CDM Smith

Memorandum

To: *Josephine Newton-Lund, PMP, Senior Project Manager, Environmental Branch,*
U.S. Army Corps of Engineers
Shannon Smith, PE, Program Manager, Veterans Health Administration

From: *Nathan Smith, PMP, Senior Project Manager, CDM Federal Programs Corporation*
Neil Smith, Project Technical Leader, CDM Federal Programs Corporation

Date: *January 22, 2020*

Subject: ***Modification #3 to Phase 2 Field Sampling Plan***
700 South 1600 East Tetrachloroethene Plume Superfund Site,
Salt Lake City, Utah

On behalf of the U.S. Army Corps of Engineers (USACE), CDM Federal Programs Corporation (CDM Smith) prepared this minor field modification (MFM) #3 to the Phase 2 Field Sampling Plan (FSP). The FSP is an appendix to the Phase 2 Remedial Investigation Work Plan (CDM Smith 2020) for 700 South 1600 East Tetrachloroethene (PCE) Plume Site located near the George E. Wahlen Veterans Affairs Medical Center (VAMC) in Salt Lake City, Utah. This MFM #3 to the Phase 2 FSP proposes slug testing locations.

1.0 Scope of Work

As presented in the Phase 2 Remedial Investigation Work Plan, slug tests were planned to be completed to provide an order of magnitude estimate of hydraulic conductivity (K) and transmissivity (T) of the aquifer, which will support the development of the groundwater flow model and fate and transport evaluation, and provide inputs to the mass discharge evaluation. This MFM provides the locations where slug testing will be completed and the approach that will be taken at each location. Lithologic logs, well construction diagrams, piezometric head data, location of wells relative to the groundwater plume, and the data quality objectives (CDM Smith 2020) were reviewed to determine slug testing locations. This work is anticipated to be completed in late January or early February 2021.

2.0 Slug Testing Locations

The 30 locations selected for slug testing are provided in **Table 1,** in order of highest to lowest priority. The location of each well selected for slug testing is shown on **Figure 1**. Several wells along the Guardsman Way and 1400 East Transect were selected to provide estimates of hydraulic conductivity to calculate Darcy velocity for use in mass discharge calculations. Other locations across the site with wells screened in both the shallow and deep aquifers were selected to support the development of the groundwater flow model and fate and transport evaluation.

Table 1. Locations Selected for Slug Testing

Well ID	Aquifer Zone	Well Diameter (inches)	Screen Start (ft bgs)	Screen End (ft bgs)	Water Level (ft bgs)	Slug Test Approach*
MW-02	Shallow	2	175.5	202.5	171	Pneumatic
MW-03RA	Shallow	1	215	220	188	Pneumatic
MW-03RB	Deep	1	267	272	204	Pneumatic
MW-03RC	Deep	1	307	312	204	Pneumatic
MW-04	Shallow	4	143	173	136	Pneumatic
MW-18	Shallow	2	80	90	81	Mechanical
MW-19	Shallow	2	84	94	81	Mechanical
MW-20D	Shallow	2	119	129	83	Mechanical
MW-20S	Shallow	2	79.5	89.5	83	Mechanical
MW-21	Shallow	2	62	72	65	Mechanical
MW-22	Shallow	2	64	74	64	Mechanical
MW-08A	Shallow	2	91	106	60	Mechanical
MW-08B	Shallow	2	180	200	58	Mechanical
MW-08C	Deep	1	304	309	62	Pneumatic
MW-32A	Shallow	1	114	124	83	Pneumatic
MW-32B	Shallow	1	170	180	83	Pneumatic
MW-32C	Deep	1	260	270	83	Pneumatic
MW-01S	Shallow	2	184	224	156	Pneumatic
MW-01D	Deep	4	364	404	171	Pneumatic
MW-13D	Shallow	2	79	84	13	Mechanical
MW-13S	Shallow	2	15.5	20.5	14	Mechanical
MW-13L	Deep	2	150	160	17	Mechanical
MW-15D	Shallow	2	69	74	50	Mechanical
MW-34A	Shallow	1	153.13	140	150	Pneumatic
MW-34B	Shallow	1	188.17	175	185	Pneumatic
MW-34C	Deep	1	262.82	250	260	Pneumatic
MW-34D	Deep	1	328.14	315	325	Pneumatic
MW-26A	Shallow	1	205	215	189	Pneumatic
MW-26B	Intermediate	1	235	245	180	Pneumatic
MW-26C	Deep	1	315	325	171	Pneumatic
MW-26D	Deep	1	347.75	357.75	217	Pneumatic

* Depending on well conditions, the specified slug test approach may be modified in the field.
ft bgs = feet below ground surface

3.0 Redevelopment Prior to Slug Testing

During groundwater sampling, several wells were observed to contain high amounts of sediment: MW-26C/D, MW-34B/C, and MW-13L. These locations will be redeveloped prior to the completion of slug testing. The 1-inch diameter wells (MW-26C/D and MW-34B/C) will be developed by applying compressed gas in the water column above the screened interval. By slightly pressurizing the well, slugs of water are brought to the surface. This process will continue until turbidity is less than 50 Nephelometric Turbidity Units (NTU).

Due to the depth of the screened interval and height of the water column, MW-13L will be developed by a drilling company with a development rig. A rig-mounted bailer will be used to remove excess sediment. A surge block will be raised and lowered throughout the screened interval. A pump will then be used to purge the well until turbidity is less than 50 NTU.

4.0 Slug Testing Approach

Slug testing will be collected following CDM Smith Technical Standard Operating Procedure 4-6 *Hydraulic Conductivity Testing* (CDM Smith 2020) and supplemented by the Midwest Geosciences *Field Guide for Slug Testing and Data Analysis* presented in **Attachment A** (Midwest Geosciences 2015). Dedicated pumps and any other hardware will be removed from the wells prior to slug testing. Mechanical or pneumatic slug testing equipment will be used to create a change in water level in each well tested. Pneumatic slug testing will be completed in all 1-inch diameter wells as well as some deep 2- and 4- inch diameter wells, and mechanical slug testing will be completed in shallow 2-inch diameter wells (**Table 1**). Mechanical slug tests use a weighted cylinder of a known volume to rapidly lower or raise the water level in a well so the rising or falling water level can be recorded over time. Pneumatic slug testing equipment increases air pressure in the well to depress the water level a known distance. Once equilibrium is reached, the pressure is released, and the rising water level is recorded over time. Because the water level in a well can change rapidly during the slug test, data will be recorded using a pressure transducer and data logger. Each test will conclude when the slug-induced water level change has recovered by 90 percent or more. Each test will be visually reviewed to check for excessive noise and will be recollected if necessary.

A mechanical slug will be used to conduct three rising head and three falling head tests at each well. For rising head tests, the slug is positioned just below the top of the water column and then quickly removed to initiate the test. Conversely for falling head tests, the slug is positioned just above the top of the water column and then quickly dropped to initiate the test. Where pneumatic slug tests will be completed, three rising head tests will be completed.

It is anticipated that this work will be completed in late January to early February 2021 by one geologist from CDM Smith with support from one Wasatch Environmental geologist.

Slug test data analysis will be completed immediately after data collection, following the guidelines in Chapter 12 of *The Design, Performance, and Analysis of Slug Tests* (Butler 2020). The storativity (S) and specific storage (S_s) calculated during each analysis in AQTESOLV will be compared to the range of specific storage values provided in AQTESOLV (Batu 1998) to assess whether the value was plausible for the lithology in the screened zone. Because slug tests are sensitive to near-well conditions (specifically, well skin effects due to borehole alteration of aquifer properties during drilling, installation, or development) if storativity and specific storage results are not plausible for the lithology, this suggests the presence of skin effects. The collection of multiple tests at each well (with at least one with 1-foot displacement and one with 2-foot displacement) will be used to determine if skin effects are present (Butler 2020)Well skin effects will be evident as deviations between the tests with different displacements.

Measured water levels will be normalized to the maximum expected displacement and plotted versus test time. The tests from each well will be plotted together in a coincident plot. If the plots for each well are coincident, then only one test (with the least noise, i.e., fluctuation in displacement early in the test) will be selected for analysis with AQTESOLV to estimate transmissivity or hydraulic conductivity. The slug test data analysis will be conducted to minimize any observed well skin effects on the aquifer test results by 1) using diagnostic plots to determine the analytical solution applicable to the site conditions (see Midwest Geosciences 2015 and Butler 2020 for flow charts guiding the analysis model selection), 2) selecting the most representative test, and 3) if necessary, selecting appropriate segments of the recovery curve for analysis. If skin effects at a slug test location are still evident, the estimated hydraulic conductivity will be flagged as biased low (as high permeability skins are less problematic for slug tests [Butler 1998]).

The analysis and results of the slug testing will be reported in the Remedial Investigation Report, and electronic results will be provided separately.

5.0 References

Batu, V. 1998. *Aquifer Hydraulics: A Comprehensive Guide to Hydrogeologic Data Analysis*. John Wiley & Sons, Inc., New York.

Butler, J. J. 2020. The Design, Performance, and Analysis of Slug Tests, 2nd edition. CRC Press, Boca Raton, Florida.

CDM Smith. 2020. *DRAFT FINAL Phase 2 Remedial Investigation Work Plan, Operable Unit 1, 700 South 1600 East PCE Plume, Salt Lake City, Utah*. Prepared for U.S. Army Corps of Engineers.

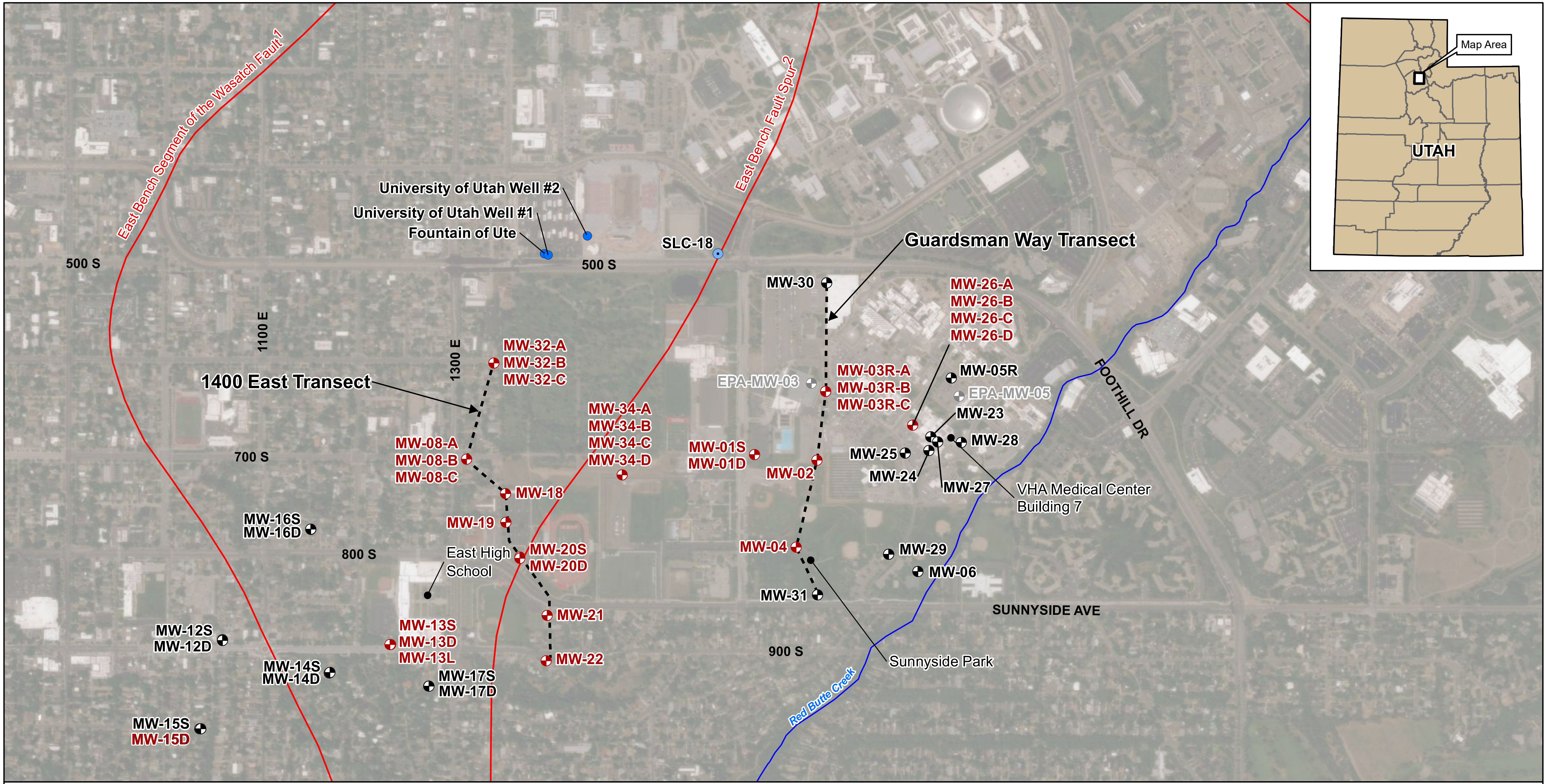
Midwest Geosciences. 2015. *Field Guide for Slug Testing and Data Analysis*. Midwest Geosciences Group Press. Available at www.midwestgeo.com.

Figures

Figure 1	Slug Test Locations

Attachments

Attachment A	Field Guide for Slug Testing and Data Analysis



Legend

- ⊕ Slug Test Location
- ⊕ Monitoring Well
- ⊕ Abandoned Monitoring Well
- ⊙ Drinking Water Supply Well
- ● Irrigation Well
- • Landmark
- - - - Monitoring Well Transect Line
- 〰 Red Butte Creek
- 〰 Fault Line

Notes:

(1) Location of University of Utah Well #1 is approximate; well is located less than 100 feet east of Fountain of Ute.

OU = operable unit
PCE = tetrachloroethene
VHA = Veterans Health Administration

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[1] Davis, F.D. 1983. Geologic Map of the Central Wasatch Front, Utah. Utah Geological and Mineral Survey. Map 54-A – Wasatch Front Series. May.

[2] Personius, S.F. and Scott, W.E. 2009. Surficial Geologic Map of the Salt Lake City Segment and Parts of Adjacent Segments of the Wasatch Fault Zone, Davis, Salt Lake, and Utah Counties, Utah

N
W E
S

0 500 1,000
Feet

1 inch = 800 feet

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Figure 1

Slug Test Locations

OU1 700 South 1600 East PCE Plume
Salt Lake City, Utah

File Path: J:\238824_VA_Medical_Salt_Lake\MXD\Sampling_2020\DSR_2020Q2\Fig1_Slug_Tests.mxd WAGNERA 12/18/2020

Attachment A

Field Guide for Slug Testing and Data Analysis

FIELD GUIDE FOR SLUG TESTING AND DATA ANALYSIS™

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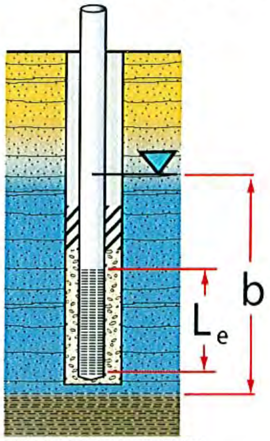
STEP ONE: TEST WELL CONFIGURATION

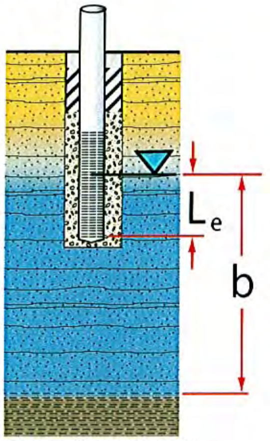
K = Hydraulic Conductivity
b = Thickness of Tested Unit
L_e = Effective Screen Length *(portion of screen through which flow occurs, usually not the length of the filter pack)*

UNCONFINED CONDITIONS



PARTIALLY PENETRATING
Screened Below the Water Table

$L_e = L$



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Screened Across the Water Table

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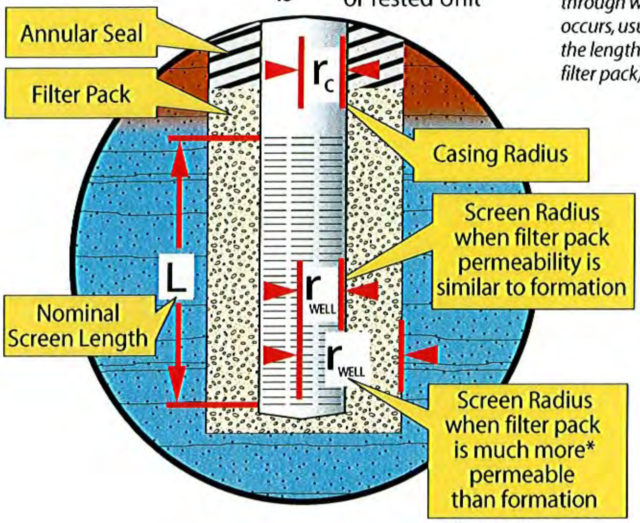
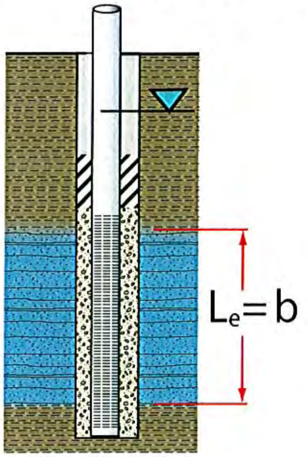


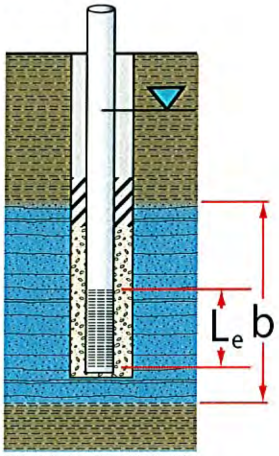
* factor of two or more

CONFINED CONDITIONS



FULLY PENETRATING
Screened Across the Entire Unit

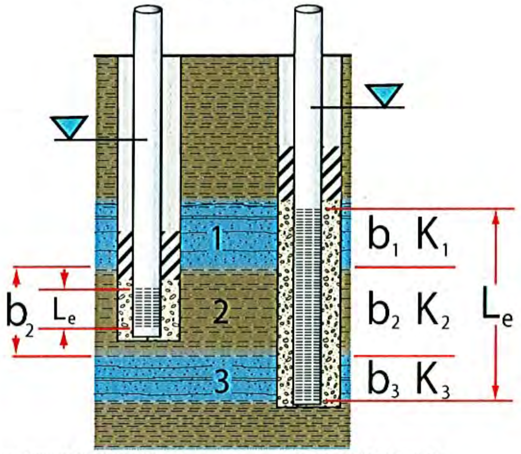
$L_e < L$



PARTIALLY PENETRATING
Screened Across a Portion of the Unit

$L_e = L$

LAYERED SETTINGS



PARTIALLY PENETRATING
Screened Across a Portion of a Layer

$L_e < b_2$

$K \approx K_2$

FULLY PENETRATING
Screened Across Multiple Layers

$$K \approx \frac{[(b_1K_1)+(b_2K_2)+(b_3K_3)]}{L_e}$$

Slug tests are also an effective means of estimating K in aquitards. See Butler (1998) for specialized test procedures. Correct screen placement is essential for testing low-permeability units.

WELL DEVELOPMENT IS CRITICAL

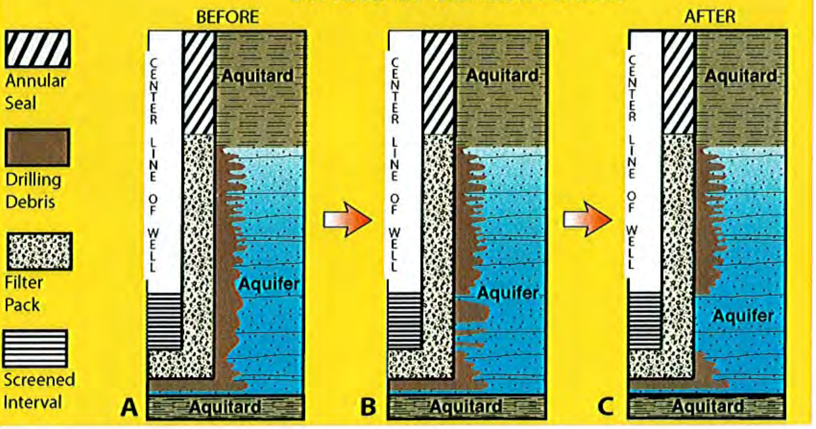
1. **MUST** develop well thoroughly before slug testing because a near-well zone of disturbance may be created during drilling. Characteristics of zone depend on formation properties and drilling method. Zone often consists of various types of "drilling debris".

> Hydraulic conductivity estimates from tests in poorly or undeveloped wells may be much less than formation K due to impact of "drilling debris".

2. Perform slug tests and assess the sufficiency of well development during data processing and analysis (see Steps 4 and 5).

> For monitoring wells, development should produce a situation between B and C. Assume $L_e = L$ for analysis.

STAGES OF DEVELOPMENT



STEP TWO: SET UP AND TEST INITIATION

FOR TESTS USING SOLID SLUGS OR BAILERS

INITIAL ACTIVITIES

1. Measure depth to water.
2. Measure depth to bottom of well.
3. Measure slug volume (solid slug or bailer)

$$V_{SLUG} = \pi r^2_{SLUG} L_{SLUG}$$

EXAMPLE: Solid slug, 2.5-cm diameter, 75-cm long

$$V_{SLUG} = (3.14)\ (1.25cm)^2(75cm) = 368.2\ cm^3$$

4. Calculate expected initial displacement

$$H_0^* = V_{SLUG} / \pi r^2_{CASING}$$

EXAMPLE: Solid slug in 5-cm diameter well

$$H_0^* = (368.2\ cm^3) / (3.14)(2.5cm)^2 = 18.8\ cm$$

5. Calculate length of water column in well.
6. Check depth limit of transducer and determine appropriate transducer position.

Height of water column above transducer should allow sufficient room for slug introduction and removal.

EQUIPMENT

Must be appropriate for expected rate of head change. Always use a transducer and data logger for tests in moderate to high permeability formations (K > 0.001 cm/s). Manual measurement of water levels is a reasonable approach for tests in lower permeability formations.

SET UP

1. Submerge transducer to pre-determined depth and allow 15 to 20 minutes for transducer to thermally equilibrate with water and transducer cable to stretch.

Submerge transducer a sufficient distance to avoid interference during slug movement. If transducer is located within screened interval, place above well bottom to avoid plugging by settled fines.

2. Secure transducer cable to prevent movement during test.
3. Check data logger to ensure connectivity and communication.
4. Track water level through time to ensure near-static conditions have been achieved prior to test.
5. Prepare solid slug or bailer for test. Check bailer for leaks.

FALLING HEAD TEST

Place bottom of slug just above top of water column. Measure drop distance on cord and fasten cord prior to test.

RISING HEAD TEST

Place top of slug just below top of water column. Measure removal distance on cord and prepare to fasten cord after removal.

TEST INITIATION

1. Double check data logger settings.
2. Verify water level has returned to static.
3. Start logging data 5 to 10 seconds prior to test initiation.
4. Create near-instantaneous water-level change relative to formation response.

For tests in high-permeability formations, water level change produced by a solid slug or bailer may not be fast enough. Use pneumatic method for tests initiation (see Step Three).

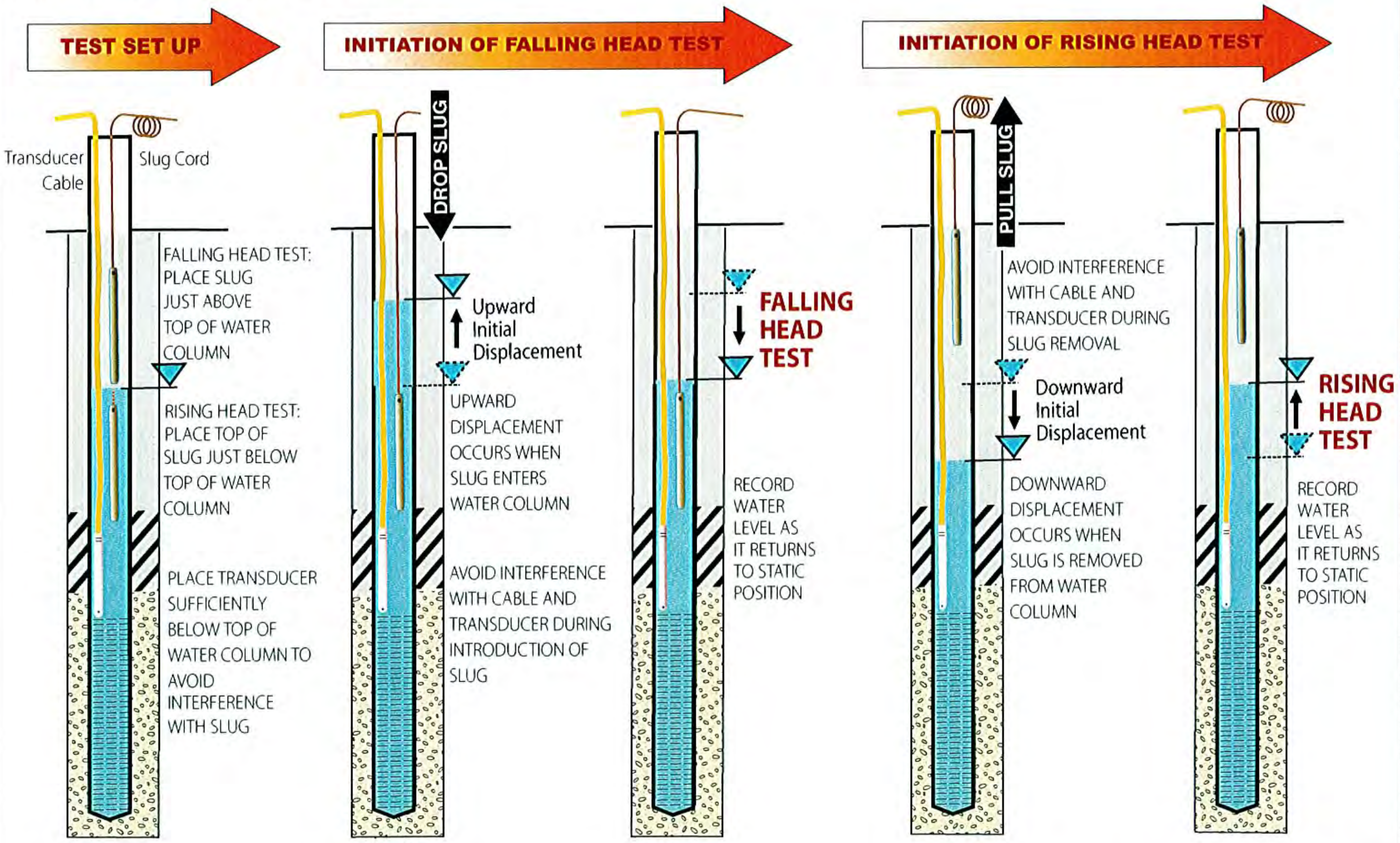
5. Avoid entanglement with transducer or its cable during test initiation.

When moving slug to initiate test, try to minimize distance of movement by positioning slug a short distance above or below top of water column. This will help avoid getting the slug entangled in the tranducer cable or hitting the transducer.

INITIAL DISPLACEMENT

In moderate or lower permeability formations (K < 0.02 cm/s), an initial displacement of 0.3 to 0.9 meters should produce a reasonable signal-to-noise ratio. In higher K formations, use smaller displacements (< 0.3 meters) to reduce non-Darcian flow losses. Slug size does not affect test radius - see Butler (1998).

FALLING & RISING HEAD TEST



FIELD GUIDE FOR SLUG TESTING AND DATA ANALYSIS™

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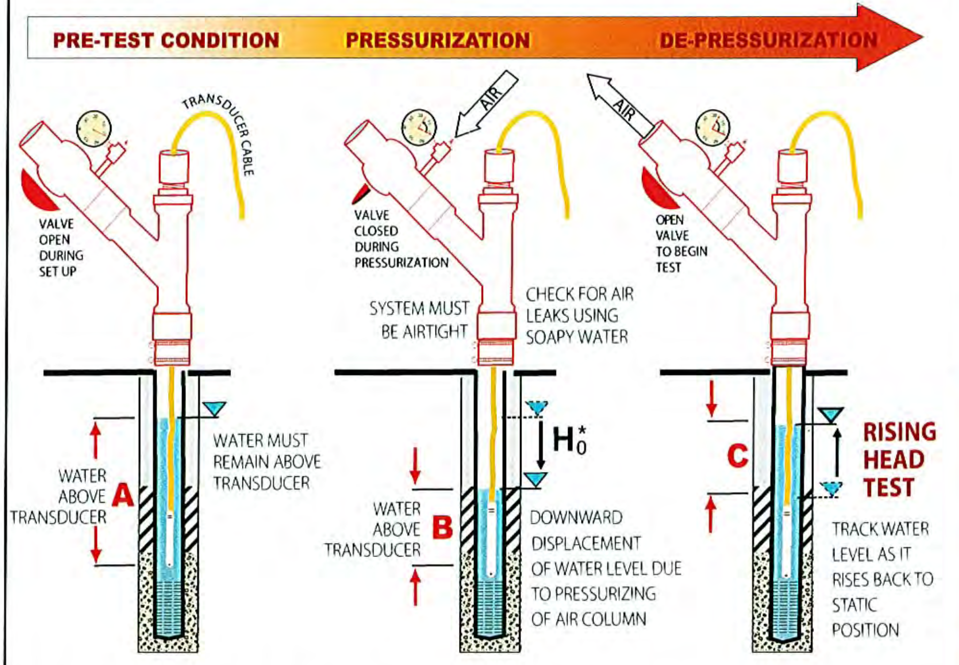
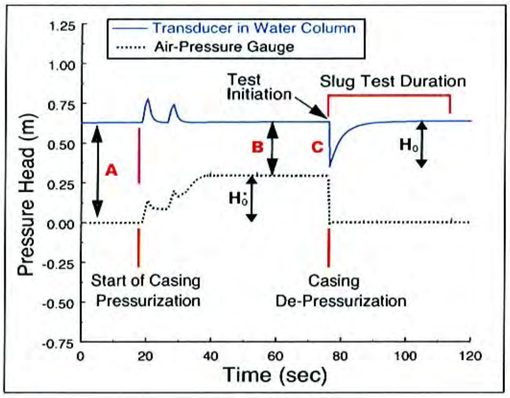
FOR TESTS USING PNEUMATIC INITIATION SYSTEM





1. Use pneumatic method to initiate tests in highly permeable formations. The pneumatic method uses air pressure, either positive or negative, to displace water. Water level must remain above screen and transducer.
2. Rising head tests are performed by pressurizing air column, allowing pressures to stabilize, and then depressurizing air column.
3. Falling head tests are performed in a similar manner by applying a vacuum to air column.

STEP THREE: TEST PERFORMANCE

GENERAL PERFORMANCE GUIDELINES

1. Perform three or more tests at each well.
2. Use at least two initial displacements varying by a factor of two or more.
3. Conduct both rising and falling head tests if possible. First and last tests should use approximately same initial displacement.

Repeat tests with different H_0^* are used to assess the viability of assumptions underlying slug test analysis methods.

4. Run each test to near completion (i.e. heads within 5% of static).

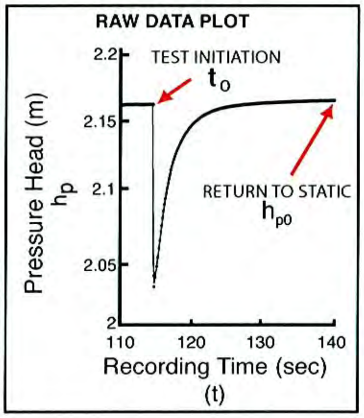
Running tests to near completion allows data to be analyzed with more sophisticated methods (Cooper et al. and KGS models). These methods can provide insights into impact of anisotropy, double-porosity behavior, and insufficient well development. See Butler (1998) for further details.

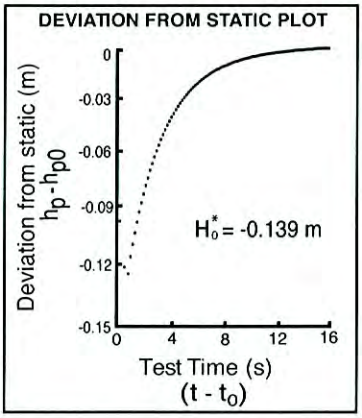
STEP FOUR: DATA PROCESSING

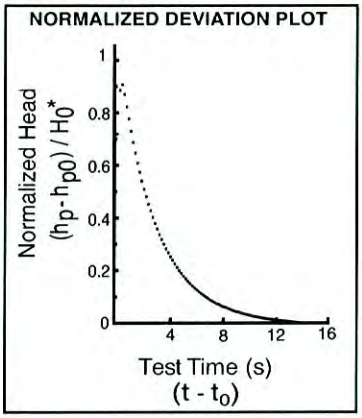
H_0^* = Expected initial displacement estimated from geometrical considerations (solid slug) or air pressure readings (pneumatic initiation).
H_0 = Initial water-level displacement measured in well.

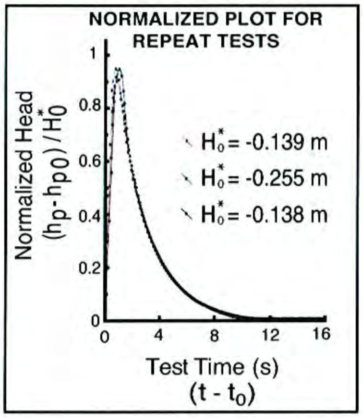
GENERAL PROCESSING GUIDELINES

1. Estimate time test began (t_0) and the pressure head at static conditions (h_{p0}) from the raw data plot.
2. Subtract h_{p0} and t_0 from the head (h_p) and time (t) records, respectively, to compute head deviation from static and time since test began (deviation from static plot).
3. Normalize data by dividing deviation data by the expected displacement (H_0^*) and plot normalized head vs. time.
4. Compare the expected displacement (H_0^*) with the initial water-level displacement measured in the well (H_0). Are they different? If so, possible explanations could include: (1) effective casing radius different from nominal casing radius, (2) test initiation too slow, (3) measurement rate too slow, and (4) transducer too deep in water column (high-K formation).
5. Compare normalized data plots from repeat tests at the same well. Coincidence of normalized plots suggests that assumptions underlying conventional analysis methods may be valid at that well. If normalized plots do not coincide, then more development may be necessary.









STEP FIVE: DATA ANALYSIS

SELECTION OF TEST FOR ANALYSIS

1. If normalized plots from a series of slug tests coincide, choose only one test for analysis. The selected test should have the lowest data noise level of that series.
2. If normalized plots do not coincide, seek explanation for lack of coincidence. Possible explanations include insufficiently developed well and non-laminar flow losses. See Butler (1998) and Butler et al. (2003) for further explanations of lack of coincidence of normalized plots.

SELECTION OF TEST CATEGORY

Select appropriate category for well-formation configuration.

CATEGORY I - Wells in Confined Formations and Wells Screened Below the Water Table in Unconfined Formations.

CATEGORY II - Wells Screened Across the Water Table.

CATEGORY III - Wells in Category I and in Highly Permeable Formations.

FRACTURED FORMATIONS

If formation is densely fractured and behaves as an equivalent porous media, standard methods are valid. If formation behaves as a double-porosity media, then validity decreases as well screen increases in length. If formation is sparsely fractured and flow is restricted to fractures, the validity of standard methods varies. If flow induced by test is radial, standard methods are valid. If flow is restricted to only a small portion of fracture plane, standard methods are not appropriate. See Butler (1998) and Shapiro and Hsieh (1998) for details.

TEST CATEGORIES

CATEGORY I ANALYSIS

A) Analyze data with Cooper et al. model for tests in fully penetrating wells.

B) Question: Can a good fit be obtained using a physically plausible storage estimate?
- If so, the hydraulic conductivity estimate can be calculated from the transmissivity (T) estimate using $K = T / L_e$
- If not, go to C.

C) Question: Is the well fully or partially penetrating?
- If fully pentrating well, test may be affected by insufficient development or double-porosity flow. See Butler (1998).
- If partially penetrating well, test may be affected by vertical flow above or below the screened interval. Go to D.

D) Analyze data with KGS model for tests in partially penetrating wells.

E) Question: Can a good fit be obtained using a physically plausible storage estimate?
- If so, the hydraulic conductivity estimate should be reasonable.
- If not, the test may be affected by insufficient development. See Butler (1998) for details.

CATEGORY II ANALYSIS

A) Question: Do data display a double straight line on a log normalized head vs. linear time plot (see Category II Figure)?
- If so, go to B.
- If not, go to A of Category I Analysis.

B) Fit a straight line to the formation response portion of the plot (2nd straight line segment).

C) Estimate K with Bouwer and Rice model.
- Use effective casing radius, not nominal casing radius, in analysis. See Butler (1998).

BOUWER & RICE AND HVORSLEV MODELS

These approximate methods involve fitting a straight line to data plotted in a log normalized head vs. linear time format. Although K estimates are obtained rapidly, these methods, unlike the Cooper et al. and KGS models, cannot provide clues that the test has been significantly impacted by insufficient development. If flow is primarily horizontal, data will display a concave-upward curvature in this plotting format. Straight line should be fit to the 0.15 - 0.25 (Hvorslev) and 0.2 - 0.3 (Bouwer & Rice) normalized head range. These ranges should be with respect to H_0^+ when data plot as a double straight line (see Category II Analysis Plot).

CATEGORY III ANALYSIS

A) Question: Are data oscillatory in nature or display a concave-downward curvature on a log normalized head vs. linear time plot?
- If so, go to B.
- If not, go to A of Category I Analysis.

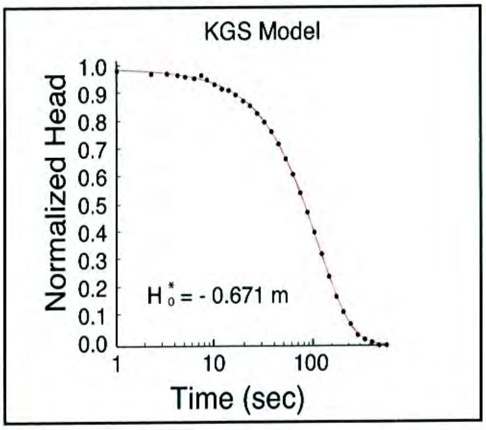
B) Question: Do normalized data plots coincide?
- If so, go to C.
- If not, go to D.

C) Question: Is well fully penetrating or nearly so?
- If so, analyze data with Butler & Zhan model.
- If not, analyze data with either Butler & Zhan model or high-K extensions of Hvorslev and Bouwer-Rice models.

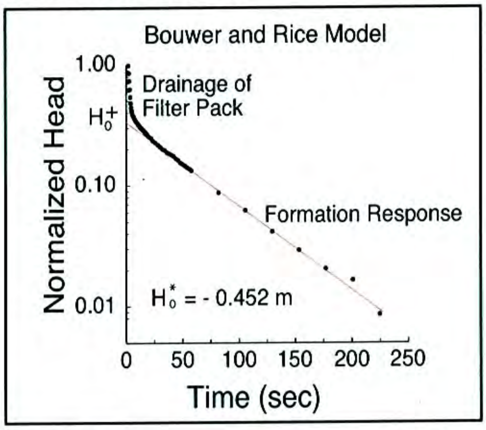
D) Question: Do normalized data plots from tests initiated with similar H_0^* coincide?
- If so, go to E.
- If not, further development may be needed.

E) Question: Can tests be repeated?
- If so, repeat tests with smaller initial displacements and go to B.
- If not, analyze data with non-linear slug test model of McElwee and Zenner. Note error in K estimate may increase as well screen approaches full penetration.

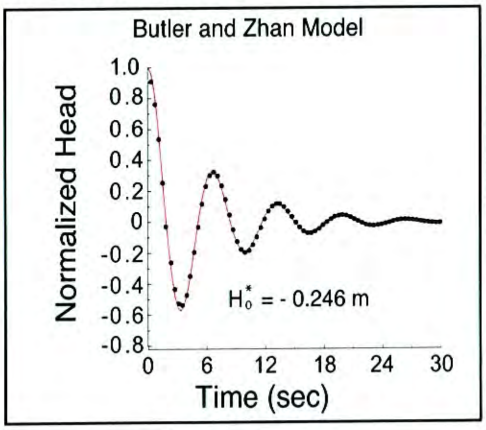
CATEGORY I ANALYSIS



CATEGORY II ANALYSIS



CATEGORY III ANALYSIS



REFERENCES *Technical Content: J.J. Butler, Jr., G.M. Duffield, and D.L. Kelleher* *Graphic Design: D.L. Kelleher*

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