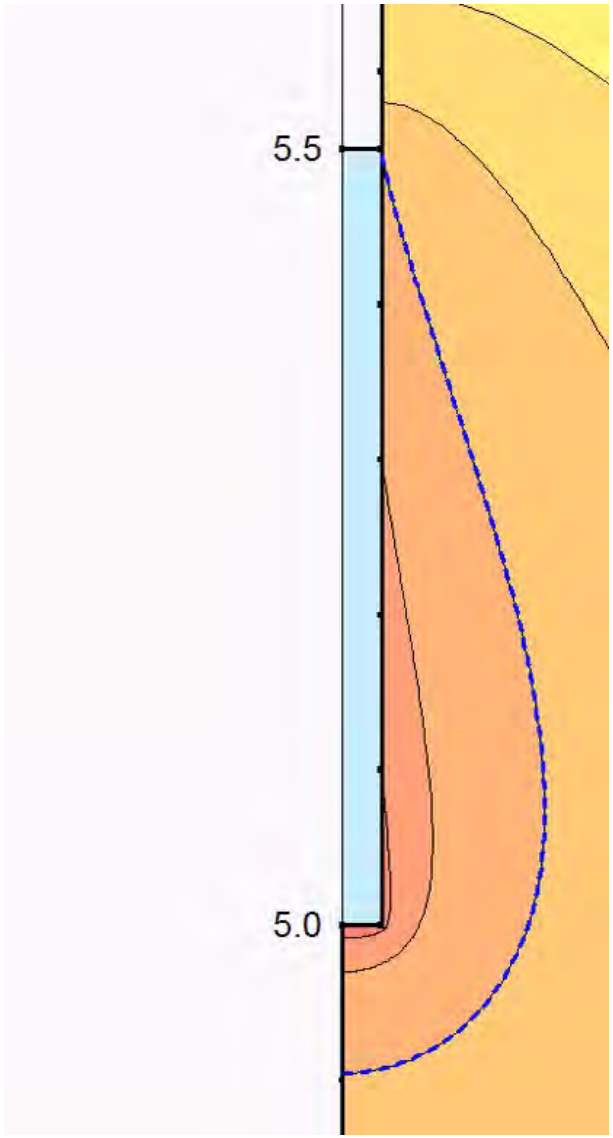
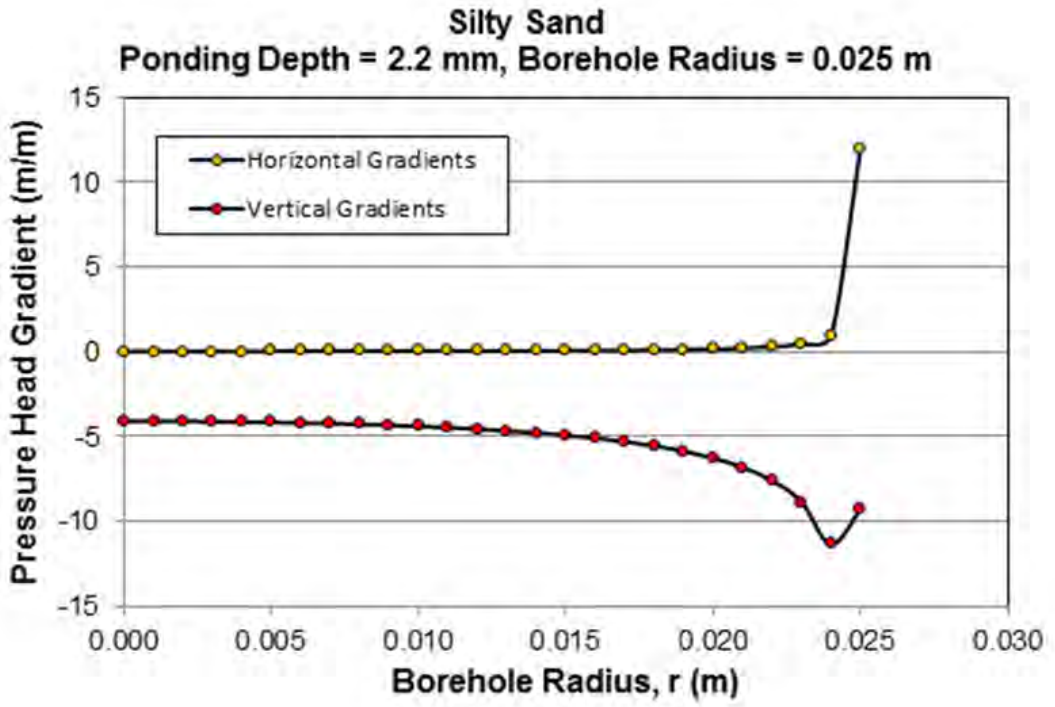
Numerical Simulation of Falling Head



Attached is a computer simulation (based on Richards' equation for variably saturated flow) of falling head in an uncased borehole after initially achieving steady flow at constant ponded head (50 cm in this case). Note that the "field-saturated zone" around the borehole (i.e. volume inside the dashed blue line which represents zero pore water pressure head) contracts uniformly back toward the borehole as the ponded head falls toward zero.

Below are the simulated vertical and horizontal pore water pressure head gradients along the base of the borehole when the ponded head is near zero (about 2.2 mm). The vertical gradients are substantially greater than zero along the entire borehole base, so the hydraulic head gradient does not approach unity as the borehole empties.



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BP Assumptions

- Isotropic (Vertical K = Horizontal K)
- Uniform K within test interval
- Steady state
- No groundwater table or perching layer near bottom of test excavation/boring

One or more of these assumptions generally not met,
Results reported as “Bulk K”

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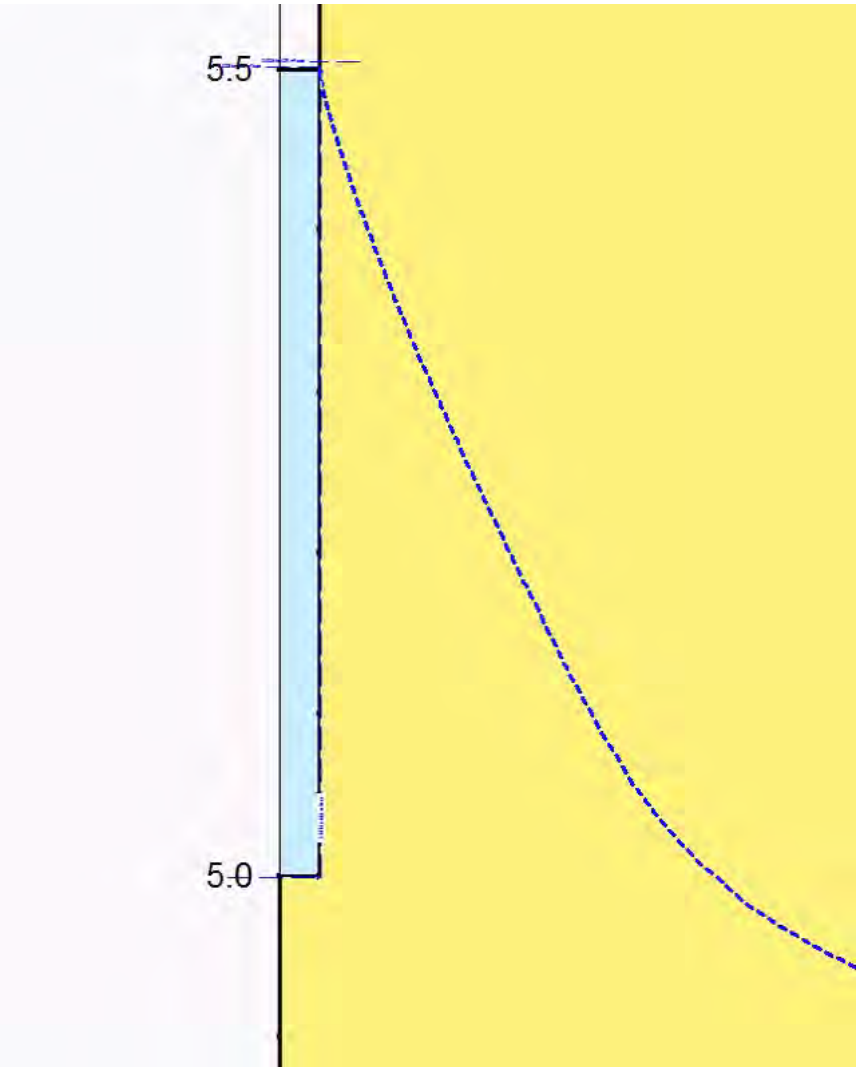
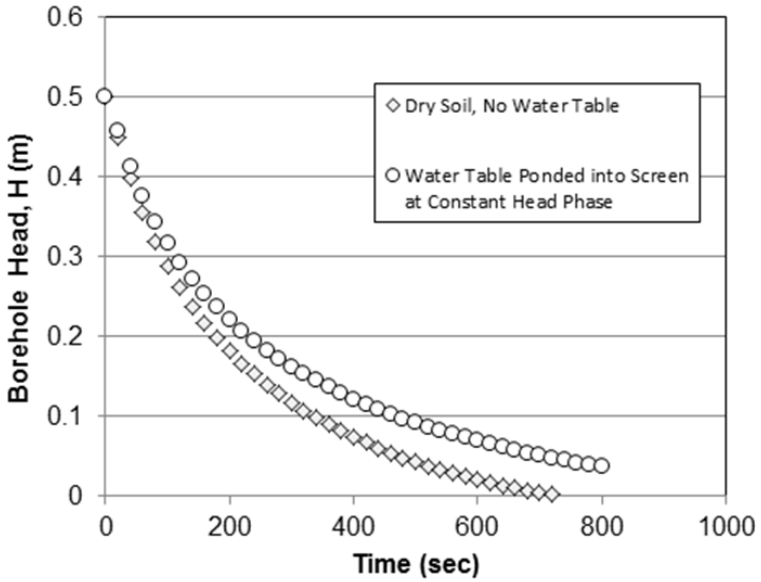
Mounding Effects of Nearby Groundwater Table



Water table initially 25 cm below base of borehole at start of constant head phase



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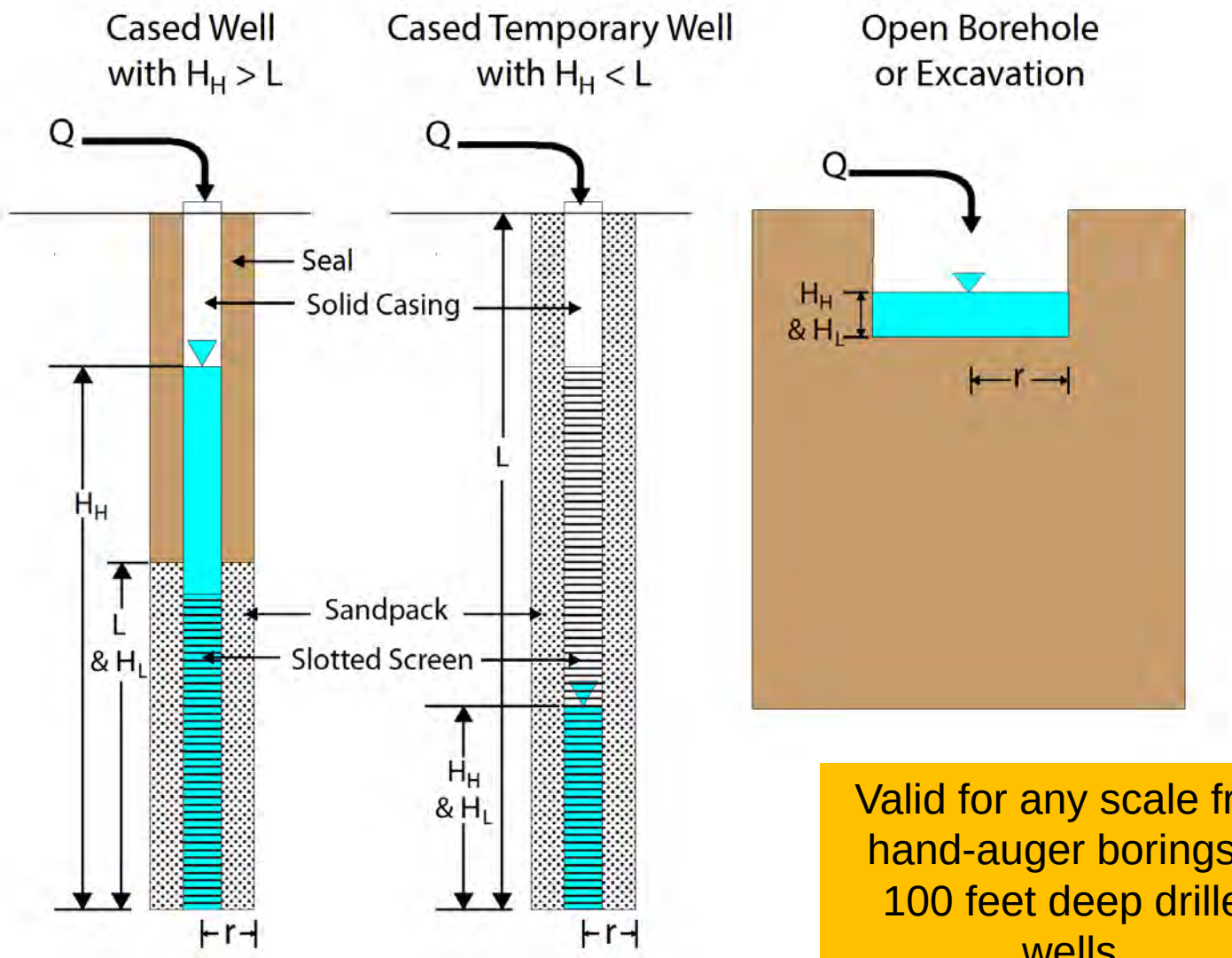
Types of BP Tests



Valid for any scale from hand-auger borings to 100 feet deep drilled wells.

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Standard Pilot Infiltration Test (PIT)



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Standard PIT



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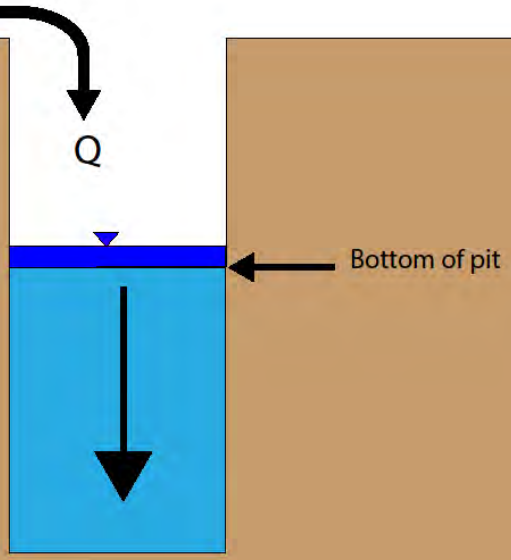
PIT Approach Only Accounts for Vertical Gravity Flow (2nd term in BP equation)

Pilot Infiltration Test (PIT) Current Approach

Assumes vertical gravity flow from the bottom of the excavation.

Infiltration Rate = K*i = Q/A

Where K = hydraulic conductivity
i = hydraulic gradient
Q= Flow
A =Area of ponding



i approaches 1 as as wetting front moves further from bottom of pit.

Therefore, infiltration rate approaches K as test approaches stready state

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What Actually Happens During a PIT

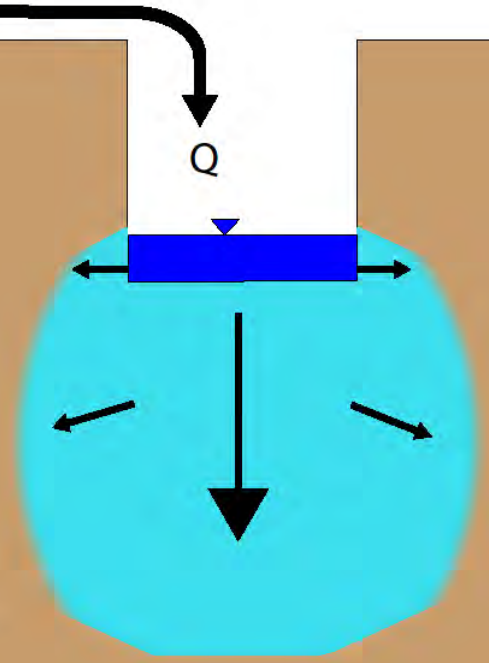
Pilot Infiltration Test (PIT) in Reality

Three Flow Componants:

- Vertical Gravity Flow
- Hydrostatic Pressure Flow
- Capillary Suction

These additional flow componants mean that Q is higher than predicted by the vertical flow model assumed by the standard PIT approach.

The standard PIT approach overesti-mates the infiltration rate.



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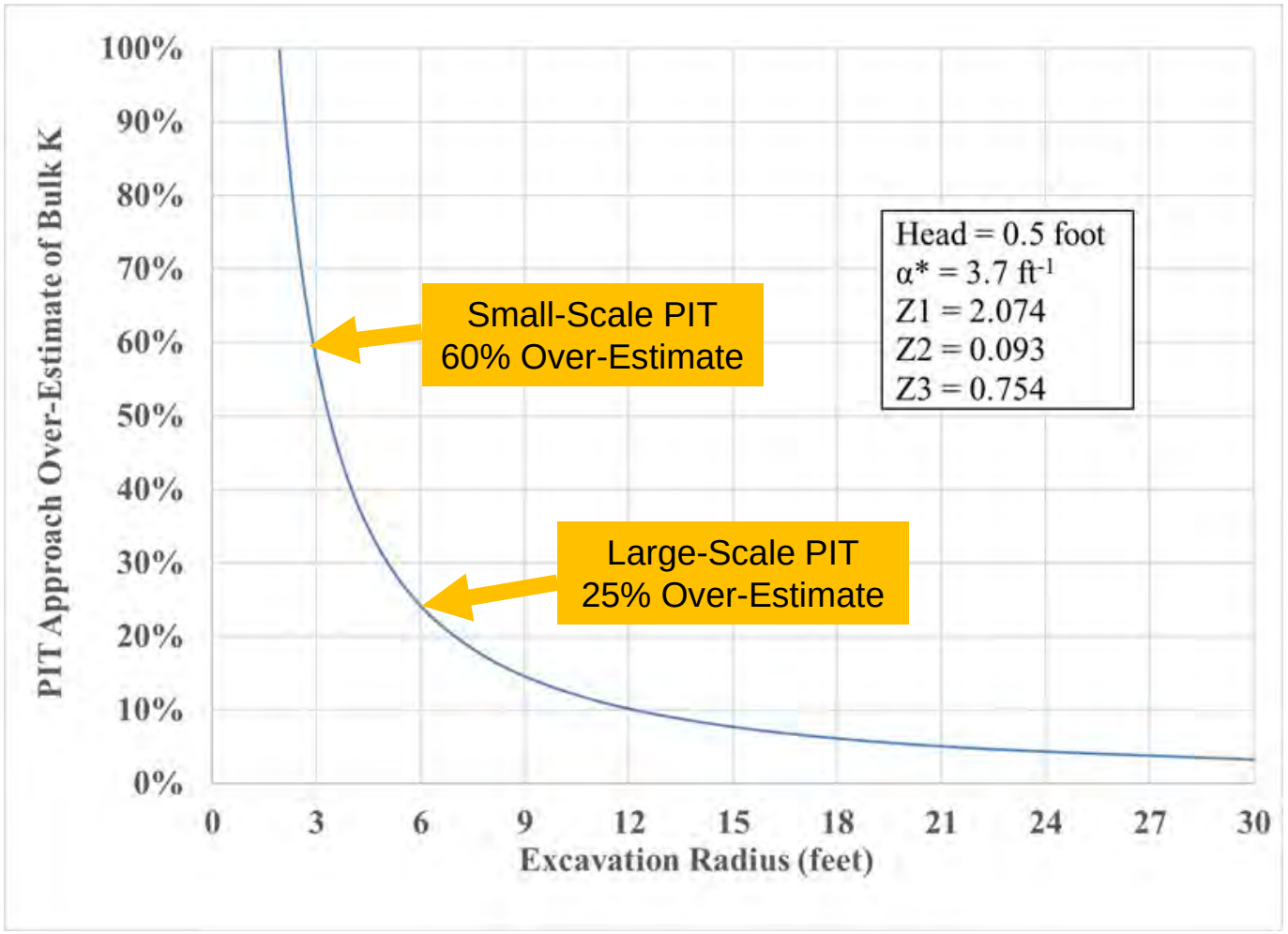
PIT Approach Infiltration Rate Error



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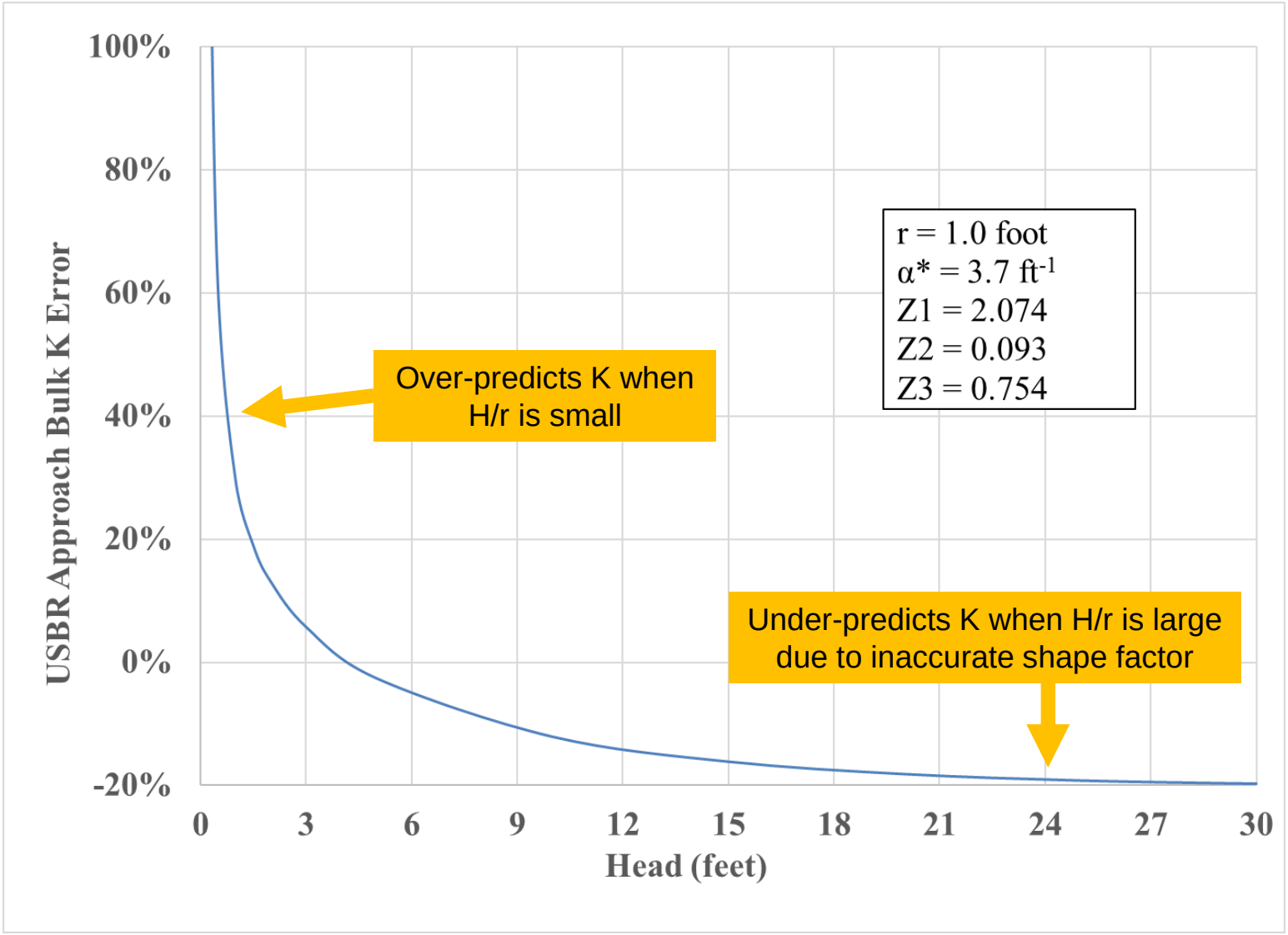
US Bureau of Reclamation 7300 Approach

- USBR approach only accounts for hydrostatic pressure flow (first term in BP equation)
  - Doesn't address vertical gravity flow or capillarity flow (thus not useful for tests in open excavations, i.e., when H/r is small)

- USBR used less accurate Zanger, 1953 shape factor

$$C = sinh^{-1}\left(\frac{H}{r}\right) - \sqrt{\left(\frac{r}{H}\right)^2 + 1} + \frac{r}{H}$$

Bureau of Reclamation Bulk K Error



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New Infiltration Test Methods

- Falling head in open excavation (updated PIT)
- Infiltration testing in hand-dug holes
- Infiltration testing in vactor explorations
- Infiltration testing in drilled borings

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Vactor Explorations



- **Advantages:**
  - Minimal disturbance
  - Less likely to break utilities
- **Vactor Exploration**
  - Loosen soil with high-pressure water jet, air-knife, or pry-bar
  - Excavate using vactor truck
  - Collect soil samples using hand auger
  - Up to 10 ft deep with no well permit

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Infiltration Test in Vactor Explorations



Build Temporary Test Well

- 2-inch PVC well screen and casing
- Fill annular space with pea gravel

Conduct Borehole Test

- Use vactor truck water tank
- Use transducer to measure water levels during fixed head and falling head portion of test

Abandon well by pulling casing and replacing dirt and sod

Daily Production

- 20-450 gallons/test
- Average ~200 gallons/test for Qva
- With 1,000 gal tank on Vactor truck, average 5 tests/day

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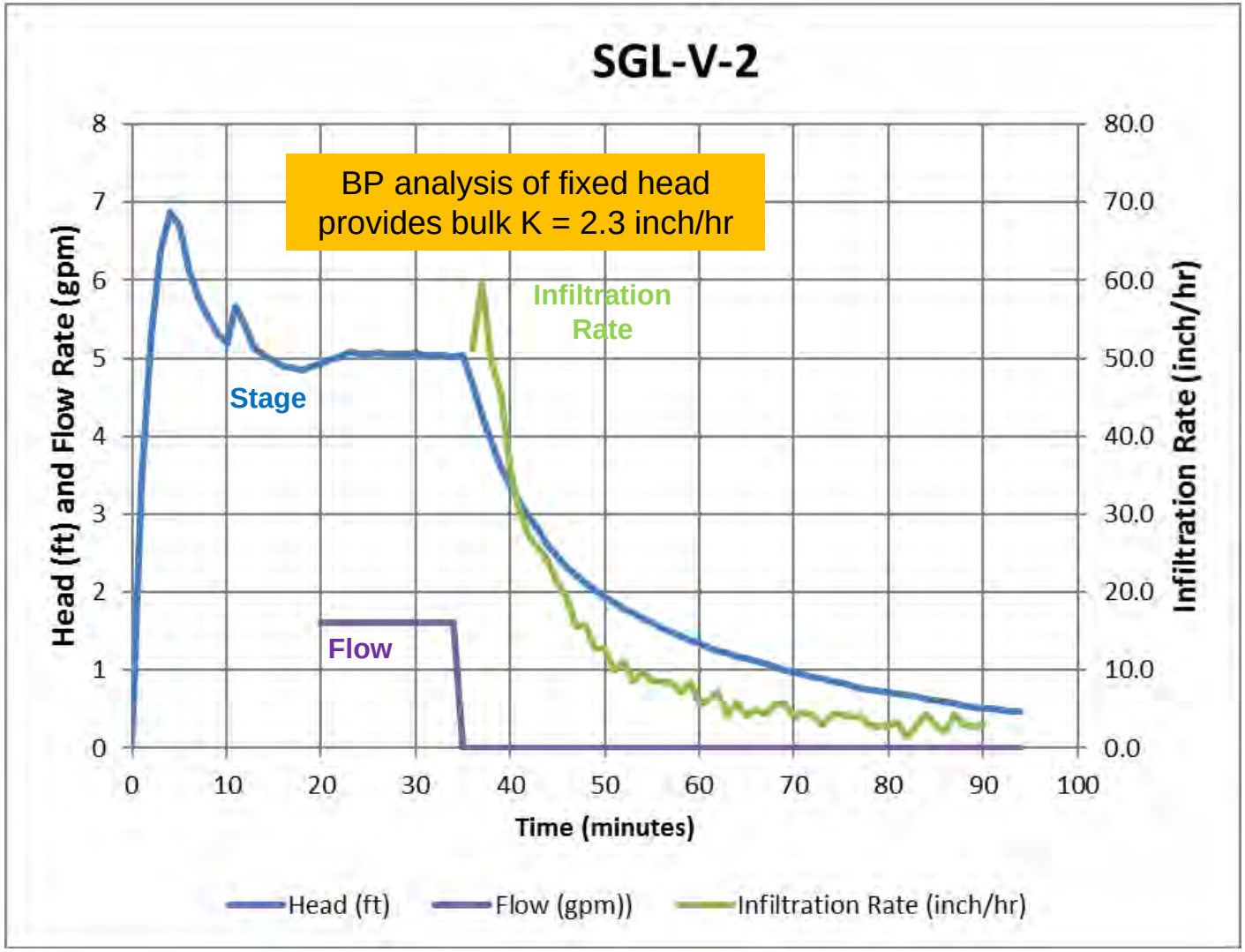
BP Results in Vactor Exploration



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BH Approach in Drilled Boreholes



Production Rate:

- 1,500-12,000 gal/test
- Average ~7,000 gal/test for Qva
- Ran 2 water trucks and completed 3 tests/day

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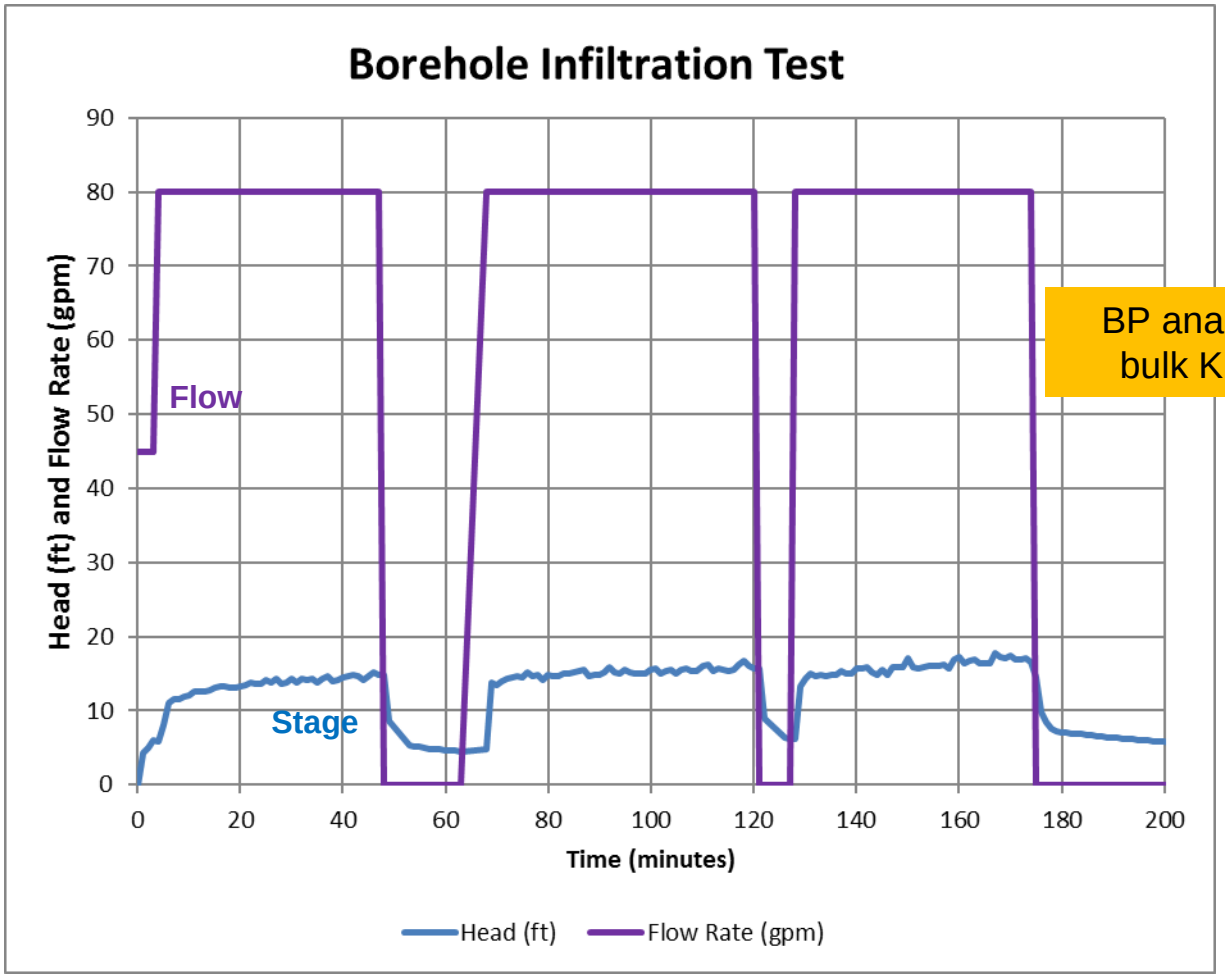
BH Results in Drilled Boring



BP analysis provides bulk K = 19 inch/hr

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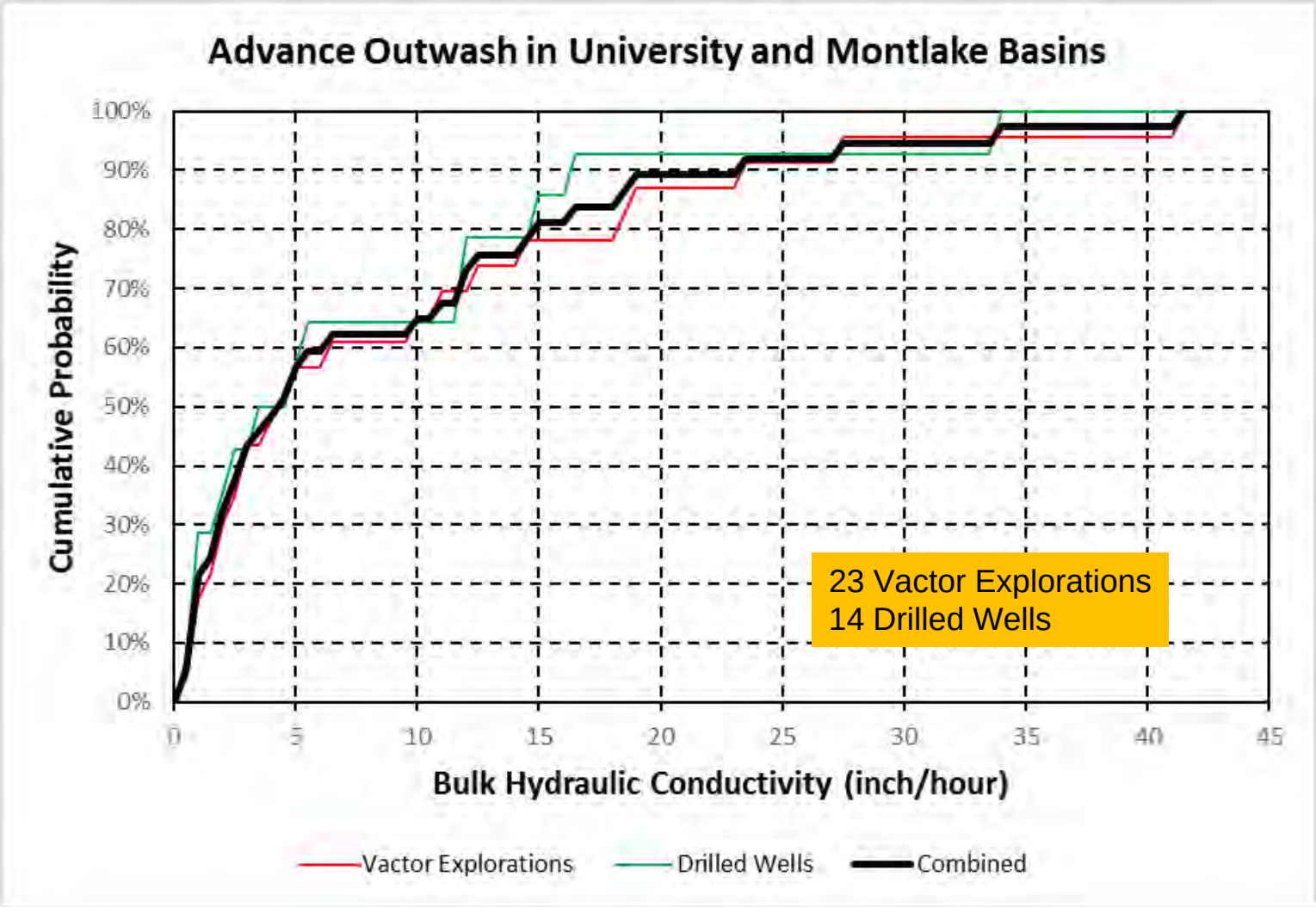
Characterizing Infiltration Feasibility Using these Methods



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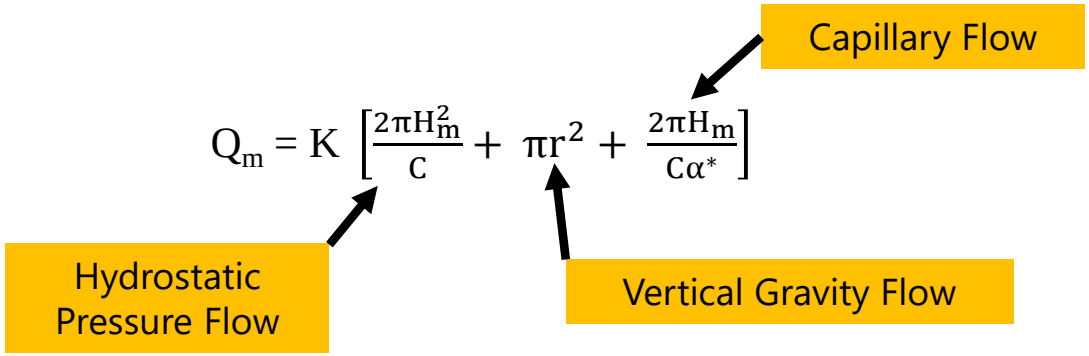
Estimating Design Infiltration Capacity



Where:

K = Bulk hydraulic conductivity (feet/day)

Q_m = Maximum flow capacity (cubic feet/day)

H_m = Maximum ponded head (feet)

r = Effective radius (feet)

α^* = Porous medium sorption number = ~3.7 (1/feet)

C = Shape factor (dimensionless)

Where: $C = \left[\frac{(H_L/r)}{Z_1 + Z_2(H_L/r)}\right]^{Z_3}$ (Zhang et al., 1998)

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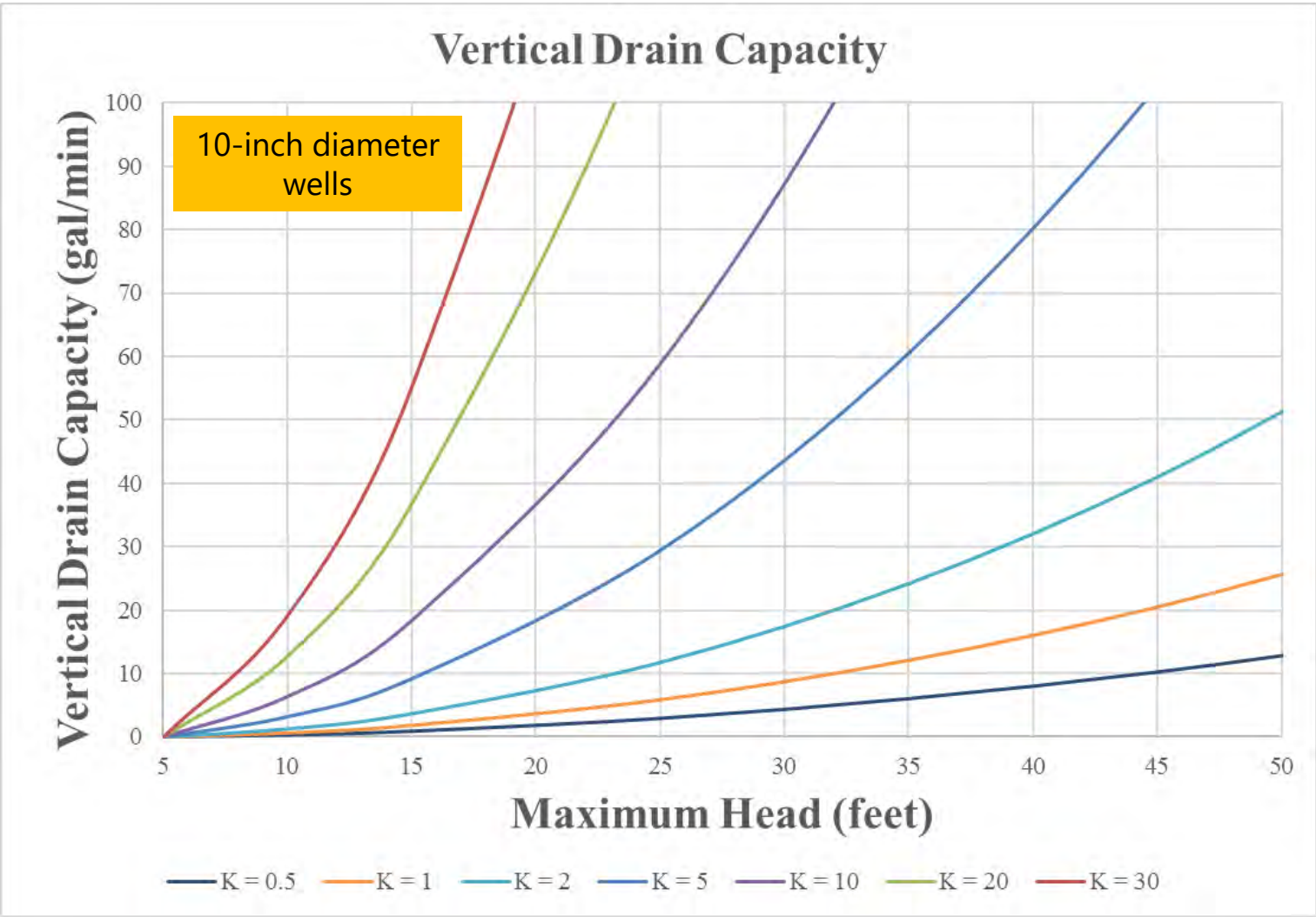
Deep Infiltration Drain Capacity



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Final Thoughts

- Open excavation, shallow head test with BP analysis provide Bulk K with a vertical K bias
  - Best suited for sizing shallow BMPs using vertical infiltration
- Borehole test with BP analysis provide Bulk K with a horizontal K bias
  - Best suited for designing BMPs with vertical infiltration drains
  - Should be acceptable approach for sizing BMPs that rely on vertical infiltration with appropriate safety factor
- Future topics:
  - Effects of groundwater or perching layer beneath test facility
  - Effects of anisotropy
  - Effects of permeability changes within tested horizon

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More Information

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