Slug Testing and Hydraulic Conductivity

1. The initial drawdown distance (y) is that distance between the measured water level at the beginning of the test and the initial static water level (draw a picture if necessary).
2. The drawdown distance or change in head (Δy) is that distance between the water level at any time during the test and the initial static water level.
3. A minimum default value of 15% shall be used for gravel pack porosity. An alternative value which is greater (i.e., 20%, etc.) may be used if justification is provided.
4. The maximum calculate hydraulic conductivity value must be used for the Tier 1 and Tier 2 pathway evaluation. Averaging calculated hydraulic conductivity values is not acceptable.
5. If bedrock is encountered above groundwater at any time, the groundwater will be considered a protected groundwater source regardless of hydraulic conductivity testing.
6. A weight value of zero (0) should be assigned to all recovery values after 90% of the initial drawdown has been reached.
7. A weight value of zero (0) should be assigned to recovery values which reflect drainage from the filter pack. This is generally the first 10 to 205 of recovery.
8. If the 'best fit' line developed by a computer program and is manually adjusted, an explanation must be provided to justify the adjustment.
9. If calculations are done by hand, the groundwater professional must include a copy of all calculations and must provide a graphical representation using semi-logathrimic paper.
10. If a partially penetrating well cannot be installed (groundwater less than 3 feet below grade), slug-in tests must be conducted on fully penetrating wells, i.e. completely submerged well screens. The adjustment for the porosity of the filter pack in this case, should not be conducted.

Bouwer-Rice: figure follows

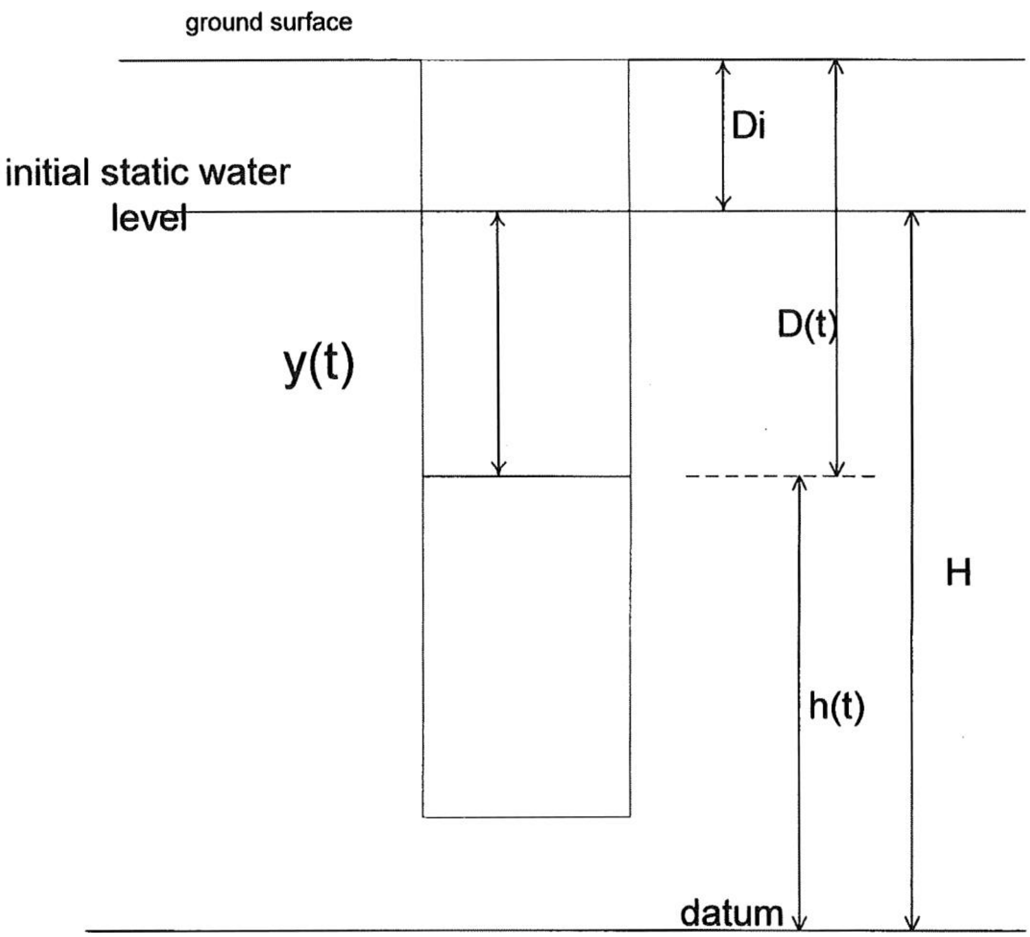
The analysis is based on:
The change in head produced by the slug test; not depth to groundwater or head measured from sea level.

If depth to groundwater or head is used, without conversion to y (your computer may do this), the wrong slope will be found and K is wrong. If your program using head or depth, does it required the initial head or depth to be used.

When the DNR requests y, they want the change in head.

Initial drawdown, y(t=O), is the vertical distance between the measured water level at the beginning of the test (immediately after slugging or bailing) and the initial static water level (immediately before slugging or bailing).

The drawdown distance or change, y(t) is the vertical distance between the water level at any time during the test and the initial static water level.

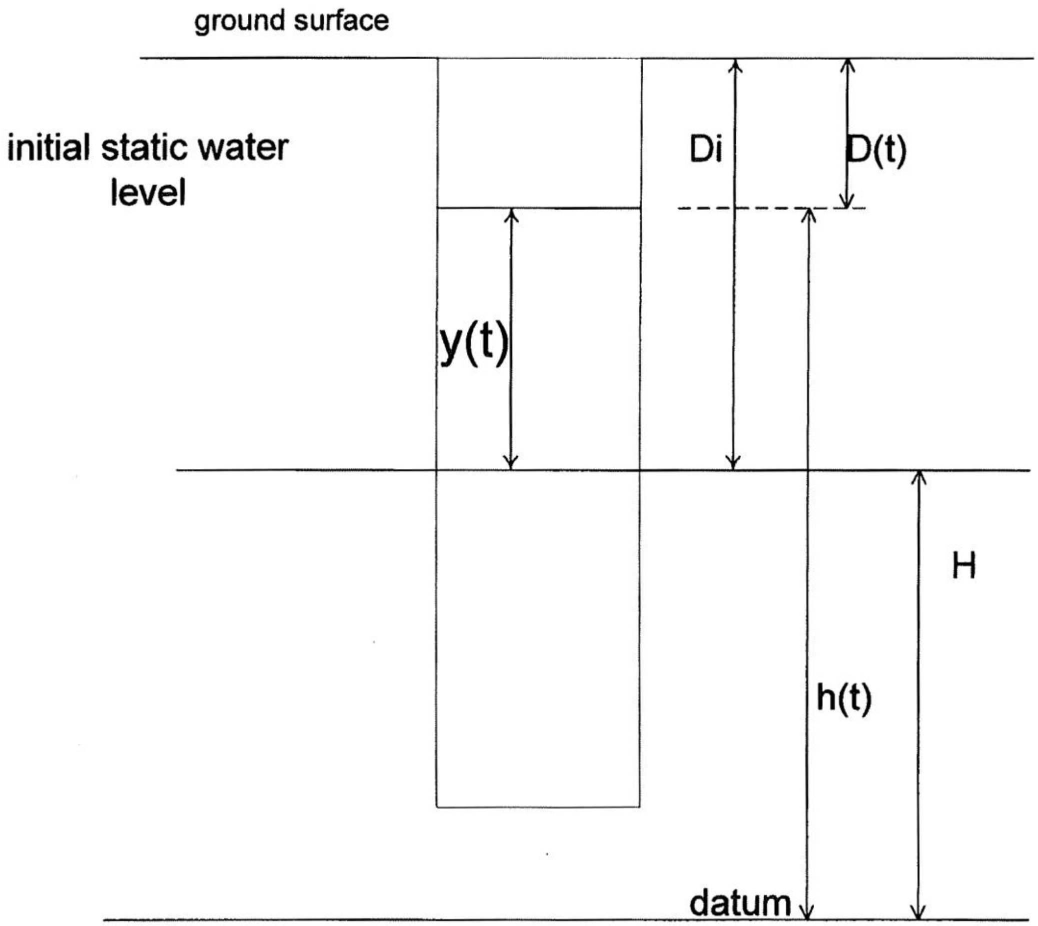


Bail down test, Rising Head Test

$$y(t) = H - h(t)$$

$$y(t) = D(t) - Di$$

Notice, y(t) is always positive and decreases with time.



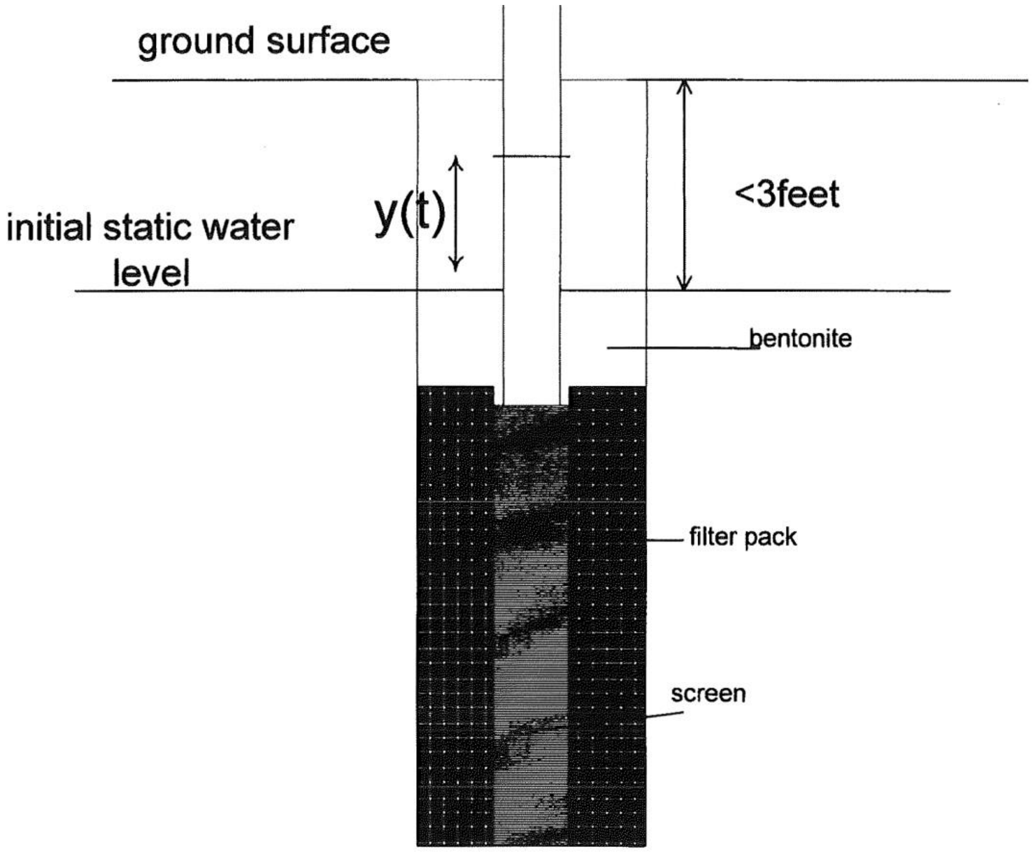
Slug In, Bail In, Falling Head Test

$$y(t) = h(t) - H$$

$$y(t) = Di - D(t)$$

Notice, y(t) is always positive and decreases with time.

Slug in Tests
If a partially penetrating well cannot be installed (groundwater less than 3 feet below grade), a slug-in test must be conducted on fully penetrating wells, i.e. completely submerged well screens. The drainable porosity is zero (0).



Drainable Porosity

Full Penetration: The well is screened entirely below the water table.

- If the well is screened entirely below the water table, the drainable porosity is zero (0).

Partial Penetration: The water level is in the well screen.

- Default Drainable Porosity: 15% (0.15)
- Minimum default value of 15% shall be used for gravel pack porosity.
- An alternative value which is greater (i.e., 20%, etc.) may be used if justification is provided.

Some slope recommendations

Plot the recovery and curve fit on both:

time versus log(y)

time versus y

For sites with low conductivity, relative to the gravel pack, first portion probably represents gravel pack drainage. Second portion is probably representative.

However, you must consider the actual y where a break in slope occurs near the end of the recovery. The plot of time versus log(y) can be deceptive. If the break occurs at less than 10% of the initial y (slug of 2 feet, breaks with y less than 0.2 feet) should be looked at as probably invalid data where the theory is no longer valid. You are unlikely to get 100% recovery.

Recommendations for Estimating the Slope

Judgement:

Generally, the last 10% of the recovery should be ignored. 10% of the initial y, the first measured change in head produced by the slug or bailing.

The first 10 to 20% of the recovery should be ignored.

For BRSLUG users, use a weight of 0 for the first 10-20% of the recovery and last 10% of the recovery.

If the slug change in head is 2 feet, ignore (assign a weight of zero) to;

first 0.2 to .4 feet of recovery and last 0.2 feet of recovery.

Base slope on y of 1.8 to 0.2, or 1.6 to 0.2 feet.

Summary and Other Considerations

1. Bouwer-Rice uses the change in head produced by the slug test, y.
2. For partial penetration, use a drainable porosity of 15%, or justify another value.
3. Generally, the recovery representing 80% to 10% of the initial change in head should be used for estimating slope of time versus log(t). What is the actual value of y where a late change in slope occurs?
4. If bedrock is encountered above groundwater at any time, the groundwater will be considered a protected groundwater source, regardless of hydraulic conductivity testing.
5. If calculations are done by hand, the groundwater professional must include a copy of all calculations and must provide a graph using semi-log paper.
6. If the 'best fit' line is developed by a computer program and is manually adjusted, an explanation must be provide to justify the adjustment.
7. For shallow groundwater(<3 feet below grade), install a fully penetrating well and use a slug in test.

Slug Tests
Single Well Response Tests

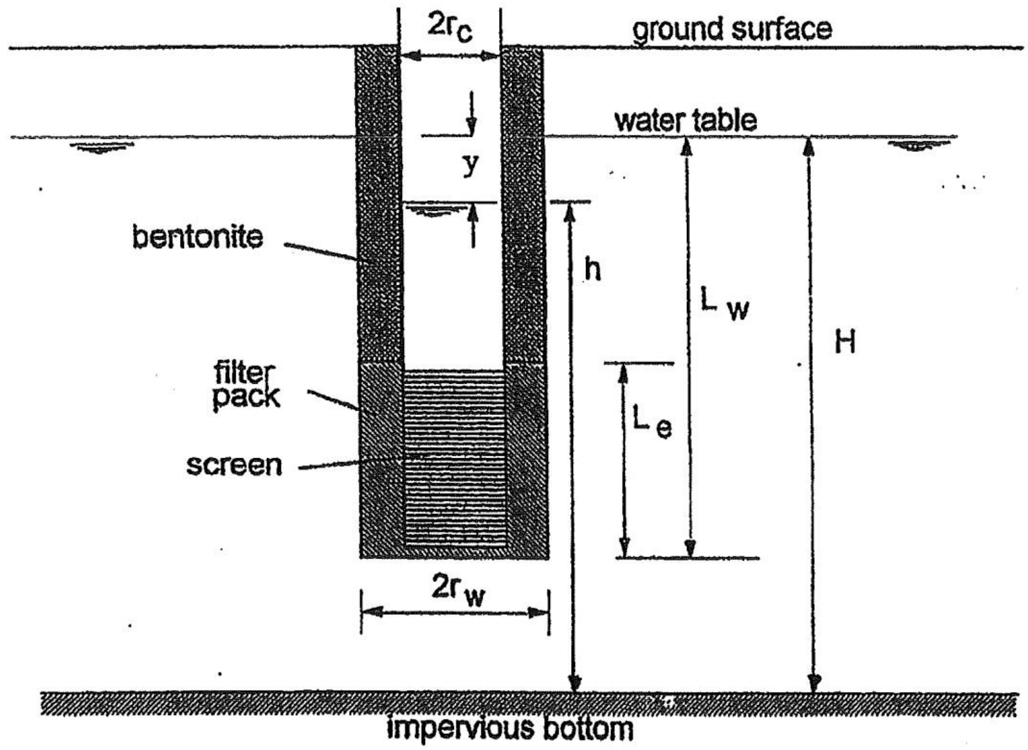
Objective: Estimate the Saturated Hydraulic Conductivity

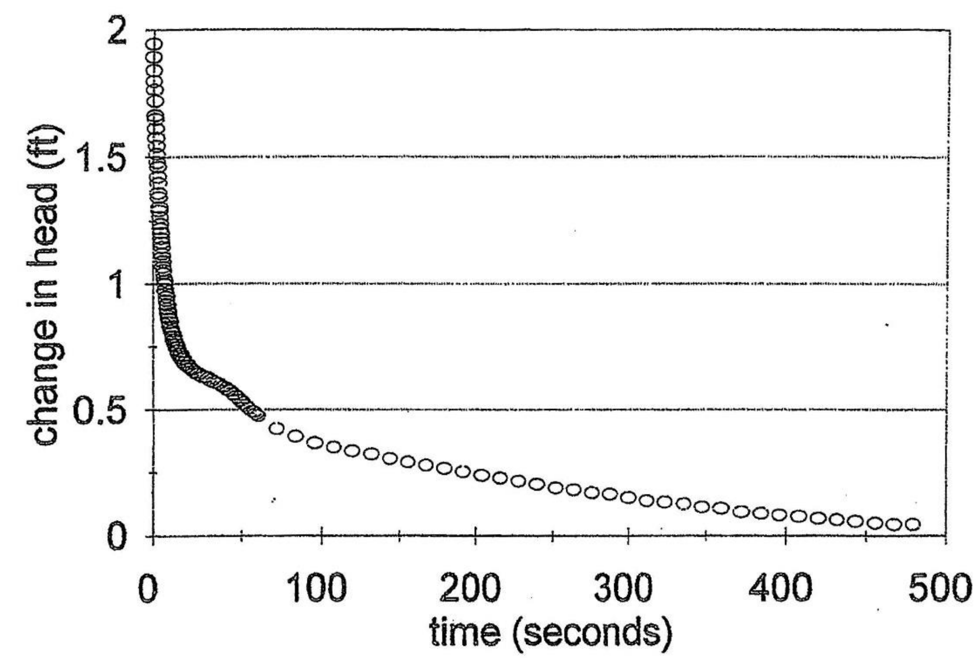
Advantages: Relatively quick and inexpensive
Disadvantages: Samples a small area around the well
Concern with accuracy.

Field Procedures

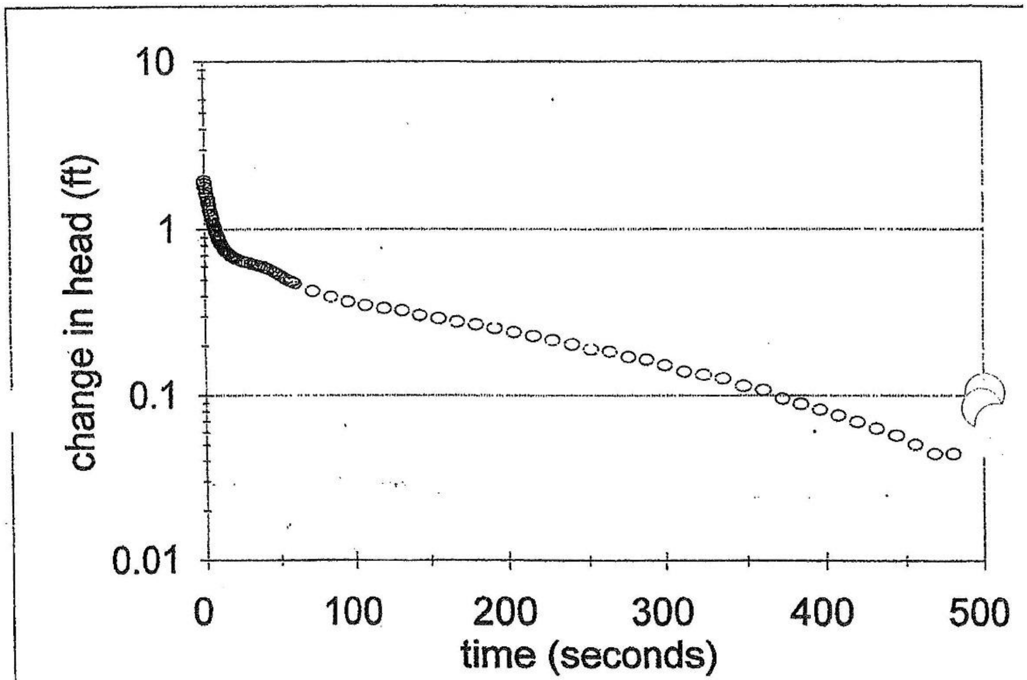
All slug test methods are the same in the field:

- Change the water level in the well as quickly as possible.
- Measure the recovery of the water level with time.



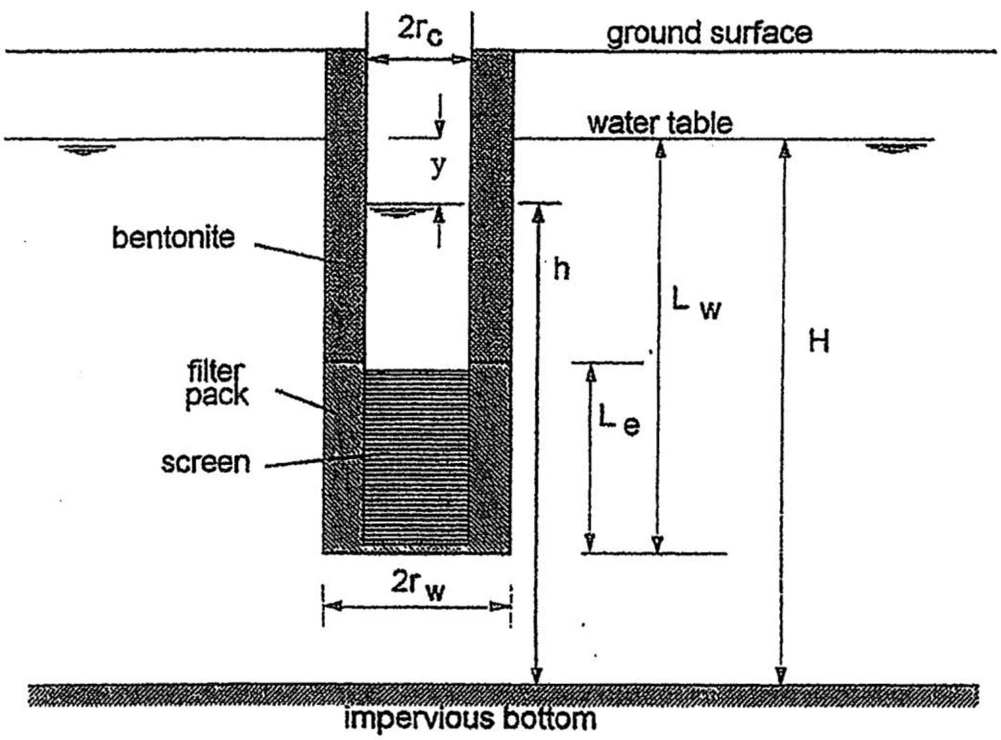


Slug Test Recovery



Slug Test Recovery

The Bouwer-Rice Method

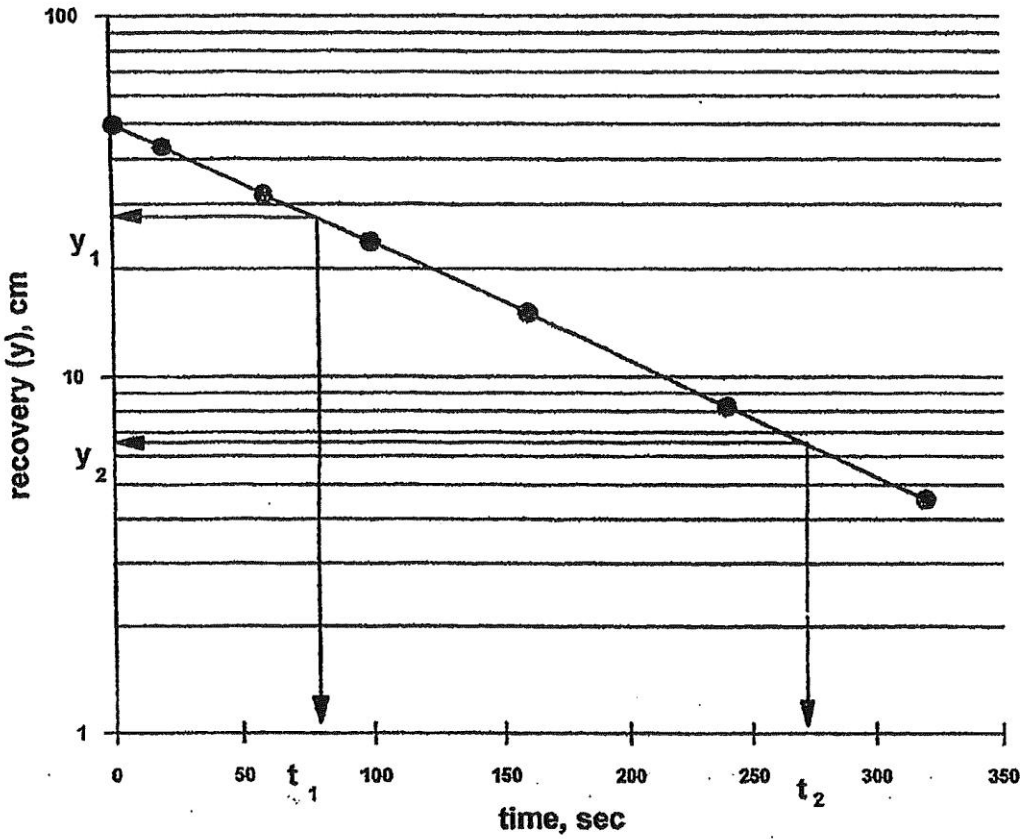


$$K = \frac{-\alpha r_c^2 \ln(R_e/r_w)}{2L_e}$$

α is the slope of ln(y) versus time (t) (theory says should be straight line)

y is the change in head (not the total head or depth to water)

Example plot of t versus y



$$K = \frac{r_c^2 \ln(R_e/r_w)}{2L_e}\alpha = \frac{-r_c^2 \ln(R_e/r_w)}{2L_e}\left[\frac{\ln(y_2) - \ln(y_1)}{t_2 - t_1}\right]$$

$$K = \frac{r_c^2 \ln(R_e/r_w)}{2L_e}\left[\frac{\ln(y_1/y_2)}{t_2 - t_1}\right]$$

Bouwer-Rice: figure follows

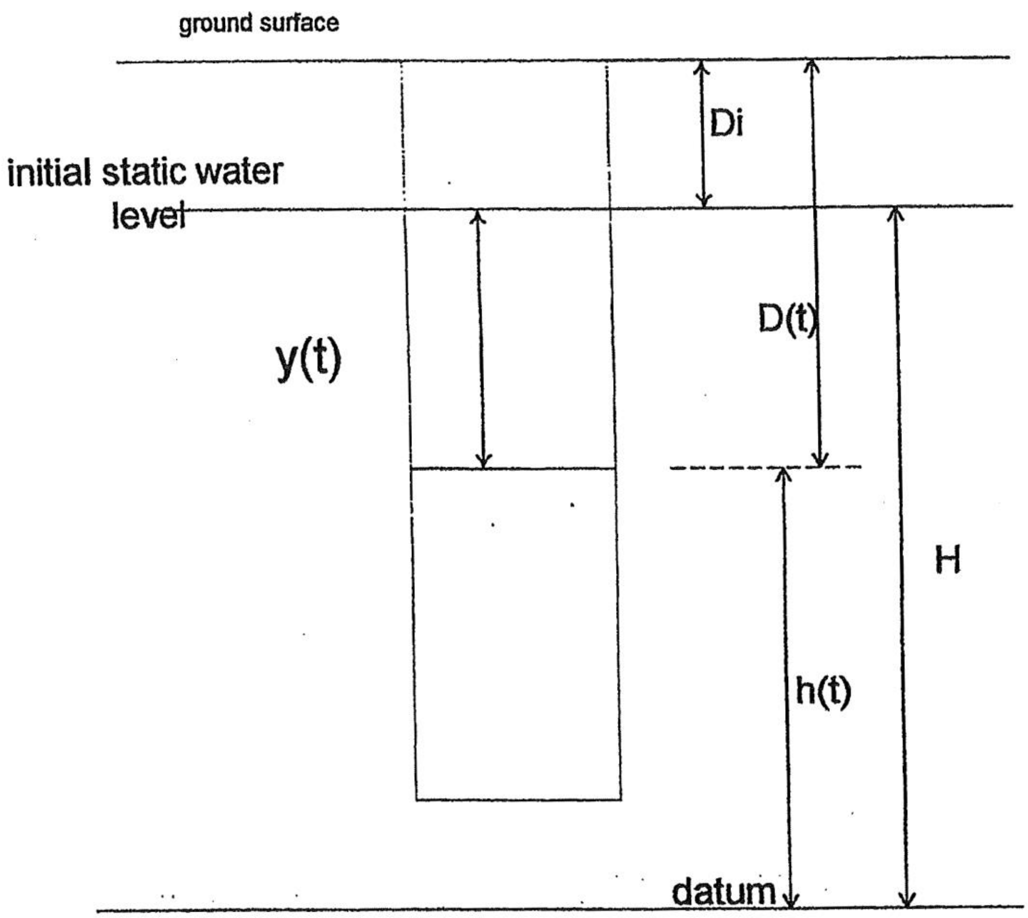
The analysis is based on:
The change in head produced by the slug test; not depth to groundwater or head measured from sea level.

If depth to groundwater or head is used, without conversion to y (your computer may do this), the wrong slope will be found and K is wrong. If your program using head or depth, does it required the initial head or depth to be used.

When the DNR requests y, they want the change in head.

Initial drawdown, y(t=0), is the vertical distance between the measured water level at the beginning of the test (immediately after slugging or bailing) and the initial static water level (immediately before slugging or bailing).

The drawdown distance or change, y(t) is the vertical distance between the water level at any time during the test and the initial static water level.

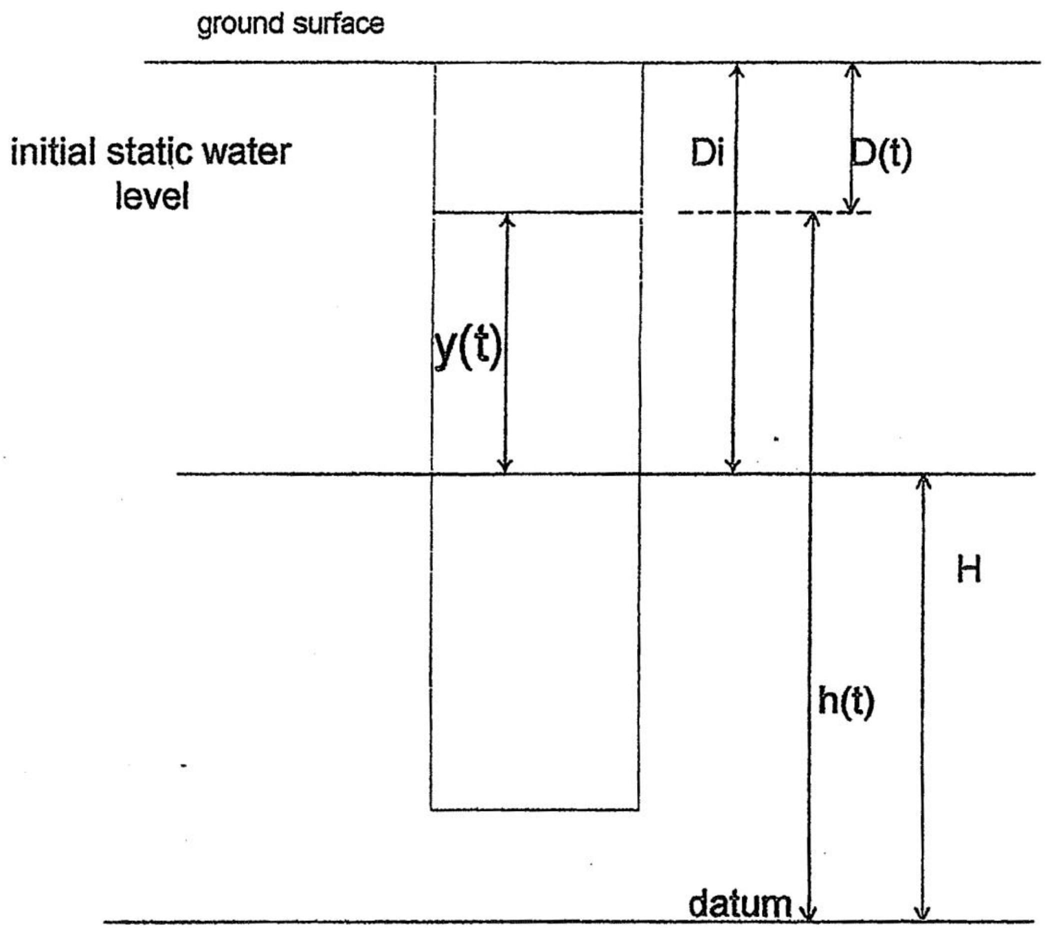


Bail down test, Rising Head Test

$$y(t) = H - h(t)$$

$$y(t) = D(t) - Di$$

Notice, y(t) is always positive and decreases with time.

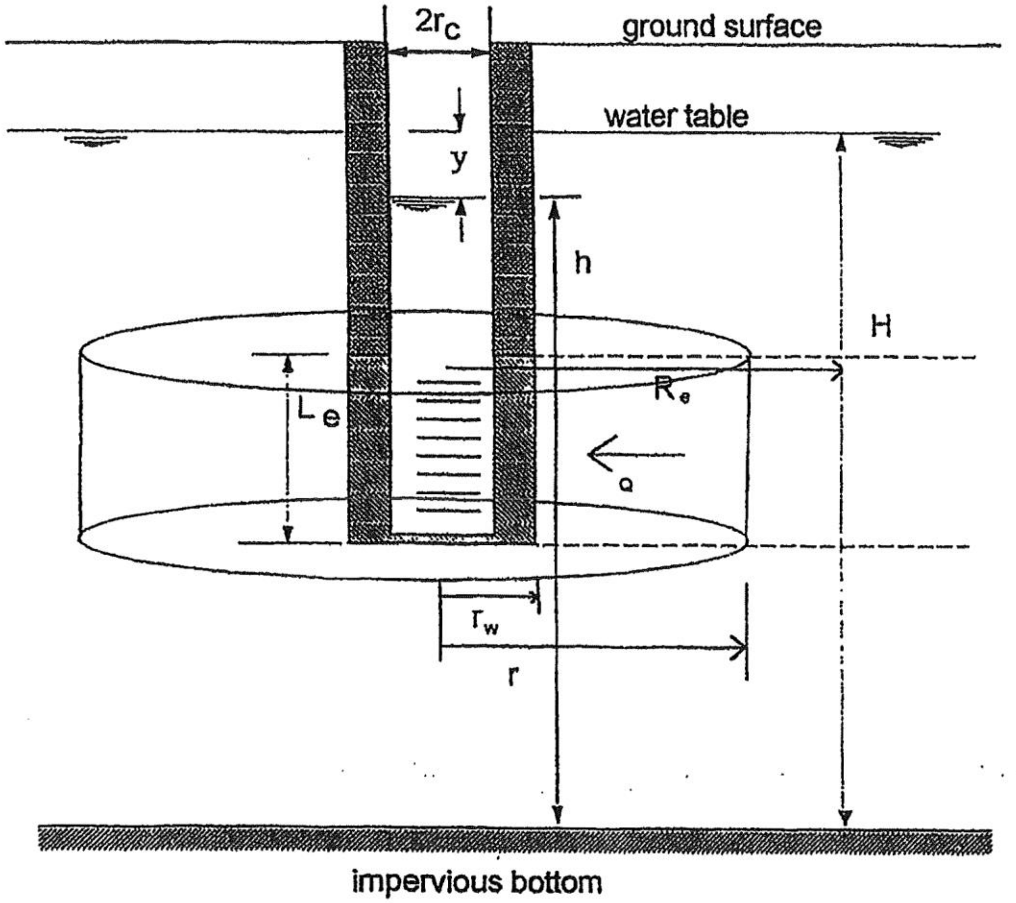


Slug In, Bail In, Falling Head Test

$$y(t) = h(t) - H$$

$$y(t) = Di - D(t)$$

Notice, y(t) is always positive and decreases with time.



$$Q = -KA\frac{d\phi}{dr} = -K2\pi r L_e \frac{d\phi}{dr}$$

$$Q\int_{r_w}^{R_e} \frac{1}{r} dr = -K2\pi L_e \int_{h}^{H} d\phi$$

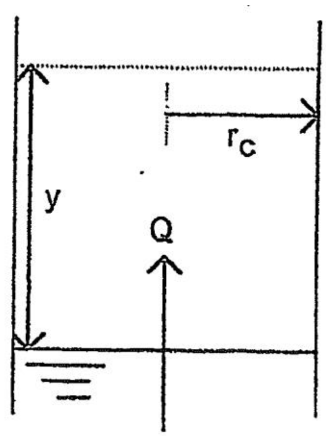
$$Q\int_{r_w}^{R_e} \frac{1}{r} dr = -K2\pi L_e \int_{h}^{H} d\phi$$

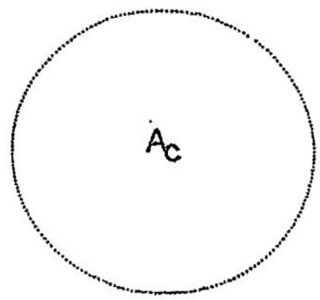
$$Q = \frac{2\pi K L_e (H-h)}{\ln\left({}^{R_e}/_{r_w}\right)}$$

$$y = H - h$$

$$Q = \frac{2\pi K L_e y}{\ln\left({}^{R_e}/_{r_w}\right)}$$

$$Q = -A_c\frac{dy}{dt}$$





$$A_c = \pi r_c^2$$

$$\frac{1}{y}\,dy = \frac{-2KL_e}{r_c^2 \ln\left({}^{R_e}/_{r_w}\right)}\,dt$$

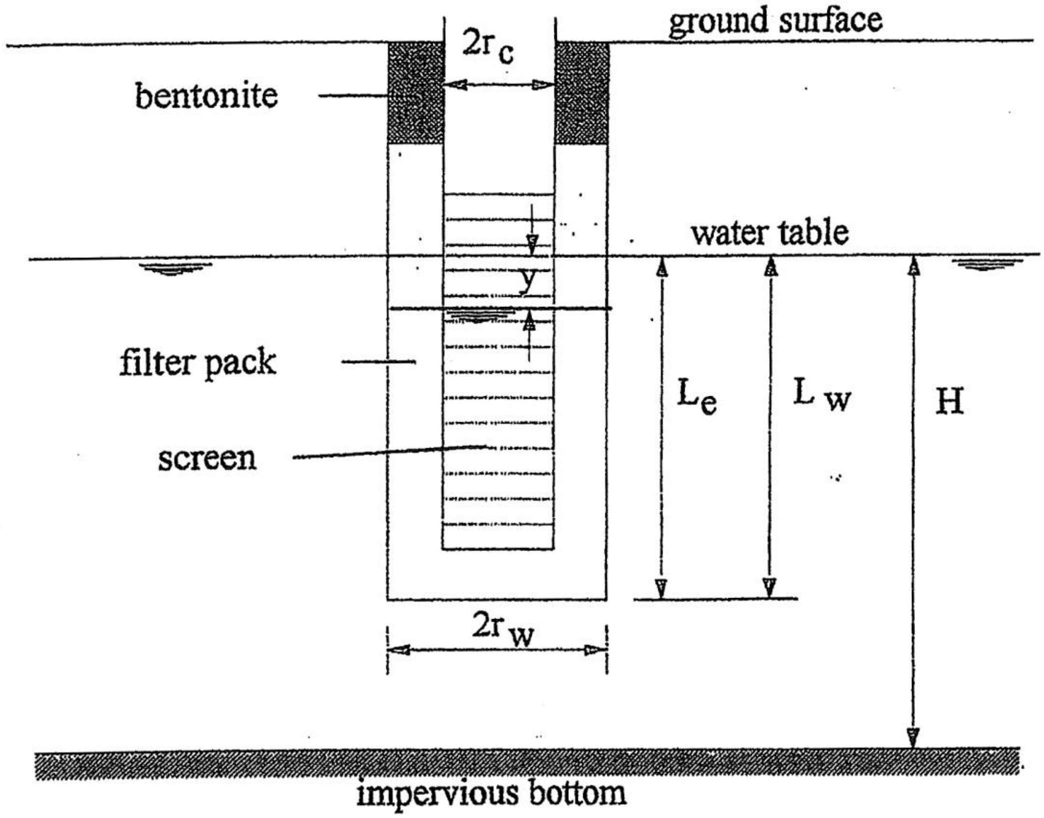
$$\ln(y) = \left[\frac{-2KL_e}{r_c^2 \ln(R_e/r_w)}\right] t + c$$

$$\ln(y) = \alpha t + c$$

$$\alpha = \frac{-2KL_e}{r_c^2 \ln\left({}^{R_e}/_{r_w}\right)}$$

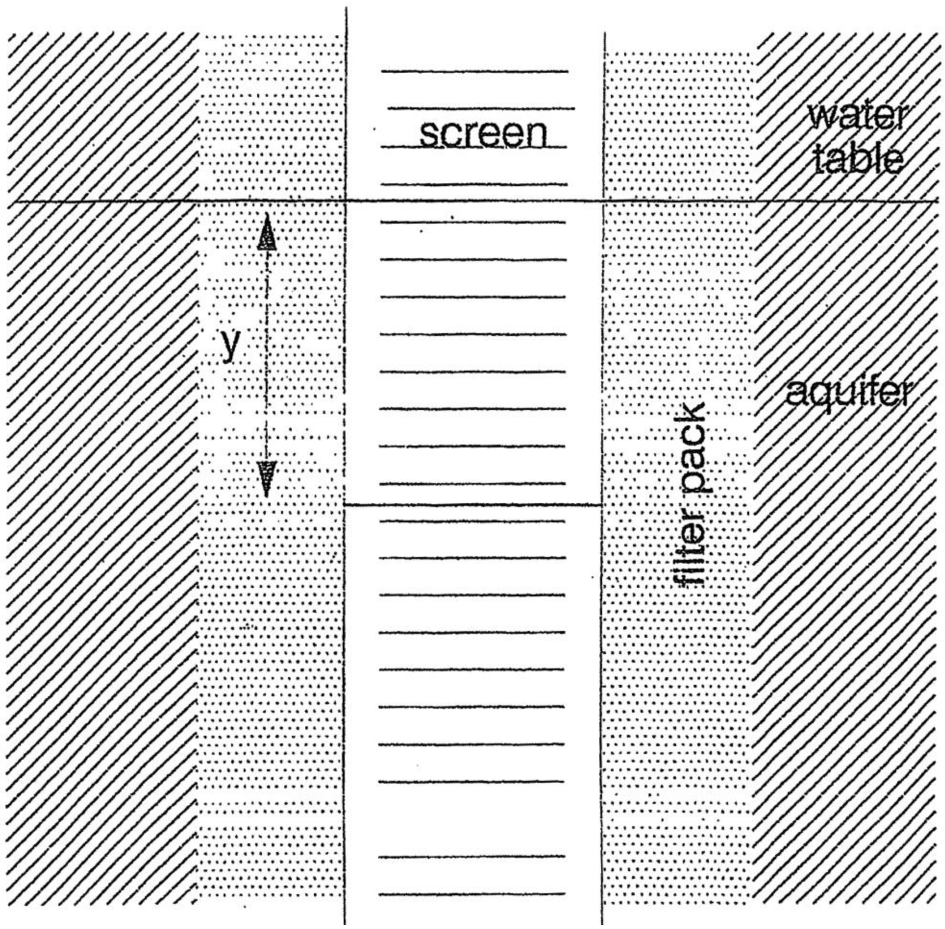
$$K = \frac{-\alpha r_c^2 \ln(R_e/r_w)}{2L_e}$$

Partial-Penetration:



Water Level is in the Screen:
Should do rising head. Theory does not account for unsaturated flow. Consideration of drainage from the filter pack.

Gravel Pack Drainage

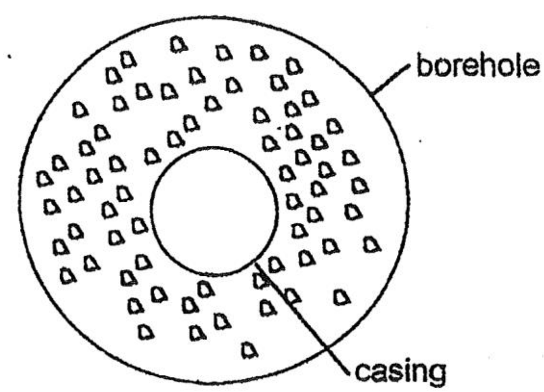


Partial Penetration

$$L_e = length\ of\ screened\ region\ below\ water\ table$$

$$L_e = L_w$$

$$A_c = \pi r_c^2 + \pi(r_w^2 - r_c^2)\Theta$$

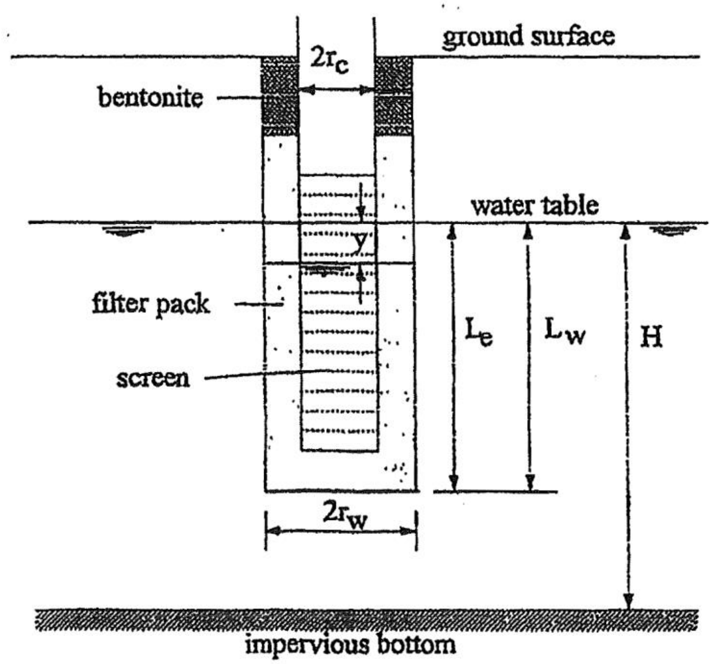


$$\Theta = Filter\ Pack\ Drainable\ Porosity$$

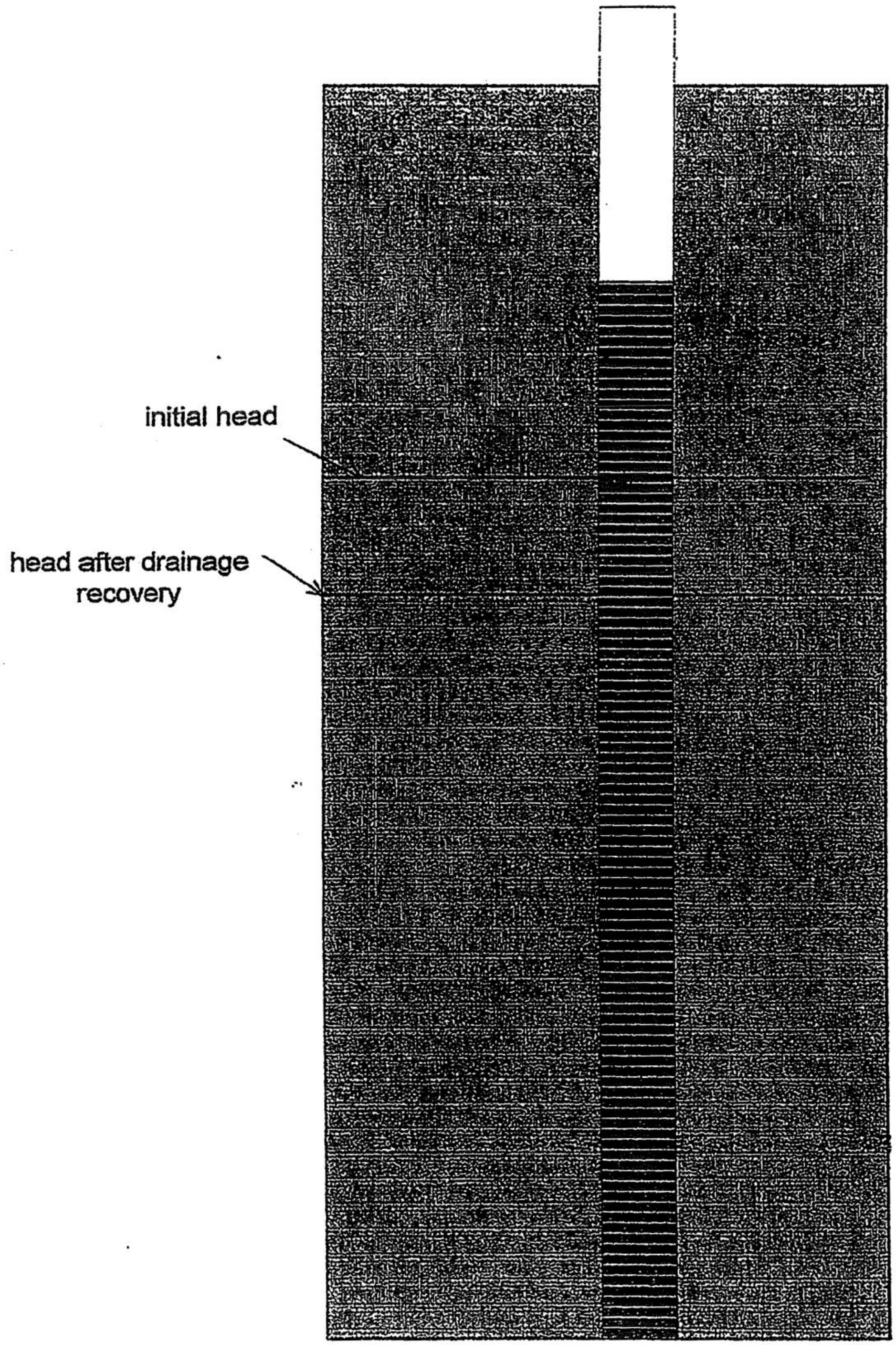
$$K = \frac{-\alpha r_c^2 \ln(R_e/r_w)}{2L_e}$$

where

$$r_e^2 = r_c^2 + \Theta(r_w^2 - r_c^2)$$



Consider a case with no inflow from the aquifer


initial head
head after drainage
recovery

Total Recovery due to gravel pack drainage when no water comes into the well from the aquifer

del y (ft)	rc (inch)	rb (inch)	ne (%)	y after filter pack drainage (ft)	fraction of del-y	effective volume(L)
2	1	4	0	2	1	1.236505
2	1	4	5	1.1428571	0.571429	1.236505
2	1	4	10	0.8	0.4	1.236505
2	1	4	15	0.6153846	0.307692	1.236505
2	1	4	20	0.5	0.25	1.236505
2	1	4	25	0.4210526	0.210526	1.236505
2	1	4	30	0.3636364	0.181818	1.236505
2	1	5	0	2	1	1.236505
2	1	5	5	0.9090909	0.454545	1.236505
2	1	5	10	0.5882353	0.294118	1.236505
2	1	5	15	0.4347826	0.217391	1.236505
2	1	5	20	0.3448276	0.172414	1.236505
2	1	5	25	0.2857143	0.142857	1.236505
2	1	5	30	0.2439024	0.121951	1.236505
1	1	4	0	1	1	0.618252
1	1	4	5	0.5714286	0.571429	0.618252
1	1	4	10	0.4	0.4	0.618252
1	1	4	15	0.3076923	0.307692	0.618252
1	1	4	20	0.25	0.25	0.618252
1	1	4	25	0.2105263	0.210526	0.618252
1	1	4	30	0.1818182	0.181818	0.618252
1	1	5	0	1	1	0.618252
1	1	5	5	0.4545455	0.454545	0.618252
1	1	5	10	0.2941176	0.294118	0.618252
1	1	5	15	0.2173913	0.217391	0.618252
1	1	5	20	0.1724138	0.172414	0.618252
1	1	5	25	0.1428571	0.142857	0.618252
1	1	5	30	0.1219512	0.121951	0.618252

Effect of changes in “drainable porosity” on Hydraulic Conductivity Estimate

rc (inch)	rw (Inch)	n (%)	re^2	Relative K
1	4	0	1	1
1	4	. 5	1.75	1.75
1	4	10	2.5	2.5
1	4	15	3.25	3.25
1	4	20	4	4
1	4	25	4.75	4.75
1	4	39	5.5	5.5

Drainable Porosity

Full Penetration: The well is screened entirely below the water table.

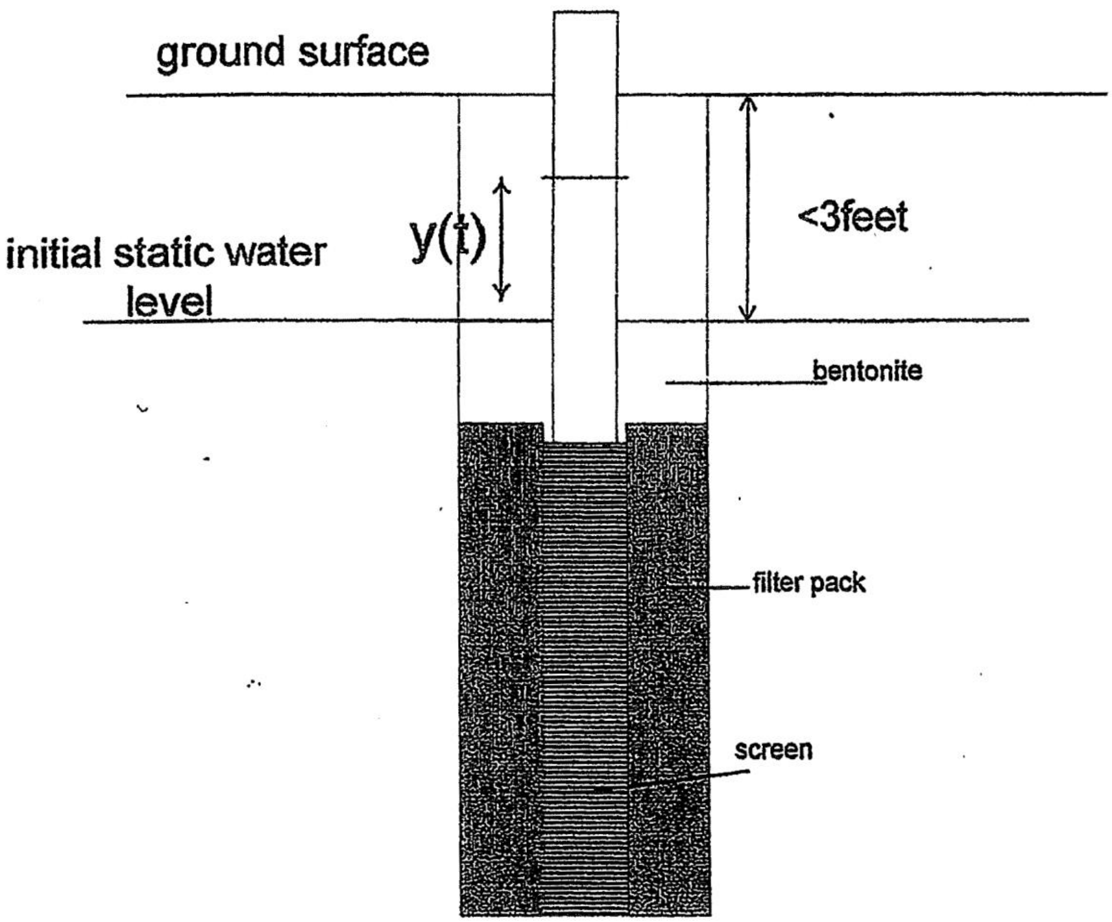
- If the well is screened entirely below the water table, the drainable porosity is zero (0).

Partial Penetration: The water level is in the well screen.

- Default Drainable Porosity: 15% (0.15)
- Minimum default value of 15% shall be used for gravel pack porosity.
- An alternative value which is greater (i.e., 20% etc.) may be used if justification is provided.

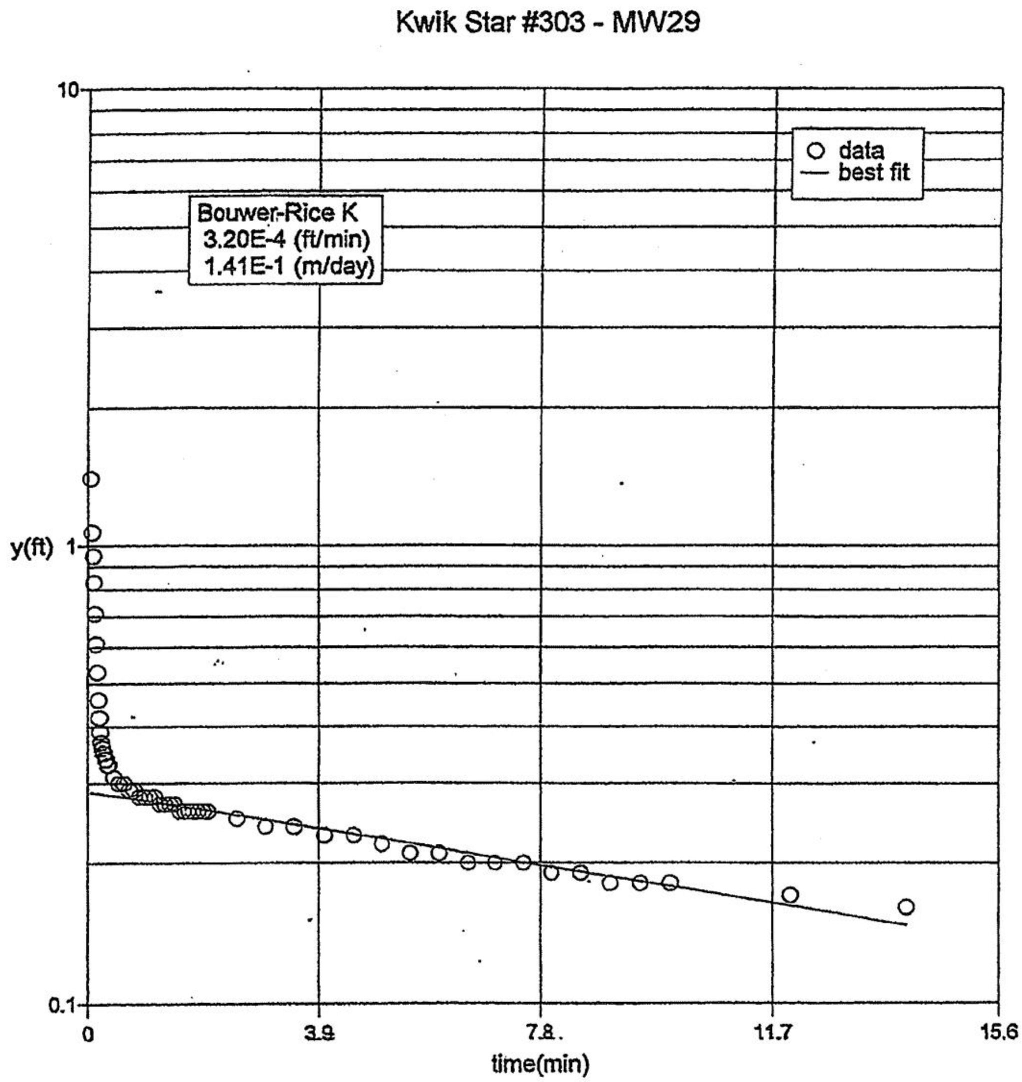
Slug In Tests

If a partially penetrating well cannot be installed (groundwater less than 3 feet below grade), a slug-in test must be conducted on fully penetrating wells, i.e. completely submerged well screens. The drainable porosity is zero (0).

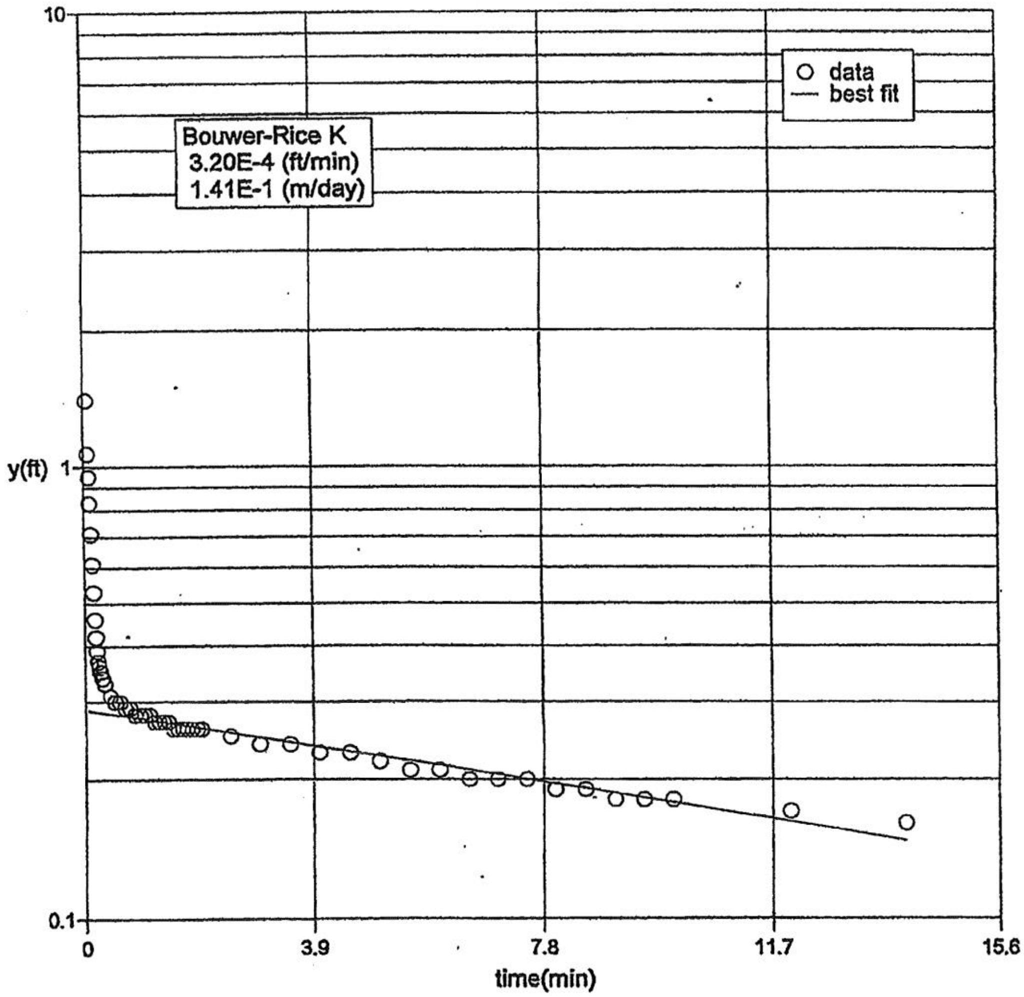


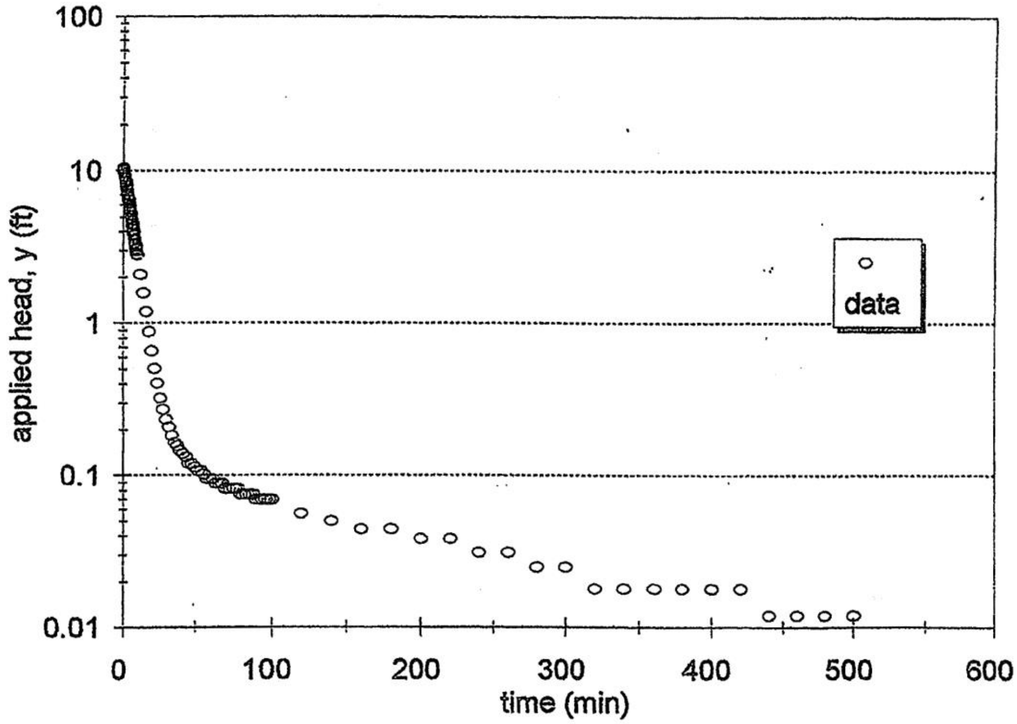
Judgment in Estimating Slope to Use.

Engineering Judgement (WAG).

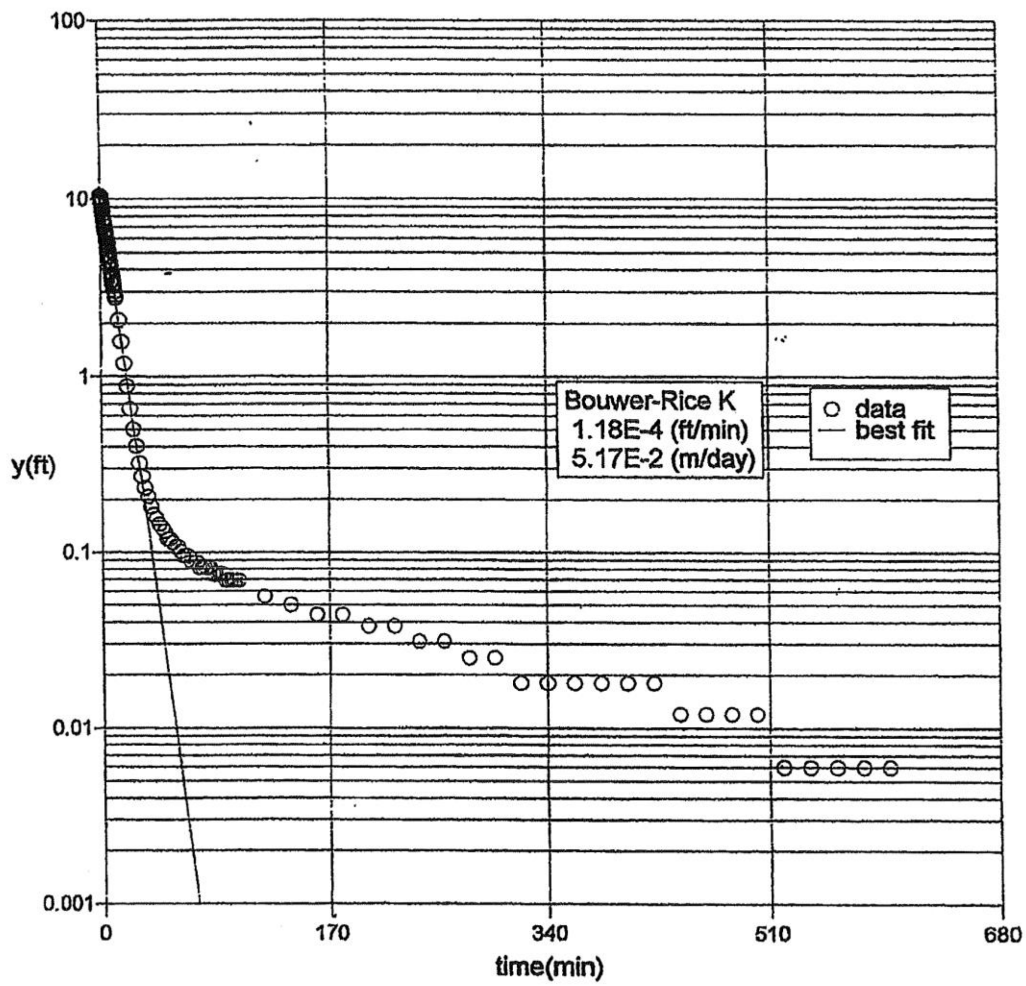

Kwik Star #303 - MW29
Bouwer-Rice K
3.20E-4 (ft/min)
1.41E-1 (m/day)
data
best fit
y(ft)
10
1
0.1
0
3.9
7.8
11.7
15.6
time(min)

Kwik Star #303 - MW29

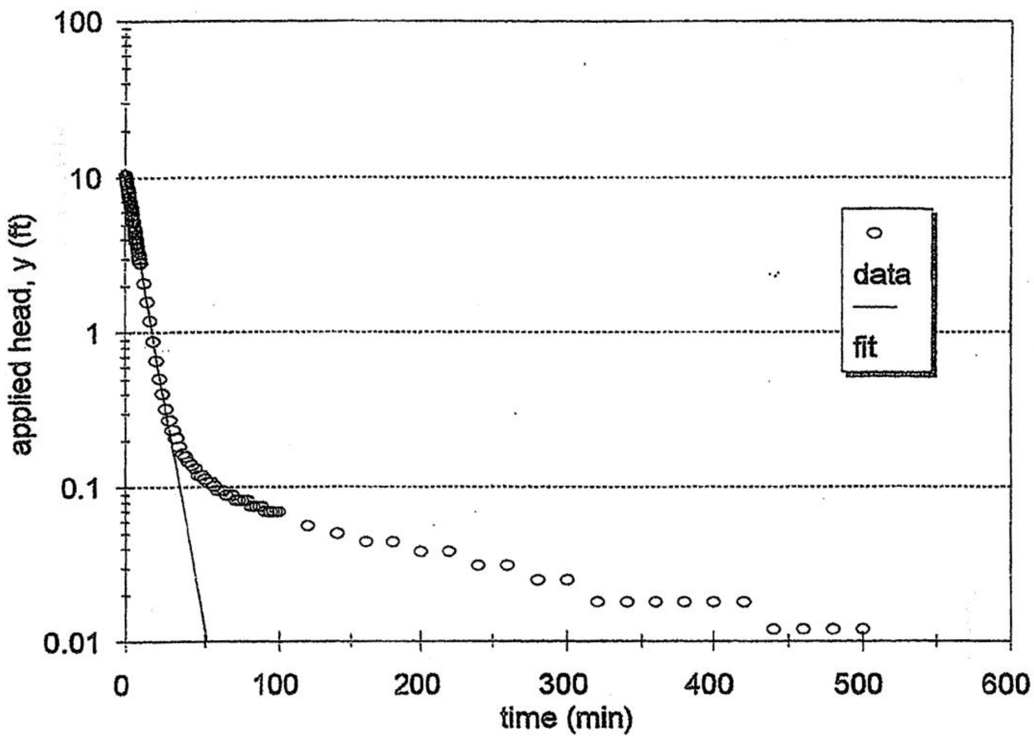


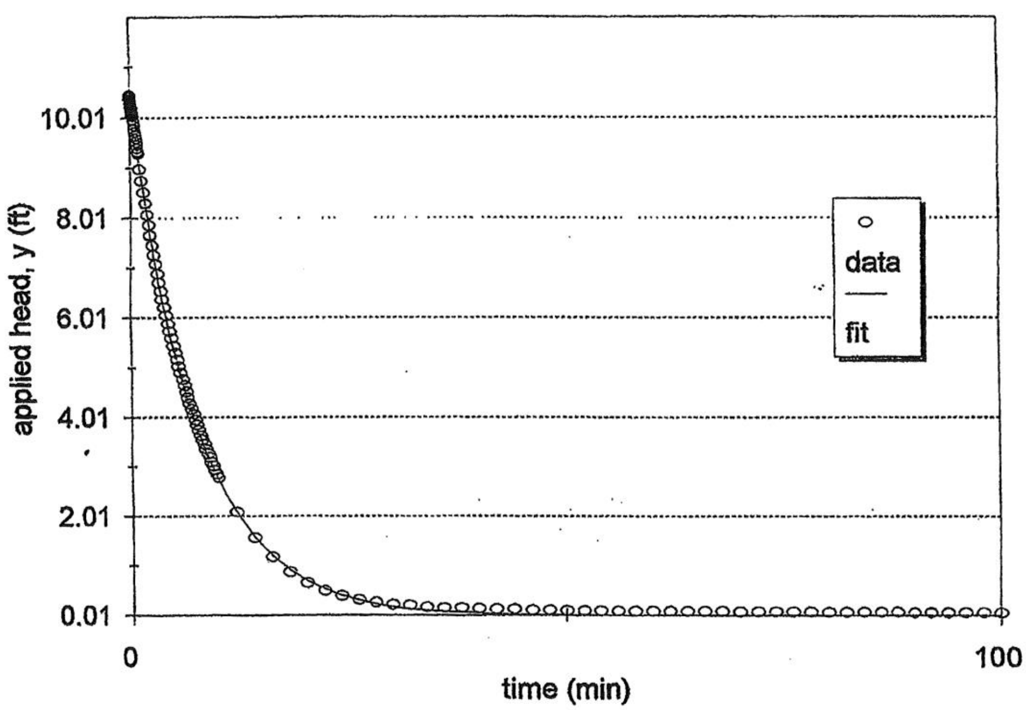


100
10
1
0.1
0.01
applied head, y (ft)
0
100
200
300
400
500
600
time (min)
data



100
10
1
0.1
0.01
0.001
y(ft)
0
170
340
510
680
time(min)
Bouwer-Rice K
1.18E-4 (ft/min)
5.17E-2 (m/day)
data
best fit

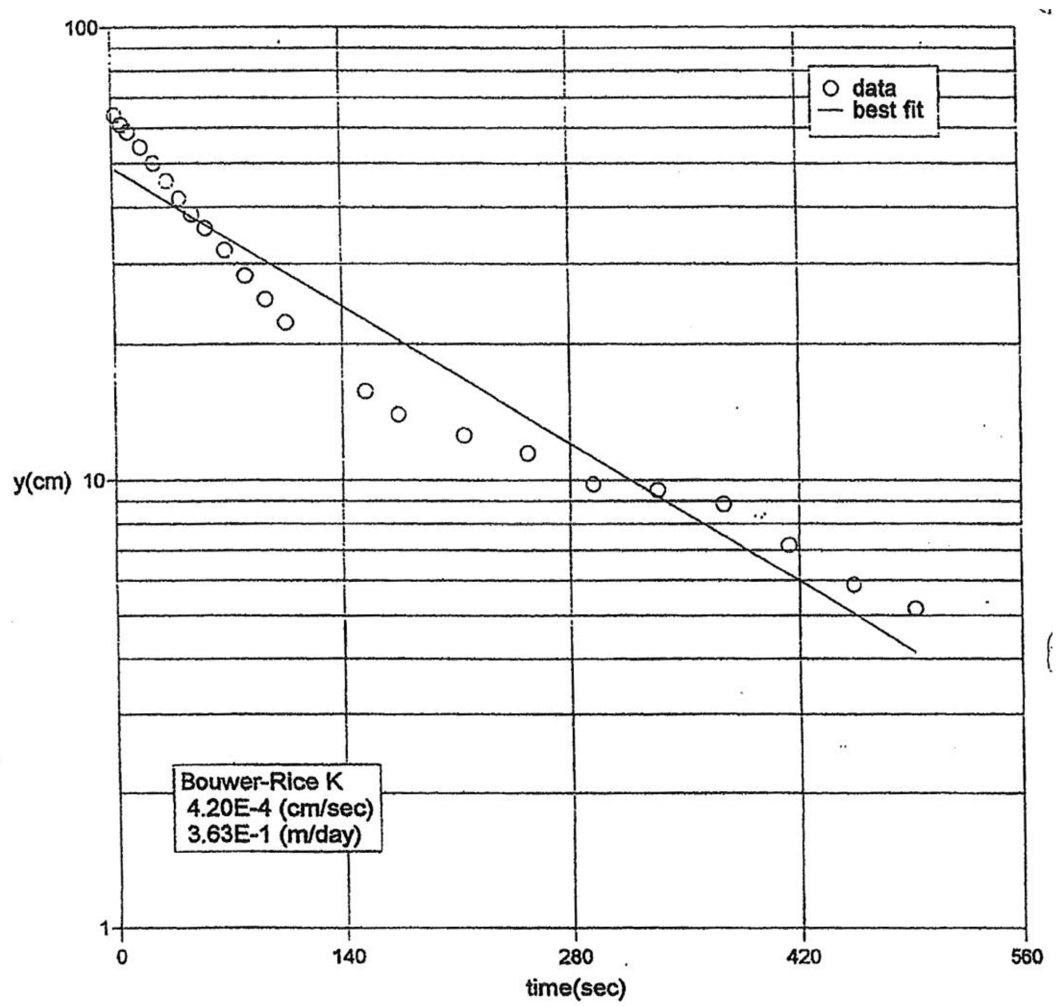




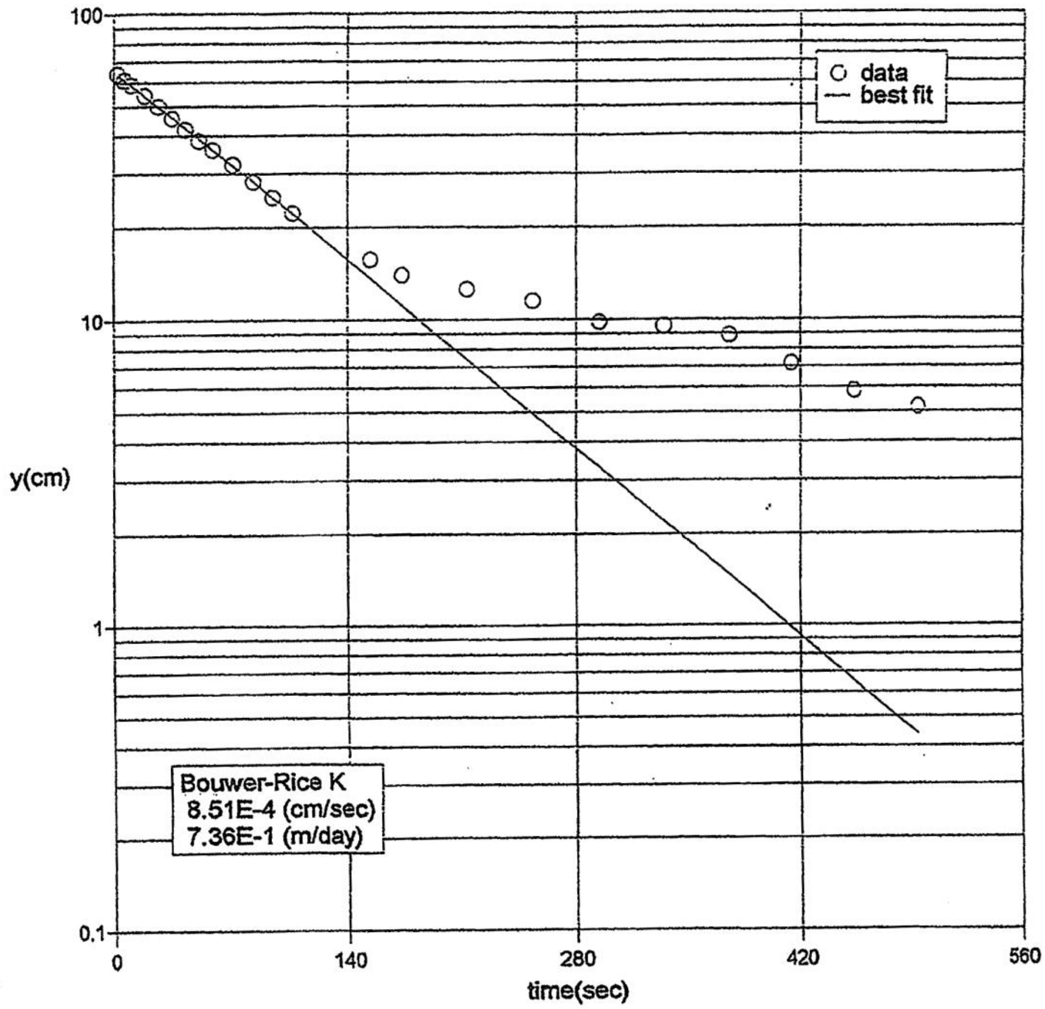
Recommendations for Estimating the Slope

Judgement:
Generally, the last 10% of the recovery should be ignored. 10% of the initial y, the first measured change in head produced by the slug or bailing.
The first 10 to 20% of the recovery should be ignored.
For BRSLUG users, use a weight of0 for the first 10-20% of the recovery and last 10% of the recovery.

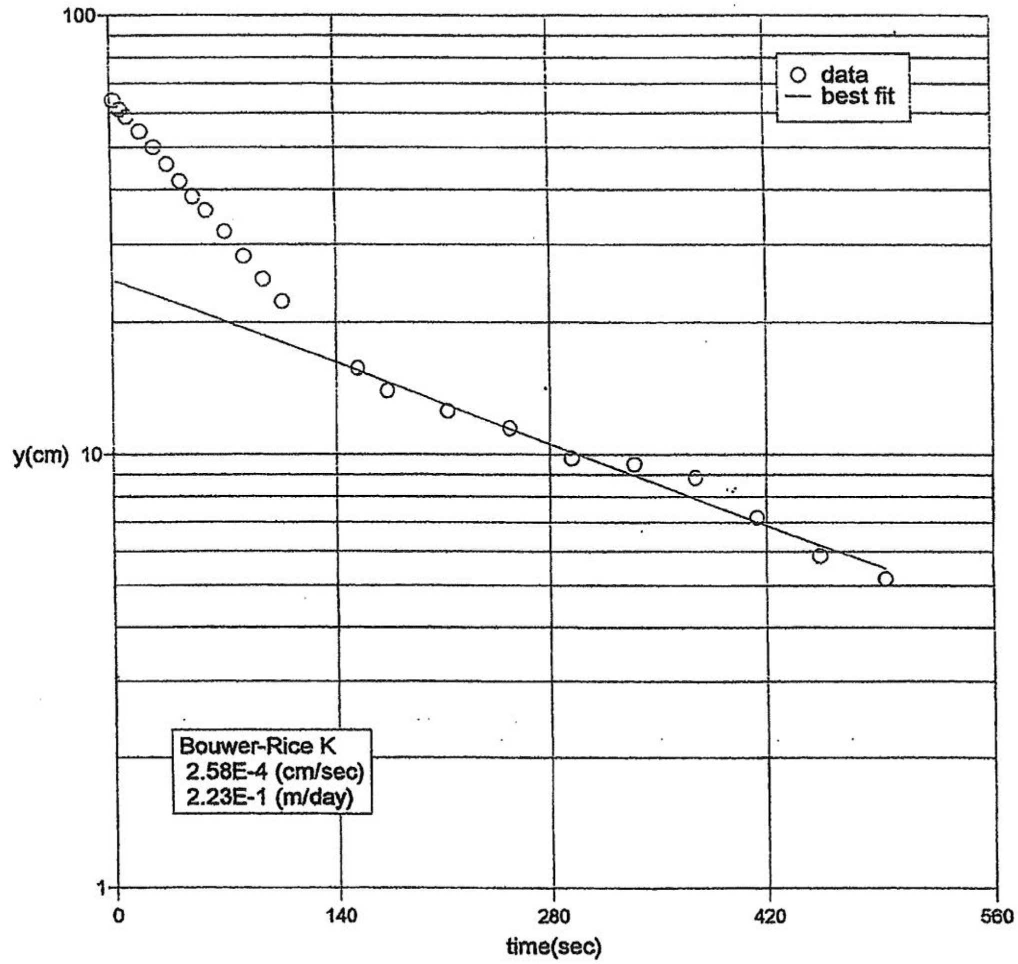
If the slug change in head is 2 feet, ignore (assign a weight of zero) to;
first 0.2 to .4 feet of recovery and last 0.2 feet of recovery.
Base slope on y of 1.8 to 0.2, or 1.6 to 0.2 feet.



Fitting All the Data, Example Problem #3



Fitting Data from 2 to 106 seconds, Example Problem #3



Fitting Data from 154 to 494 seconds, Example Problem #3

Slug Tests

Ideally, should be from well screened entirely below the water table.

Drainable porosity is an ad-hoc attempt to account for the effect of drainage from the filter pack on the recovery. Is OK when the drainage from the filter pack is much faster than inflow from the groundwater system.

In reality, drainage from the filter pack and groundwater inflow often take place at the same *time.*

What are slug tests measuring?

Even without drainage from the filter pack, slug tests are an estimate of K with a factor of 2 to 4 times.

Repeated slug tests in the same well can vary by a factor of 3.

$$\mathcal{L}n(y):$$

Slug Tests: Relatively Easy:

Difficult for sites with fast recovery.

Accuracy is probably plus or minus two to four times.

Comparison to Pumping Tests:

Order of Preference:

Pumping Tests

Slug Tests

Laboratory Tests (Often 2 to 3 orders of magnitude too low).

Software:
Aquisolv
BRSLUG

Summary and Other Considerations

1. Bouwer-Rice uses the change in head produced by the slug test, y.
2. For partial penetration, use a drainable porosity of 15%, or justify another value.
3. Generally, the recovery representing 80% to 10% of the initial change in head should be used for estimating slope of time versus log(t). What is the actual value of y where a late change in slope occurs?
4. If bedrock is encountered above groundwater at any time, the groundwater will be considered a protected groundwater source, regardless of hydraulic conductivity-testing.
5. If calculations are done by hand, the groundwater professional must include a copy of all calculations and must provide a graph using semi-log paper.
6. If the 'best fit' line is developed by a computer program and is manually adjusted, an explanation must be provided to justify the adjustment.
7. For shallow groundwater (<3 feet below grade), install a fully penetrating well and use a slug in test.

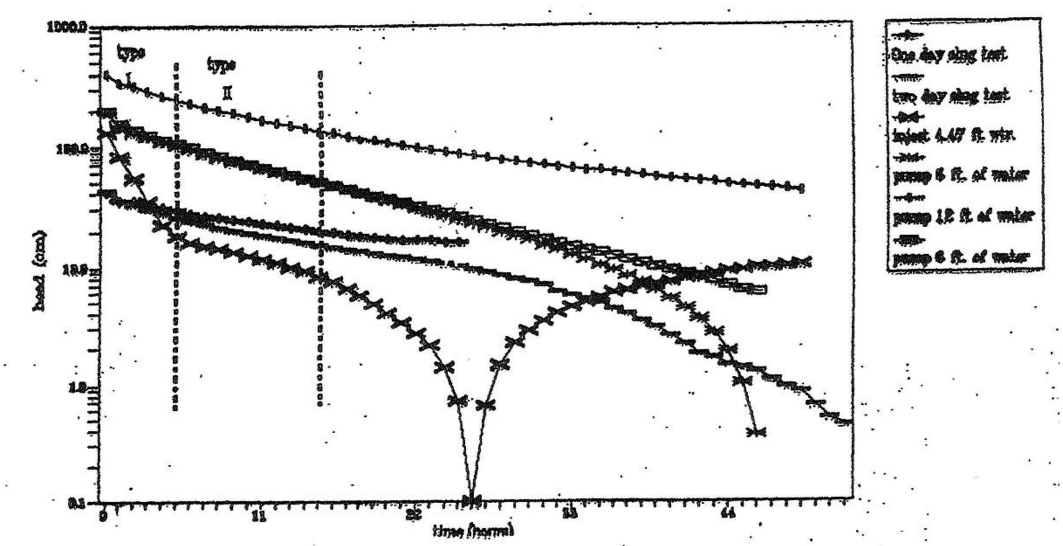


Figure 23. Type II slopes in S-4 E well

The Bouwer-Rice Slug Test
by LaDon Jones

If the water level in a well is suddenly raised or lowered, the speed at which it returns to equilibrium is related *to* the hydraulic conductivity of the surrounding medium, the geometry of the screened region of the well and the boundary conditions (location of the water table and impervious layers). This has led to several methods for estimating hydraulic conductivity from single well response tests (also called bail or slug tests). The methods often differ in their assumptions, but all use the same field procedure: the water level in the well is quickly raised or lowered and the recovery to the initial water level is measured against time.

The Bouwer and Rice Slug Test (Bouwer and Rice, 1976, Bouwer, 1989) was developed to account for the presence of a water table (unconfined aquifer) and an impervious boundary below the well as illustrated in Figure 1.

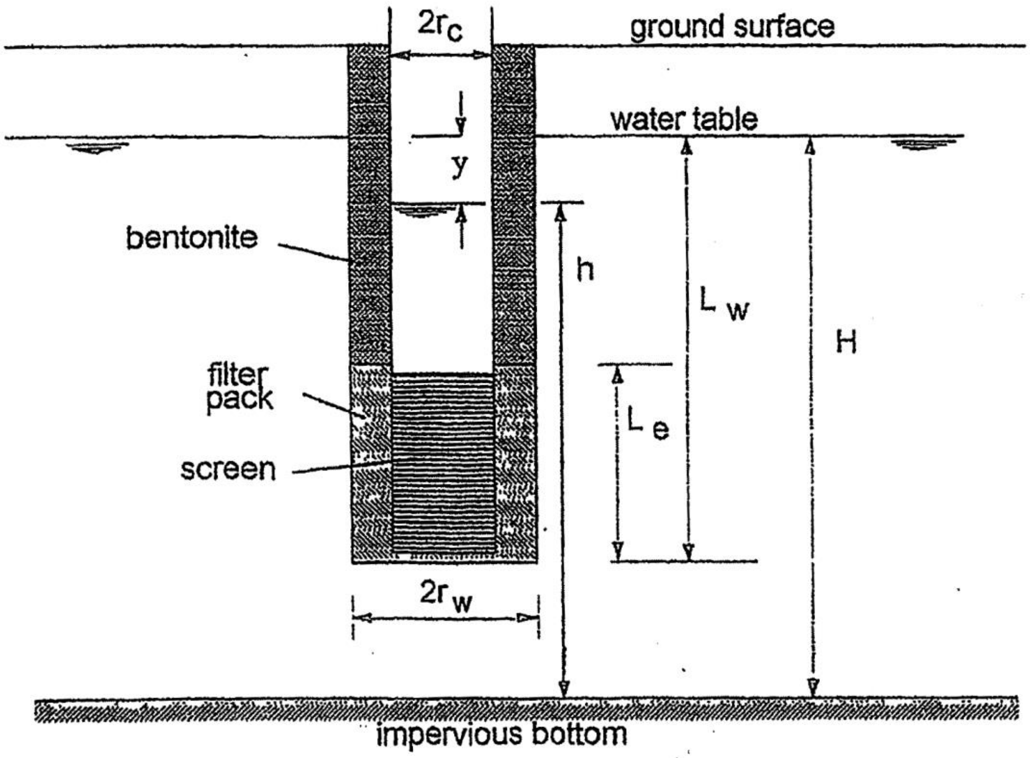


Figure 1. Slug test Geometry

Theory

The governing equation for the Bouwer-Rice slug test is based on Darcy's law. Darcy's Law can be written as,

Equation 1

$$Q_x = KA\frac{d\phi}{dx}$$

where Q is the flowrate, K is the hydraulic conductivity, A is the cross-sectional area of flow, ϕ is the head, and x is the direction. An approximate expression for Darcy's law for the situation shown in Figure 1 can be written by assuming radial flow to the well and neglecting vertical flow,

Equation 2

$$Q = 2\pi r L_e K\frac{d\phi}{dr}$$

where L_e is the length through which water enters the well from the aquifer, and r is the radial distance from the well. Neglecting contributions from storage (2) can be integrated between two boundary conditions,

Equation 3

$$Q\int_{r_w}^{R_e}\frac{1}{r}dr = 2\pi L_e K\int_{h}^{H}d\phi$$

where h is the head in the well at r_w and H is the undisturbed head at R_e (R_e is the distance at which the slug test has no measurable effect on the initial undisturbed head H). Performing the integration of (3) and rearranging yields,

Equation 4

$$Q = \frac{2\pi K L_e(H-h)}{\ln(R_e/r_w)}$$

Noting that h = H -y and substituting in (4) gives, Equation 5

$$Q = \frac{2\pi K L_e y}{\ln(R_e/r_w)}$$

where y is the change in head in the well due to the slug test (see Figure 1). Equation (5) includes the flowrate (Q) into (or out of) the well, however this is not measured directly during a slug test. The flowrate can be related to the measured recovery in the well by,

Equation 6

$$Q = -A_c \frac{dy}{dt}$$

where A_c is the cross-sectional area of the casing where the water is rising in the well and t is time. Noting that $A_c = \pi r_c^2$, substituting (6) into (5) for Q, and separating variables leads to

Equation 7

$$\frac{1}{y} dy = \frac{-2KL_e}{r_c^2 \ln(R_e/r_w)} dt$$

Recovery versus time
After slugging the well, the theoretical rate of recovery *is* found by integrating (7), which leads to

Equation 8

$$\ln(y) = \frac{-2KL_e}{r_c^2 \ln(R_e/r_w)} t + contant$$

Noting that the coefficient oft on the right hand side of (8),

Equation 9

$$\frac{-2KL_e}{r_c^2 \ln(R_e/r_w)}$$

is presumed to be composed of known values or constants, the key result of (8) implies that a plot oft versus ln(y) should) in theory, be linear, and the coefficient (9) is equal to the slope of the line. This can also be seen by integrating (7) between two points during the recovery, say (t_1,y_1), (t_2,y_2), where $t_2 > t_1$ (Figure 2), and solving for K,

Equation 10

$$K = \frac{r_c^2 \ln(R_e/r_w)}{2L_e} \left[\frac{\ln(y_1/y_2)}{(t_2 - t_1)} \right]$$

The second fraction on the right hand side of (10) is minus the slope of t versus ln(y), so (10) can also be written as,

Equation 11

$$K = \frac{-\alpha r_c^2 \ln(R_e/r_w)}{2L_e}$$

where a. is the slope oft versus ln(y). The slope can be easily determined directly by linear regression of ln(y) on t, where tis the independent variable and ln(y) is the dependent variable. Almost all spreadsheets feature linear regression.

It can be noted in Figure 2, the plot of an actual slug test, that in practice a plot oft versus ln(y) may deviate from the expected straight line behavior. For this test the well was developed prior to slug testing and it is felt the initially rapid recovery represents a zone of increased hydraulic conductivity in the immediate vicinity of the well The later straight line portion is thought to be more representative of the undisturbed aquifer material. Some judgment is often required.

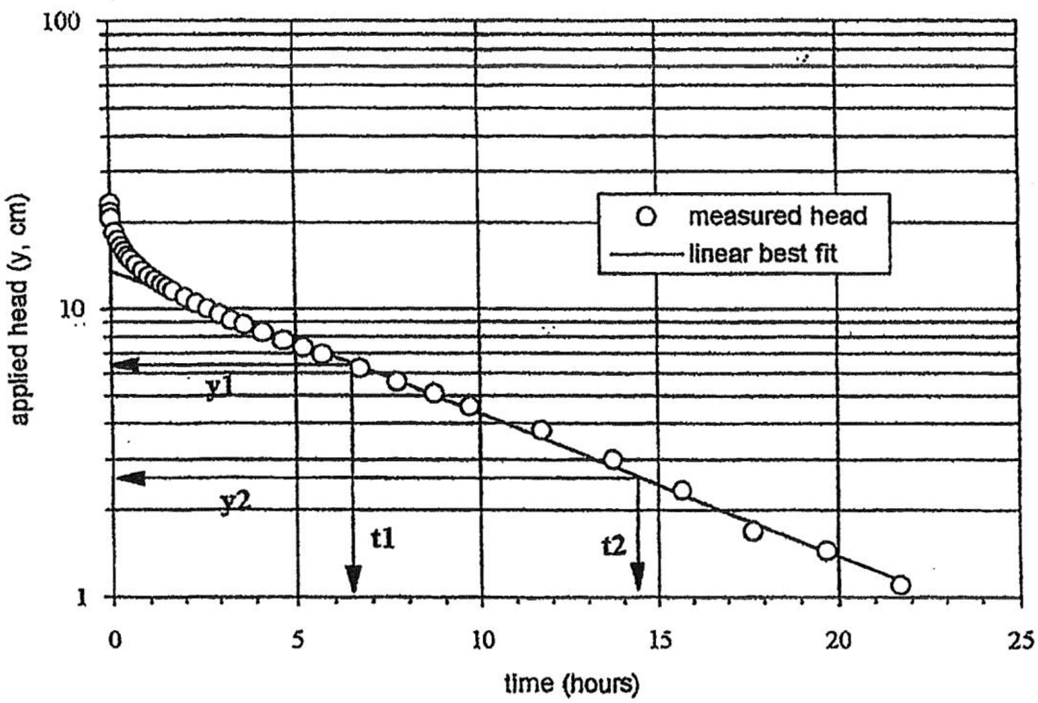


Figure 2. Slug test results

Estimating the Slope

In estimating the slope of ln(y) versus t, it should be noted that this is not the slope of the graph of y versus ton semi-log paper (for example> Figure 2.). The slope is found from

Equation 12

$$slope = \alpha = \frac{\ln(y_2/y_1)}{(t_2 - t_1)}$$

where $t_2 > t_1$. If ln(y) versus time is plotted on linear scales, then the slope of the graph will give the correct slope.

The equations (10) or (11) are based on the change in the head from the slug (y) and not on the head (h) or the depth to water. Plotting the head or depth to water will not give the correct slope.

Estimating ln(R_e/r_w)

Before (10) or (11) can be used the term ln(R_e/r_w) must be estimated. Specifically R_e is unknown (there are no additional wells to estimate the influence of the slug at some distance from the slugged well), and in particular the effect of different values of H, L_e,·L_w and r_w on R_e is unknown. The primary contribution of Bouwer and Rice (1976) was the use of an electrical analog model to derive empirical relationships for estimating Re as a function of the boundary conditions and well geometry. In fact, most slug test methods are similar (t versus ln(y) is linear) in practice, but differ in their evaluation of the influence of well geometry and boundary conditions on K (Chapuis, 1989).

There are two equations for estimating ln(R_e/r_w).

Case 1: $L_w < H$

Equation 13

$$\ln\left(\frac{R_e}{r_w}\right) = \left[\frac{1.1}{\ln(L_w/r_w)} + \frac{A + Bln[(H - L_w)/r_w]}{L_e/r_w}\right]^{-1}$$

Case 2: L_w=H

$$\ln\left(\frac{R_e}{r_w}\right) = \left[\frac{1.1}{\ln(L_w/r_w)} + \frac{C}{L_e/r_w}\right]^{-1}$$

where A, B, and C are dimensionless numbers plotted in Figure 3 as a function of L_e/r_w

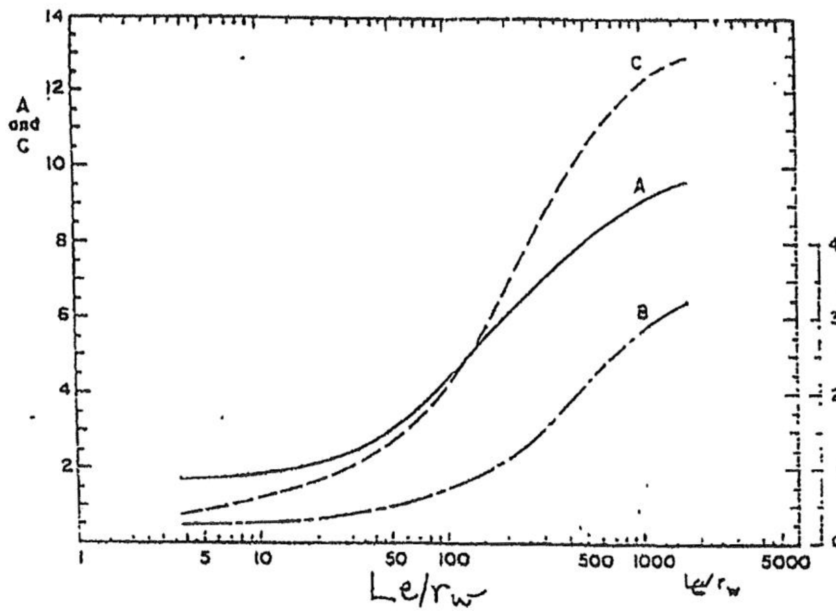


Figure 3. Dimensionless parameters A, B, and C as a function of L_e/r_w

Partial Penetration

It is common in the placement of monitoring wells at hazardous sites to place the well to monitor the water table. In this case the water level in the well is usually in the screened region and the value of L_e which should be used in the BR analysis is the saturated thickness of the screened region (shown in Figure 4), not the total length of the screened region (Figure 1).

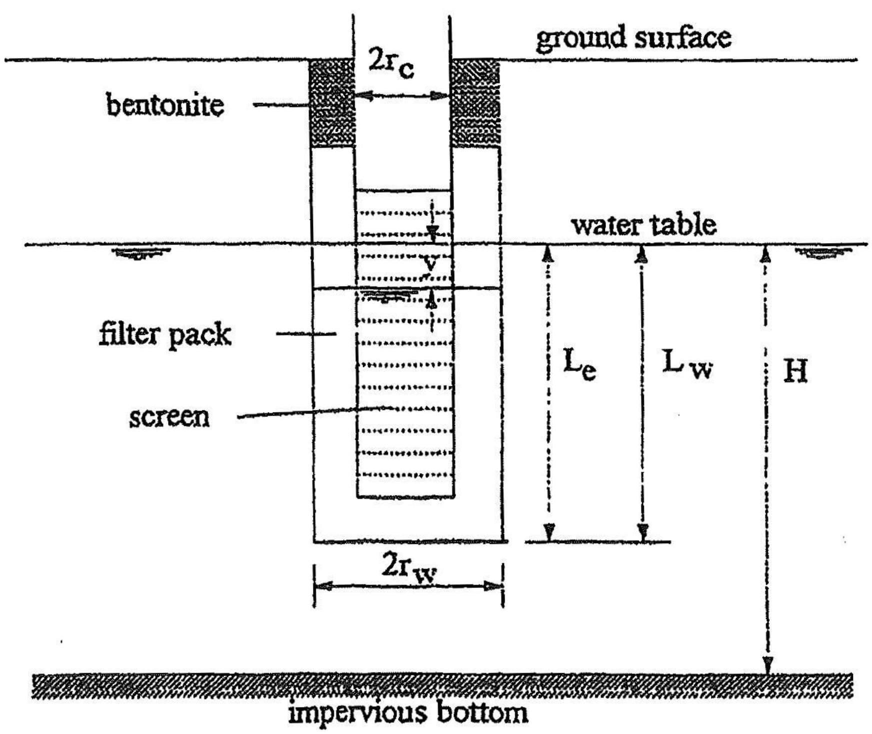


Figure 4. Partial penetration

In addition, the cross-sectional area in which the water is rising now includes the porosity of the gravel or sand pack between the well casing and the borehole. Hence A_c in (6) should account for this and is estimated from

Equation 15

$$A_c = \pi r_c^2 + \pi(r_w^2 - r_e^2)\Theta$$

where Θ is the porosity of the:filter pack. Using this expression in developing (10) or (11) results in the same equations, except for the replacement of r_c with r_e (effective radius). For example, the result for (11) is,

Equation 16

$$K = \frac{-\alpha r_e^2 \ln(R_e/r_w)}{2L_e}$$

where

Equation 17

$$r_e^2 = r_c^2 + \Theta(r_w^2 - r_c^2)$$

Equation (16) is a general form. If the water level is in the casing, then use Θ = 0 in (17).

Summary of Slug Test Analysis

To summarize the procedure for the Bouwer-Rice Slug Test.

- Determine the slope of the best linear fit to ln(y) versus t. where y is the change in head and t is time. Call the slope α.
- Find $\ln(R_e/r_w)$ from equation (13) or (14) and Figure 3.
- Find K from (16).

Units

You must use consistent units. For example, if y is in cm and t is in hours, then cm should be used for all measurements (H, L_e, r_c, etc.) and the units of K will be cm/hour.

References

Bouwer. H and RC Rice. 1976. A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells. Water Resources Research. v. 12, no. 3, pp. 423-428.

Bouwer, H. 1989. The Bouwer and Rice slug test-an update. Ground Water. v. 27, no. 3, pp. 304-309.

Chapuis, RP. 1989. Shape factors for permeability tests in boreholes and piezometers. Ground Water. v. 27, no. 5, pp. 647-654.