Geoprobe® Slug Test Analysis (STA) Software - V2.0

User's Guide

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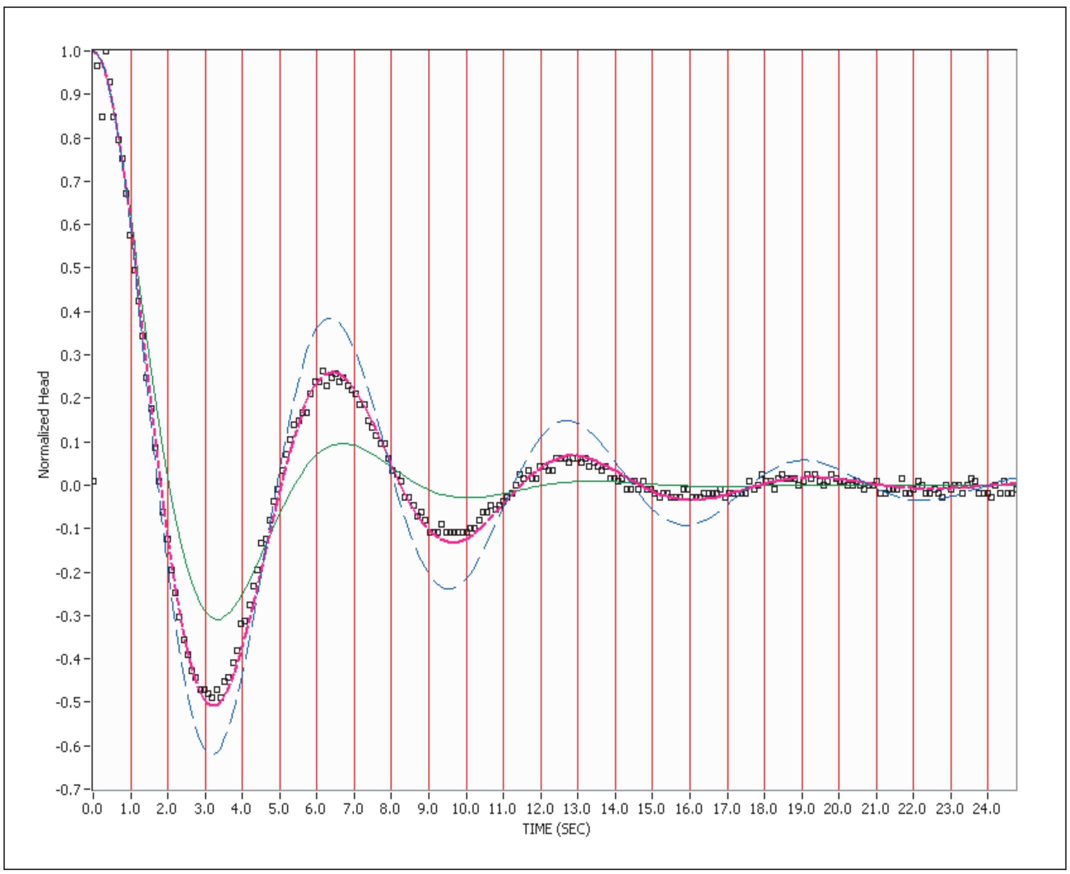

Curve matching for a high hydraulic conductivity formation with the STA software.

Section 1.0
INTRODUCTION

The Slug Test Analysis (STA) software is a simple, user-friendly software package designed for use with slug test data obtained with the Geoprobe Systems® GW1600 Pneumatic Slug Test Kit. The Slug Test Acquisition software included with the GW1600 kit is loaded on a portable computer and used to observe and acquire slug test data in the field. The slug test data are saved in files with format **.dat*. This file format may be opened directly into the STA software for curve matching, input of well construction parameters, and calculation of hydraulic conductivity. The software also provides for print out of simple graphics and data for documentation and reporting.

The STA software is provided to the user on a Compact Disc (CD) for installation on a laptop or desktop computer. Simply insert the CD into the drive, click on the Start icon on the Windows® screen and select *Run* from the menu. Select *SETUP.EXE* from the CD and follow on-screen instructions for installation. This usually requires less than 5 minutes.

A HASP key is provided with the STA software package. The HASP key must be installed in one of the USB ports of the computer to enable operation of the software. If the software is started without the HASP key you will be prompted to install the key or exit the software. Simply install the HASP key in one of the USB ports to use the software. The STA software may be installed on several computers but it will be necessary to have the HASP key installed on the computer in use to operate the software. Additional HASP keys may be purchased for a license fee if desired.

The STA software is designed with five screens or pages. Each screen is accessed by clicking on the appropriate tab at the top of the open STA window. Each screen allows the user to conduct certain functions to complete the slug test modeling operation and estimate the hydraulic conductivity for the screened formation.

The primary functions performed on each STA screen are:

Log Screen:

- Open (import) a log file into the program for graphing
- Selection of a baseline segment for normalization
- Selection of slug test response data segment for type curve or line fitting
- Edit (remove) erratic data points

Interval Screen:

- Select aquifer response type
- Conduct type curve fitting for underdamped aquifer response
- Determine damping parameter (Cd) for underdamped responses
- Modulate the period of oscillation on underdamped data for time correlation with type curves
- Conduct line fitting for overdamped aquifer responses
- Determine best-fit-line and T_o value for overdamped responses
- Clip data interval to remove late time flattening or curvature

INF Screen:

- Print or review the information (*.inf) file generated when the slug test was conducted

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Parameter Screen:

- Enter well construction parameters (screen length, casing diameter, etc.) for calculation of hydraulic conductivity
- Enter site specific information such as location, well number, etc.
- Select well construction type as partially or fully penetrating
- Select aquifer type as confined or unconfined
- Determine hydraulic conductivity of screened formation

Documentation and Reporting Screen:

- Print selected graphs and supporting documentation for reporting/review

Section 2.0
BACKGROUND

Slug tests have been conducted for many years in conventional monitoring wells and water supply wells to estimate the hydraulic conductivity (K) or transmissivity of the screened formation. A slug test is a single well test in which the water level (pressure head or simply "head") is quickly raised or lowered a measured amount and the recovery of the water level to equilibrium is measured with respect to time. This recovery data may then be modeled by various mathematical methods to estimate the hydraulic conductivity of the formation. Two of the most common models used include the Bouwer and Rice Method (1976, 1989) for unconfined formations and the Hvorslev method (1951) for confined formations. These models were originally developed for application only to overdamped aquifer responses. More recently these models have been modified (Butler 1997, Garnett and Butler 2000) so they may be applied to underdamped aquifer systems that exhibit oscillatory responses to a slug test.

The Pneumatic Slug Test Kit (GW1600) developed by Geoprobe Systems® is designed so it may be used to conduct slug tests on small diameter tools or wells installed with direct push techniques. The kit also may be used to conduct slug tests on larger diameter wells installed with traditional drilling methods. Research has been conducted to evaluate slug testing with direct push installed tools (Butler et al. 2002, McCall et al. 2002) and indicates that representative results are obtained. The STA software reviewed in this user's guide provides a relatively simple means for modeling slug tests to estimate the formation hydraulic conductivity whether the tests are conducted in direct push tools or conventional monitoring wells. The STA software may be applied regardless of whether the slug test was initiated with the pneumatic method or a mechanical slug, or even a bucket of water. However, the quality and accuracy of the calculated hydraulic conductivity will depend heavily on the use of appropriate field methods to install and develop the well or sampler (ASTM D5092, D6001, D6725, D5521) and use of appropriate methods to conduct the slug test (Butler 1997, ASTM D4044).

Cautionary Statement

This software is intended for use by engineers and scientists trained in methods for the estimation of hydraulic conductivity using slug testing methods. Use of this software by persons untrained in this art may result in erroneous estimations of formation parameters. The user is responsible for determining the suitability of field data sets for input into this software. The user is also responsible for determining which analytical model is applicable to the geologic and hydrologic setting of a given slug test.

Section 3.0
THE STA SOFTWARE

The following sections will review each screen of the software in sequence. The steps required to conduct modeling for both underdamped and overdamped test responses will be reviewed. While many of the steps are the same for both types of aquifer responses, the curve or line fitting steps on the Interval Screen are unique to the type of response observed. Examples of both response types are reviewed where needed to provide examples of both curve fitting for the underdamped case and line fitting for the overdamped case.

3.1 Log Screen

English/ Metric Units: When you first open the STA software it opens on the Log screen (Fig. 1) and you are prompted to select either English or Metric units to display the graphical data. Simply point and click on your desired option.

Open Log File: Now with units selected you can open a data file for graphing and analysis. Click on the OPEN LOG FILE icon on the lower right side of the screen. This brings up the Select Slug Test File window. Browse through your folders and files and select the file you want to graph and analyze. This must be a **.dat* file extension for the STA software. Double-click on the desired file or highlight the file name and click on the OPEN icon. Slug test data and information files are normally saved in the *Logfiles* folder under the *Dirim95* directory when acquired in the field.

Print Graph: There is a Print Graph icon on the lower right hand side of the screen. If you want to print a copy of the graphed data simply click on this icon. A similar print option is available on each page of the software to allow for printing of graphs, information, or entered parameters to assist with preparation of reports and necessary documentation.

Cursors: There are two cursors on the screen (Fig.1) that are used to select data/graph intervals for defining baseline,

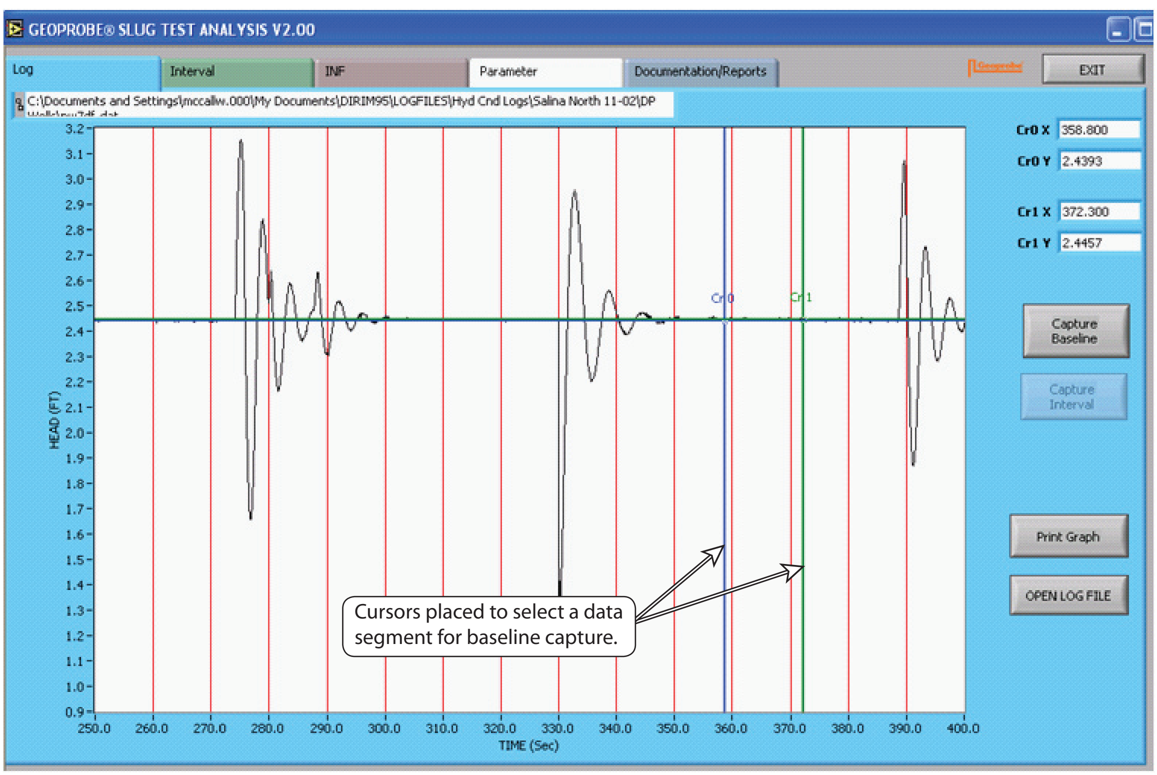

Figure 1: Baseline interval is selected from the Log screen.

curve fitting, and modeling. Cursor Cr0 is shown as a set of perpendicular bold blue lines. Cursor Cr1 is shown as a set of perpendicular bold green lines. Simply click on the cursor and drag it to the desired location on the graphed data.

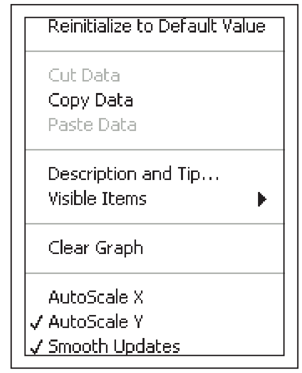

Figure 2: Right-click on the X- or Y-axis to view the menu shown above.

NOTE: You may right-click on the X or Y-axis to open the dialog box shown in Figure 2 so you can turn off the auto-scaling function. Then double-click on the value at either end of an axis to edit the minimum or maximum value as desired. This will enable you to zoom in on a desired segment of the graph for better viewing, interval selection, and curve fitting.

Select Baseline: Decide which interval on the graph you want to select as the baseline for the slug test to be modeled. The baseline represents the undisturbed water level in the well (H_o) either immediately before the test or directly after the test. Move Cr1 to the end of that time interval and Cr0 to the beginning of the desired time interval for the baseline (Fig. 1). Now click on the Capture Baseline icon to select this interval as your baseline. The average head value will be calculated across this interval and used as the baseline value for modeling of the slug test response. As the baseline may drift while a series of slug tests are run due to outside influences (pumping well etc.) it is best to select a baseline interval close to the slug test response curve to be modeled. Using a baseline different from that of the slug test being analyzed will affect normalization and can cause bias in the results.

Select Slug Test Response Curve: After the baseline interval has been selected you can now select the data interval for the slug test response to be modeled (Fig. 3). Move Cr1 to the end of that time interval and Cr0 to the beginning of the desired time interval for the test to be modeled. Now click on the Capture Interval icon to select this interval for analysis and curve fitting.

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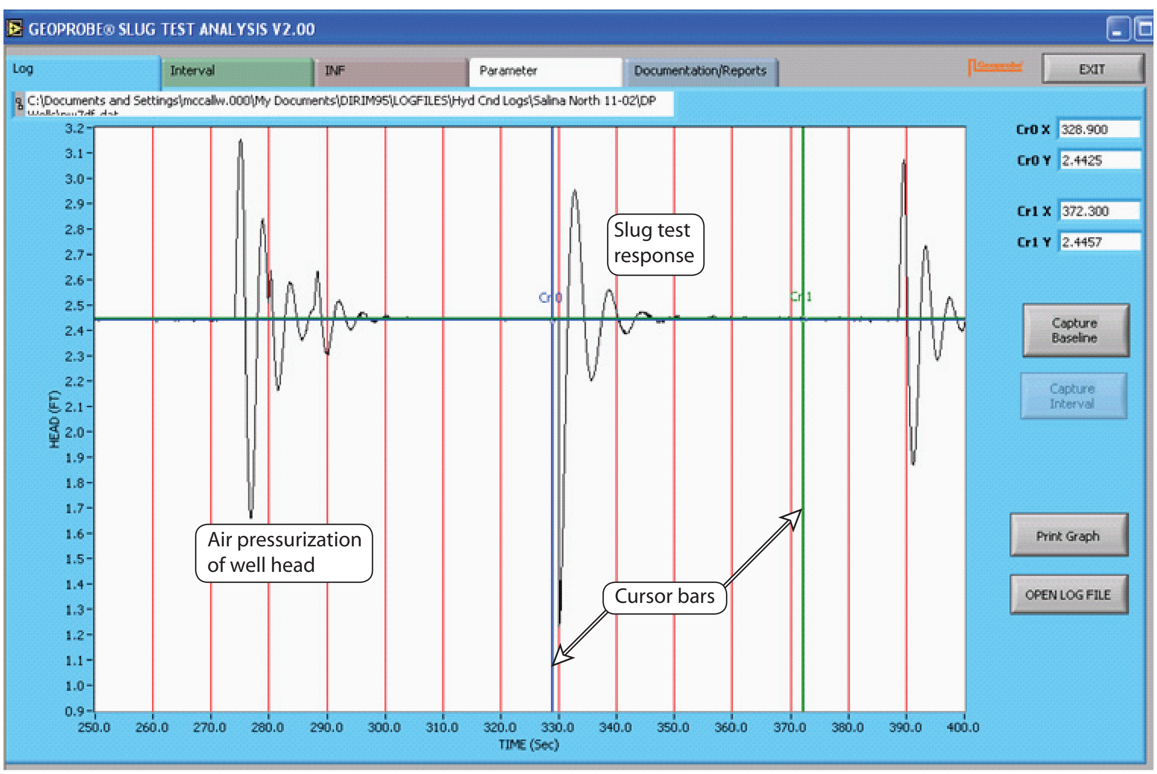


Figure 3: Selecting an interval for curve matching from graphed data showing an underdamped response.

Clicking on the Capture Interval icon on the Log screen opens a spreadsheet segment and dialog box that contains the data from the selected slug test interval (Figure 4). The displayed data columns include the time and head values. Use the pointer and cursor bar to navigate up and down the data column to locate where the slug test begins.

For overdamped (log response) select the point that represents the largest magnitude in head change just after the test was started as the START TIME for the test. For underdamped (oscillatory) test data select the last point on the stable baseline just before the slug test started as the START TIME. These start times usually provide the best fit to model curves or lines.

Now the END TIME must be selected to fully define the desired test interval. Move the cursor down the data column until the test data have returned to the equilibrium baseline value. Highlight the selected data pair with the pointer and click on the Select End Time icon.

Once the baseline interval and test interval have been selected the software will automatically open the Interval page in the software and display the selected data segment.

Editing Data Point(s): Before selecting the start time in the Capture Interval dialog box you have the option to edit out nonrepresentative data points (Fig. 5). Erratic data points may occur just after the slug test is started and are essentially "noise" generated in the wellhead. An erratic data point is much higher or lower than adjoining data points and does not fit the symmetry of the recovery curve when compared to the overall slug test response.

To remove a data point, simply click on the desired data pair in the data columns. The data pair is highlighted in blue. Click on the Delete Point icon. A dialog box pops up to verify that you want to delete the selected data point. Click on the OK icon to delete the data point, or click on CANCEL if you decide not to remove the data point. While this data point is removed from this interval it is not deleted from the original data file. Data values cannot be altered or inserted with this editing function, only deleted.

Data points can only be deleted one at a time. If multiple data points need to be removed consider using another data set or rerunning the slug test.

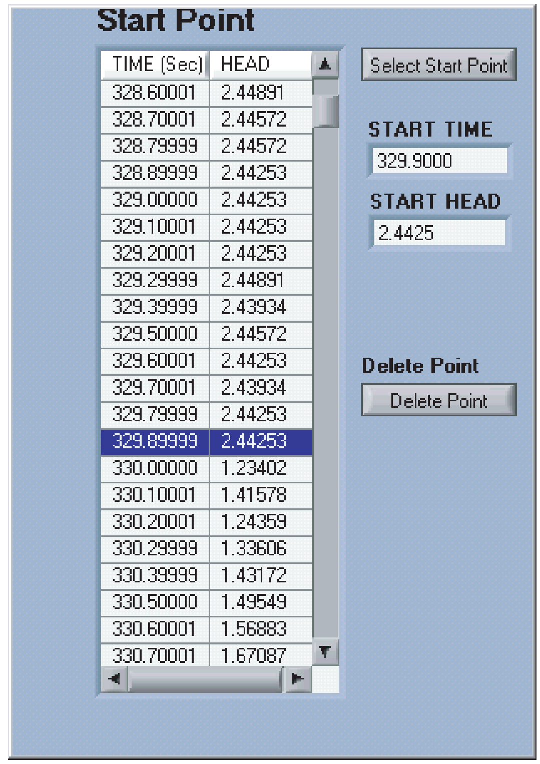


Figure 4: Selection of start time for data showing an underdamped response.

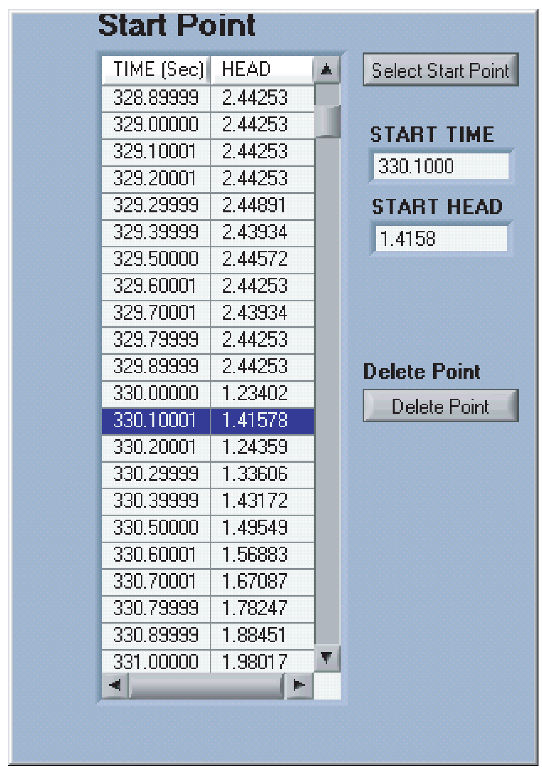


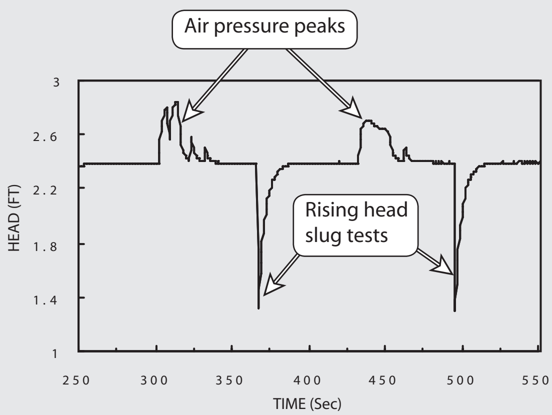
Figure 5: Selecting erratic data point to delete.

Which curve is the slug test?

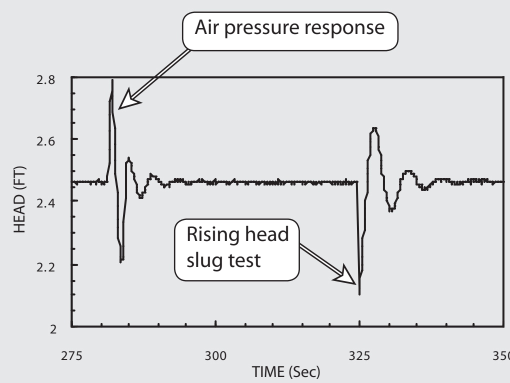
If you are not familiar with pneumatic slug testing it may not be obvious which curve in the data file is the actual slug test and which curve is the result of air pressurization (or application of vacuum). To be sure, the data analyst must know if the tests were conducted by pneumatic methods and if the tests are rising or falling head tests. Document the field methods used in the field notebook or on appropriate data forms.

The Geoprobe® Pneumatic Slug Test Kit (GW1600) is currently designed so that only rising head tests may be conducted with the system. Air is pumped into the wellhead to raise the air pressure in the wellhead and force water to flow out of the well and into the aquifer. This results in a positive pressure increase in the well that is detected and recorded by the transducer and computer (see figures below). Since air is compressible the change in water level during the pressurization of the wellhead will not provide an accurate measure of the formation behavior. Therefore, only the rising water level after the air pressure is released should be used to estimate the hydraulic conductivity when positive pressure pneumatic tests are performed.

Note that for underdamped pneumatic tests there will be a positive pressure spike when pressure is increased and a negative pressure spike when the pressure is released to start the rising head slug test.



Overdamped: Pneumatic



Underdamped: Pneumatic

3.2 Interval Screen

From this screen the user is able to conduct type curve matching for underdamped responses by selecting the appropriate damping coefficient (Cd) and conducting time modulation of the test data as required. The best fit line and To value for overdamped responses also may be obtained from this screen.

Aquifer Response Type: Once the baseline interval has been selected and the test interval has been captured the software opens the Interval screen to display the selected data interval. A dialog box pops up to remind you that the appropriate Aquifer Response Type must be selected to continue with the modeling. To select the correct aquifer response type click on the drop down arrow on the box in the upper right corner of the interval graph (Figure 5). You can select either OSCILLATORY for underdamped data or LOG for overdamped data. The selection here will determine which math model is used in the Parameter page for the calculation of hydraulic conductivity.

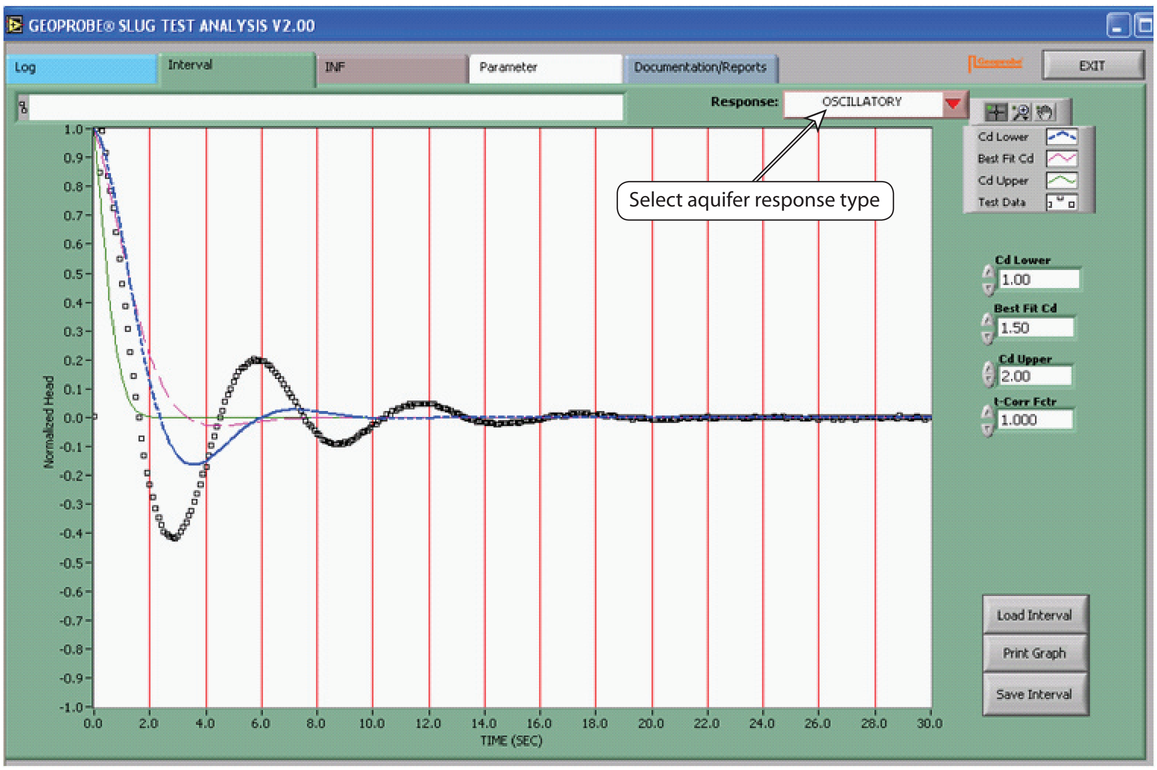


Figure 6: Selection of aquifer response type on the Interval page of the STA software.

A. Curve Matching Underdamped (Oscillatory) Aquifer Responses

Underdamped aquifer response is characterized by behavior like that of the test data in Figure 6 (open squares). After the initial displacement the water level returns and then continues beyond the original baseline (one or more times) resulting in negative head values when normalized. Multiple oscillations may occur under appropriate aquifer and well construction conditions. This is not noise but genuine and accurate response of the aquifer/well system. When multiple oscillations occur (as in Fig. 6) it is best to use higher frequency sampling (e.g. 10 Hz) during data acquisition to ensure sufficient data is obtained to enable accurate fit of the type curves. Use of only the early time data in such an aquifer response to conduct a straight-line match will not yield a good approximation of the hydraulic conductivity.

On the Interval Page the selected data interval is displayed as open squares on the graph. Default values for the damping parameter (Cd) of 1.00, 1.50 and 2.00 are used to display possible type curves along with the selected data interval. The type curves may be changed by clicking on the toggle buttons next to the Lower, Best Fit and Upper Cd windows on the right side of the screen. Alternatively, you may double-click on the Cd values and type in the desired number. <u>The final value selected in the Best Fit Cd window is the value used in the software for calculation of the hydraulic conductivity.</u> The Best Fit Cd value is automatically input into the Parameter Page for the calculation.

The Upper and Lower Cd values may be used to help you select the correct Cd value (Figure 7) and may be used in reporting to show bracketing values for the Best Fit Cd curve. The test data (open squares) and three type curves bracketing the amplitude of the test data response are shown (Figure 7). This provides an example of how the software can be used to assist in selecting the correct type curve and damping parameter. Of the three Cd values selected the 0.50 value yields a type curve that most closely matches the amplitude and frequency of the test data. However, it is apparent that the type curve and test data are not aligned along the X-axis. Because of this, the time of the test data must be modulated using the time correction factor (t-Corr Fctr) to obtain a true type curve match.

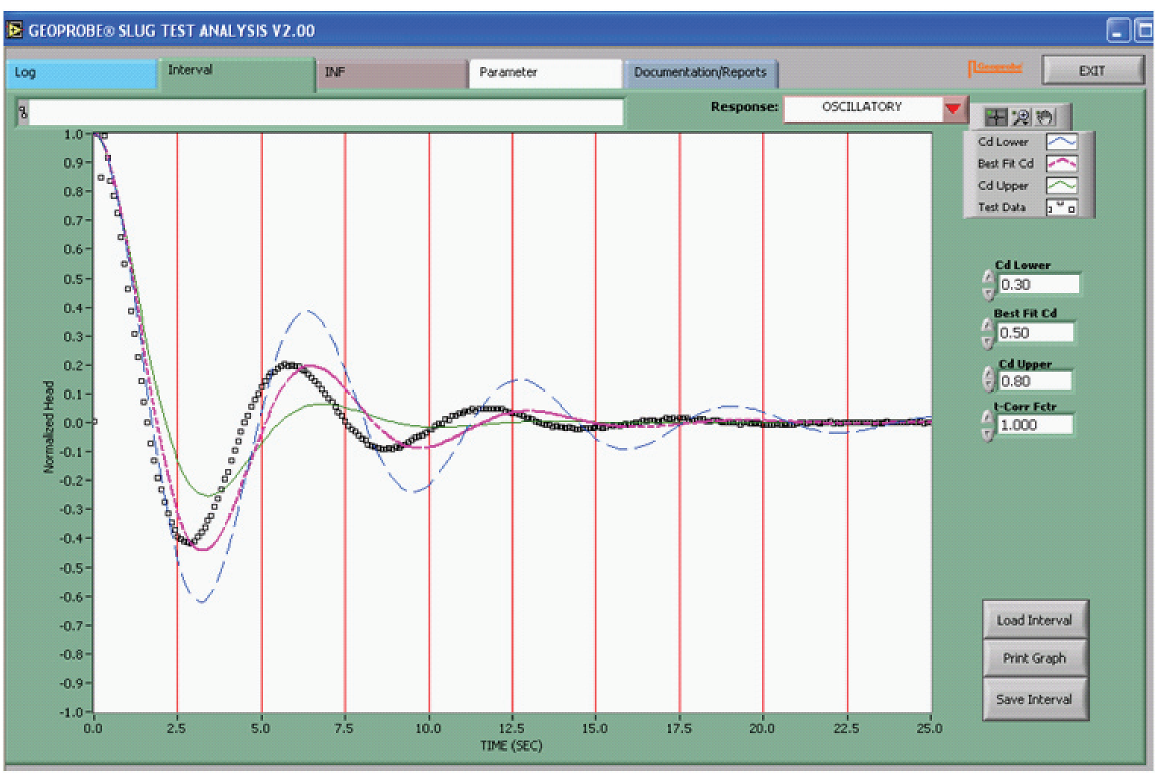


Figure 7: Curve matching for data showing underdamped response.

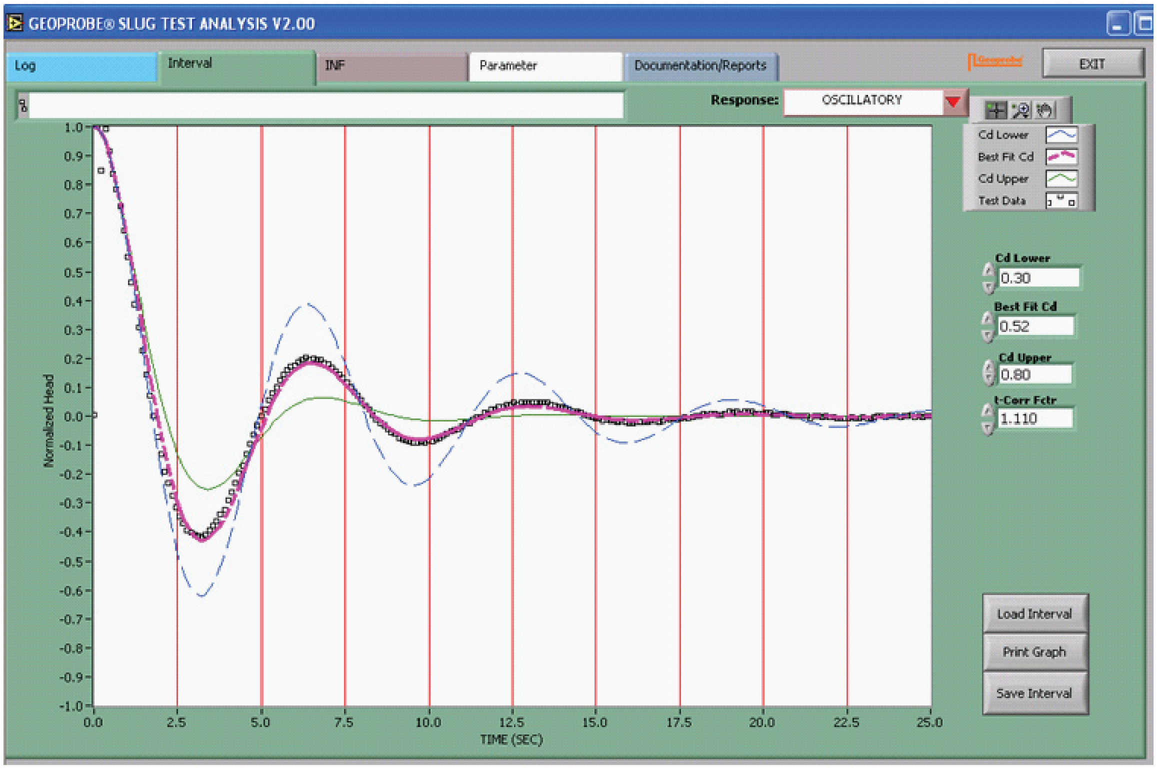


Figure 8: Modulation of test data time.

Modulation of the test data is accomplished by simply clicking on the toggle buttons next to the t-Corr Fctr window. The time values of the test data may be modulated up or down, as required, to obtain good alignment with the Best Fit Cd type curve. In this example the test data was modulated up to 1.120 to obtain good alignment along the time scale (X-axis) and then the Cd was increased to 0.52 to optimize the type curve fit with the test data (Fig. 8). Once you are satisfied with the selected damping parameter and modulation factor you may proceed to the Parameter page to input data on well construction, aquifer geometry and type, for final calculation of the hydraulic conductivity. The selected Best Fit Cd value and the modulation factor (t*d/t*) are automatically input into the Parameter page for calculation of hydraulic conductivity for underdamped aquifer responses.

Note: Line width, color, point style and other functions may be modified by right clicking on the desired type curve label in the legend (Fig. 9). Upper and Lower Cd curves may be made white or transparent to minimize their appearance during optimization or for printing a report graphic if desired.

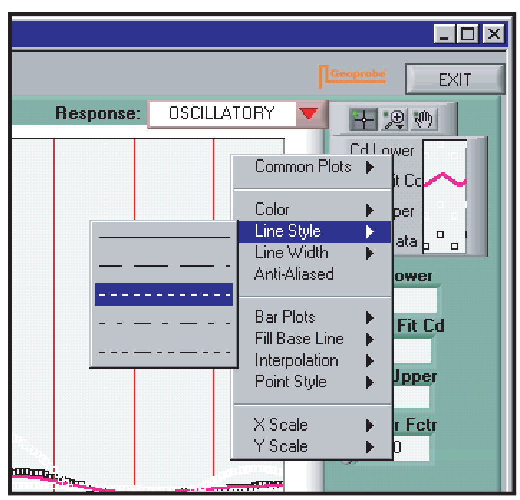


Figure 9: Close-up view of the Interval screen showing the plot options menu.

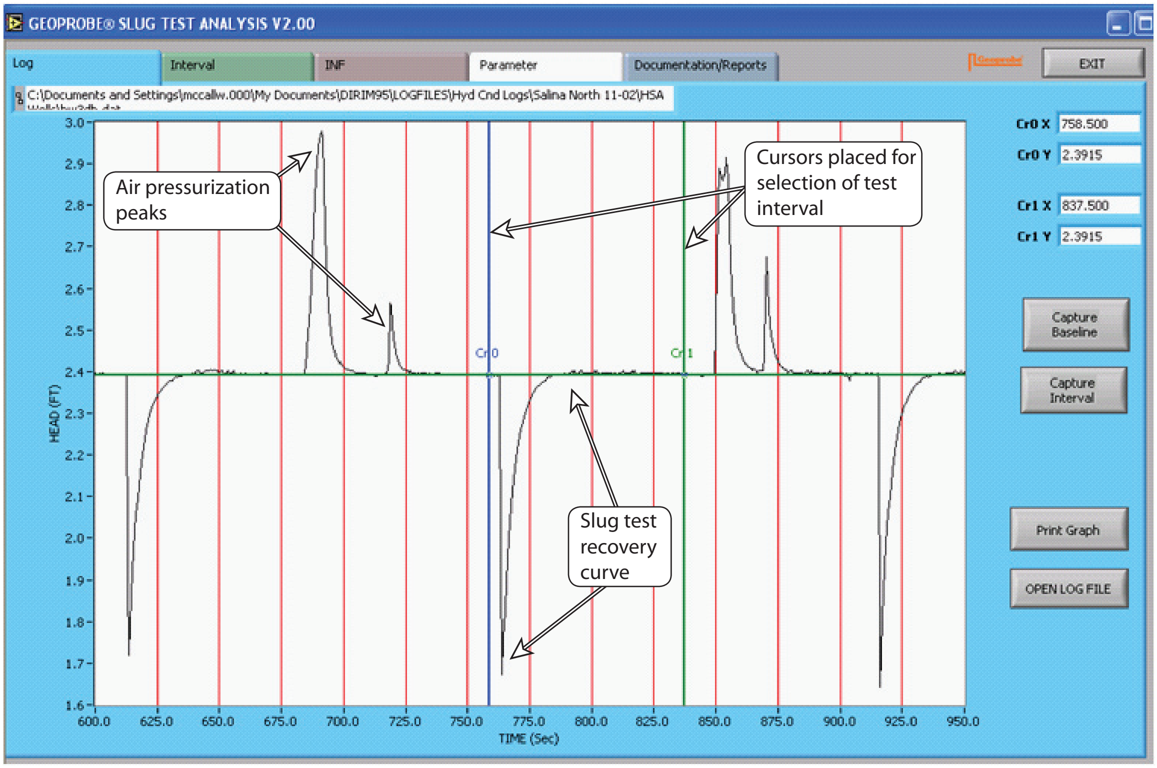


Figure 10: Interval selection for data showing overdamped response.

B. Modeling Overdamped (Log) Aquifer Responses

The overdamped aquifer response is more commonly observed during slug tests in the field. The software is used in the same manner here to select a baseline interval as demonstrated above for the underdamped aquifer response. Once the Capture Baseline is completed the cursors are used to bracket the desired test response. And again, to select a test response for modeling the cursors (Cr0 and Cr1) are placed just before the start of the test and after the test response has returned to baseline. Then click on the Capture Interval icon to select the desired interval (Fig. 10) for modeling and determination of the T_o value. Notice that the cursor windows on the upper right of the page give the specific X-Y coordinates of each cursor intersection on the plotted data.

Once you click on the Capture Interval icon the spreadsheet segment and dialog box is opened for selection of the exact Start Point (Fig. 11). Use the pointer and cursor to select the specific start time for the slug test and then click on the Select Start Point icon to make your selection (Fig. 11). Move the cursor down the spreadsheet data to locate the desired stop time for the slug test interval. Click on the desired end time for the test interval and then click on the Select End Time icon. Once the end time is selected the software opens the Interval screen and displays the selected data interval (Fig. 12).

As demonstrated in the section on underdamped curve fitting erratic data points may be deleted before selection of the start time. Simply click on the data pair with the pointer so it is highlighted. Then click on the Delete Point icon to remove the selected data point. The data pair is not removed from the original data set. You may return to the log page and re-select the same interval if you decide later that the data point should not be removed.

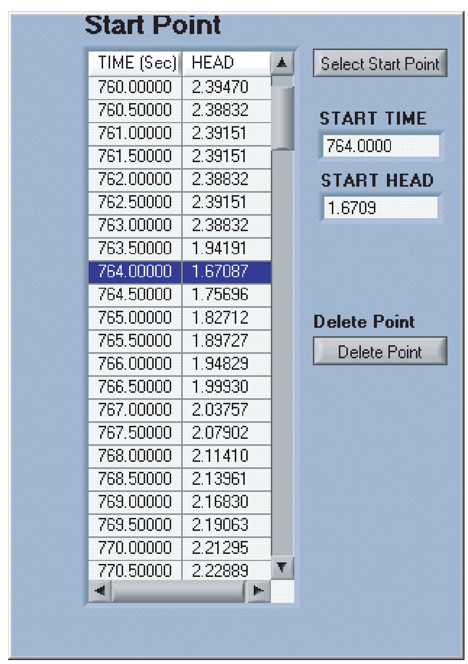


Figure 11: Menu for selecting start time or deleting points.

C. Interval Screen and Determining T_o - Overdamped Response

After the test interval is selected the Interval Page is opened and the data interval is displayed. If the incorrect aquifer response type is chosen the data will be plotted and shown with underdamped type curves (Fig. 12). While high value Cd curves can be calculated to approximate the overdamped response it is not recommended. The STA software will allow you to use a maximum Cd value of 10.0 (ten). However, for accurate estimation of K from overdamped responses the data should be plotted in the semilog format and used to determine the best fit line and To value. Simply click on the aquifer response drop down box and select LOG for correct graphing and modeling (Fig. 13).

It is normal to observe flattening of the slug test response curve toward the end of the test time (late time). An example of this behavior (Fig. 13) indicates how the data may appear. Notice that between 90% (0.10) and 99% (0.01) recovery the plot of the head data with time begins to broaden until almost completely flattening as recovery approaches 100% in late time for the test. If any of the selected data in the recovery curve happens to fall below the average baseline selected, a negative value will be generated during normalization. This may result in NaN (not a number) read out in the windows for the Slope (Dampening Coeff), Intercept (amplitude), and To values displayed on the graph. Additionally, a best-fit line will not be displayed fitted to the response data. This broadened and flattened data and any negative values will not permit an accurate best-fit line to be determined for the slug test. Under some field conditions you also may observe curvature of the late time data. This may cause poor line fitting and inaccurate estimates for hydraulic conductivity.

To remove this unwanted late time data click with the pointer on the CLIP cursor and move it down the plotted data. Usually flattening of the response data begins at or beyond about 95% recovery. Move the CLIP cursor down the graphed data and stop just before noticeable broadening, flattening, or curvature begins. Stop the CLIP cursor at the desired data point and click on the Clip Interval icon located at the lower right of the screen. This will remove the unwanted, flattened or curved data segment. This will enable the program to determine a representative best-fit line (Fig. 14). The best-fit line is used to determine the T_o value that can be used to calculate the estimated hydraulic conductivity. A bold vertical line is dropped from the best-fit line to the X-axis to graphically indicate the T_o value. The numerical T_o value is posted in the window at the right side of the Interval Page. The value also is entered on the Parameter Page and used in the overdamped models for calculation of hydraulic conductivity. The conventional Hvorslev or Bouwer and Rice models may be applied to estimate the hydraulic conductivity on the Parameter page.

If you are not satisfied with the selected data interval or the calculated best-fit line and T_o value you may simply return to the Log Page, select a new data interval, and repeat the modeling process.

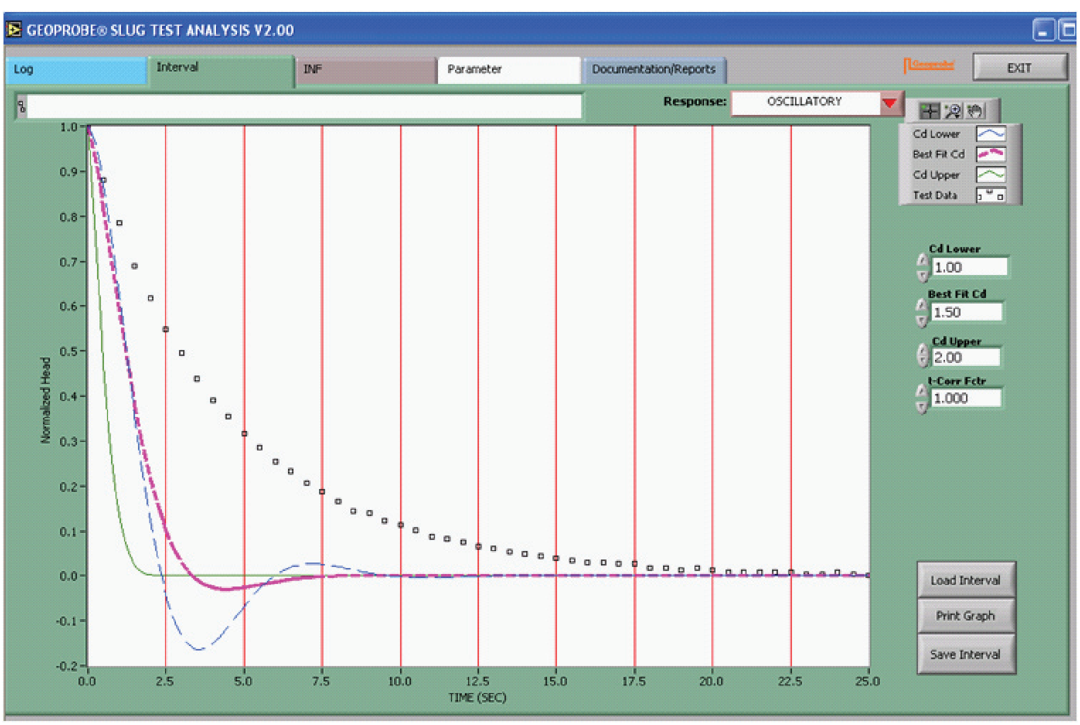


Figure 12: Overdamped data incorrectly plotted on underdamped response format.

D. Interval Files

Once you are satisfied with the fit of the line (or model curve), you may click on the SAVE INTERVAL icon to save the selected data interval, best-fit line equation and T_0 value in a separate file. The interval files are saved with a *.inv extension. This will enable you to access this exact interval for review, printing or modification at a later time if desired.

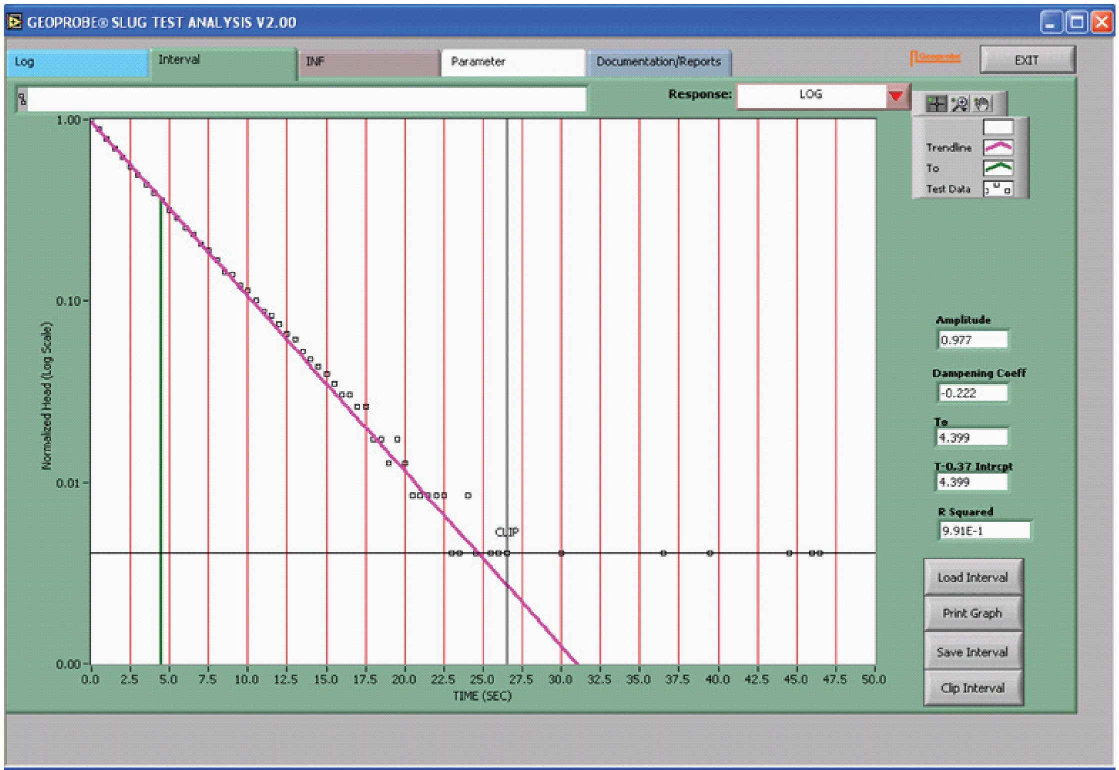


Figure 13: Plot of overdamped data demonstrating late-time flattening.

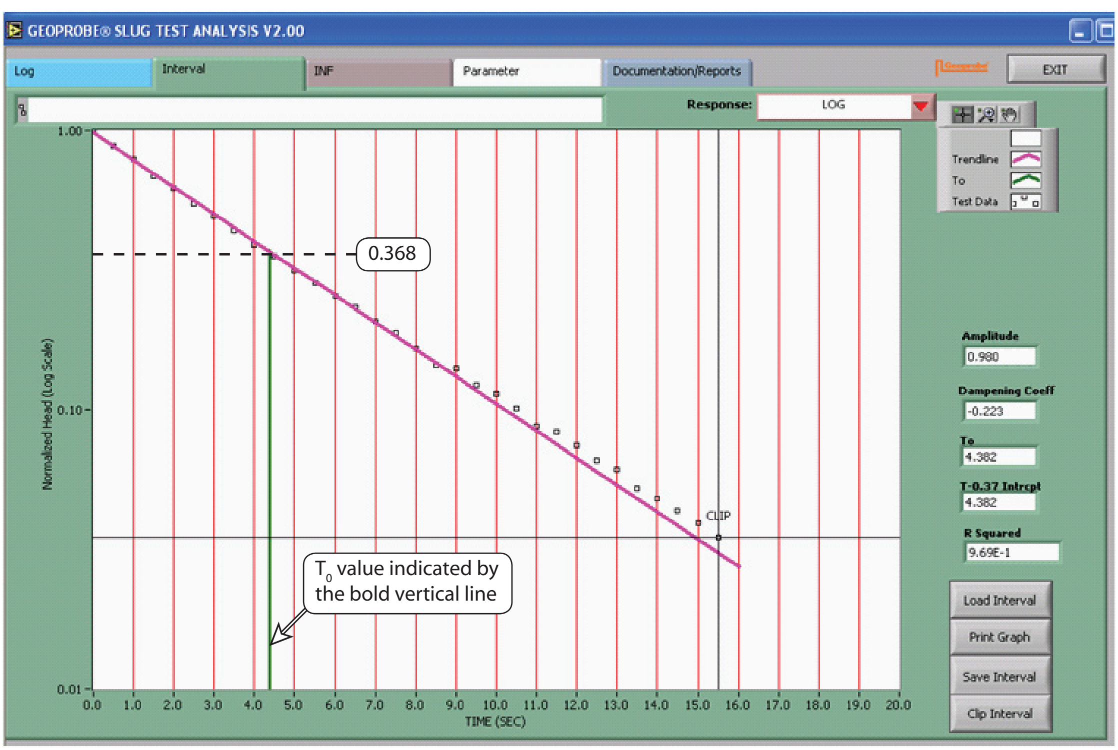


Figure 14: Best-fit line and T_0 Values determined for overdamped data, clipped interval.

3.3 Parameter Screen and Calculation of Hydraulic Conductivity (K)

A. Well Construction Parameters Block

Once the T_o value is determined for overdamped responses or the damping parameter and modulation factor are selected for underdamped responses well construction parameters are entered on the Parameter page (Fig. 15) so hydraulic conductivity may be calculated. A figure that graphically depicts the input parameters can be opened from the Parameter Page by clicking on the View Parameter Graphic icon. This opens an Adobe .pdf file that provides a visual representation of the well and aquifer parameters required to calculate the hydraulic conductivity (Fig. 16). To review written definitions of these parameters simply click on the View Parameter Definition icon to open the Adobe® pdf file. Multiple copies of the parameter graphic may be printed out and used to record data while in the field.

Default values of (-1.0) are given in each parameter window when the Parameter page is opened. Double-click on a parameter window to type in a value, or toggle the up/down arrows to modify the given value. Tab to move to the next window or simply double-click on the desired window to enter or modify data. The parameters that must be entered in the Well Construction Parameters block are highlighted in red. Entry of the other parameters is recommended so that clear definition of the well construction, aquifer and test conditions are provided in the documentation and reporting.

Well Construction (Well Dropdown Menu): Data obtained during site investigation and well construction or temporary DP sampler installation must be used to determine if the well is fully or partially penetrating (Fig. 17). If the length of the well screen (Le = effective screen length) is equal to or greater than the thickness of the saturated aquifer (H) the well is fully penetrating. If the screen length is less than the thickness of the saturated aquifer the well is partially penetrating. Click on the drop down arrow and select either partially penetrating or fully penetrating for the Well (Fig. 15). This selection will affect the model equation(s) used to calculate the hydraulic conductivity. Incorrect selection can lead to erroneous results. For some aquifer and well geometry conditions selection of the incorrect option here can provide an unreal result for the hydraulic conductivity. Results may be reported as negative values or simply as NaN (not a number). If that result occurs simply toggle to the other well construction option or correct the input parameters for well construction.

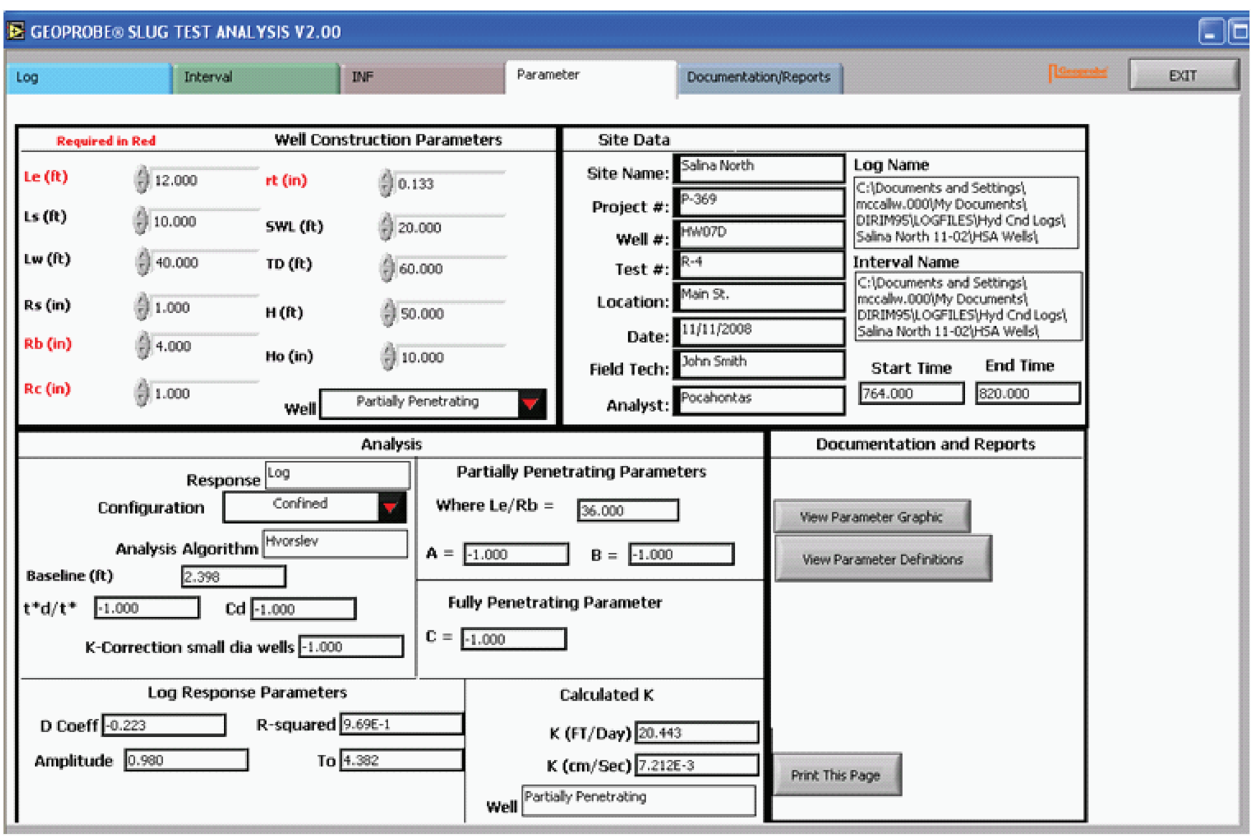


Figure 15: Parameter page data entry, calculation, and reporting.

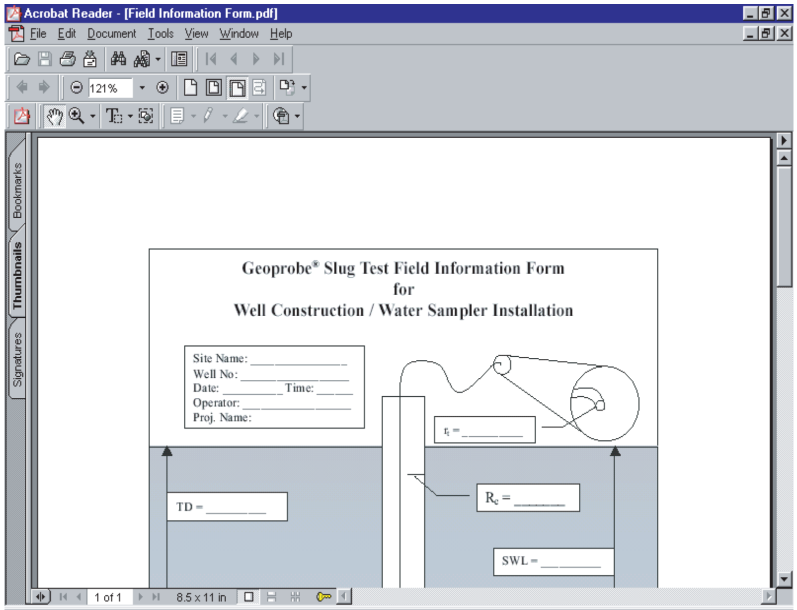
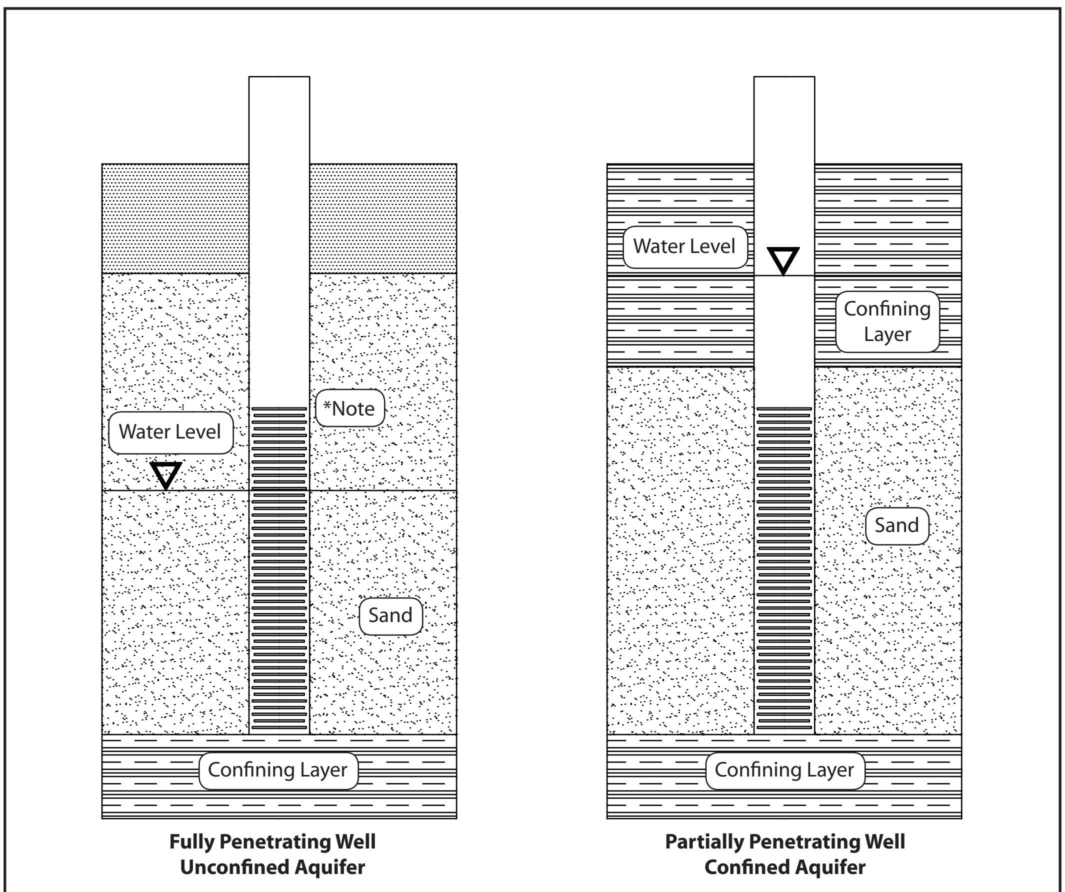


Figure 16: Access the well construction form from the Parameter screen using Adobe® Reader®.



*Note: It is not possible to perform a pneumatic slug test on any well where the screen extends above the water table unless a packer is used to seal off the open screen. When part of the screen is unsaturated any air injected into the well will simply vent into the formation without causing a change in the water level.

Figure 17: Well construction and aquifer type.

B. Site Data Block

The upper right quadrant of the Parameter Page (Fig. 15) allows you to enter site-specific data for the slug test report. Simply click inside each box to add or edit information. The Log Name box in the upper right corner automatically shows the name and location of the file used to conduct the modeling. If an interval file is saved from the Interval Page this information is provided in the Interval Name box. For ease of reference with graphs or later reviews both the Start Time and End Time of the selected interval from the Log Page is provided in the Site Data block.

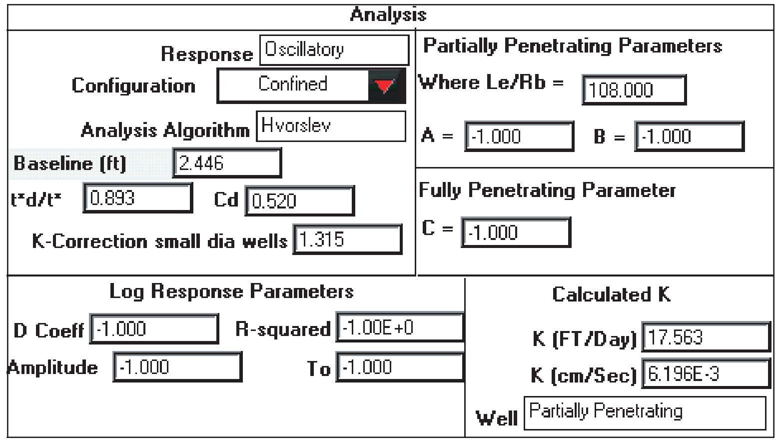


Figure 18: Close-up view of the Parameter screen showing layout of the Analysis block.

C. Analysis Block

The Analysis Block is located in the lower left hand portion of the Parameter Page (Figs. 15 and 18). The upper left hand corner of this block includes windows defining the aquifer **Response** type, aquifer **Configuration,** and **Analysis Algorithm**. The average **Baseline** value is also reported here.

Response: The response type is defined on the Interval screen and automatically input here for documentation.

Configuration: Field observations must be made to determine if the aquifer being tested is a confined or unconfined system. Collection of core samples, completion of electrical logs, CPT logs or similar methods may be required to adequately define the aquifer type. Review of site specific boring logs from previous investigations may be a good resource. The simplified schematic in Figure 17) indicates the difference between a confined and unconfined aquifer. Reality is usually not so simple.

Analysis Algorithm: The window for Analysis Algorithm shows which analysis model (Bouwer and Rice or Hvorslev) is being used for this result. Whether an aquifer is confined or unconfined determines which model is used to calculate the hydraulic conductivity. The Bouwer and Rice model is used for unconfined aquifers and the Hvorslev model is used for confined aquifers. The hi-K variants of these models are used for underdamped aquifer responses (Butler and Garnett 2000).

Baseline (ft): The average baseline value calculated from the baseline segment selected on the Log screen is automatically reported here for documentation.

The other information reported in the upper left box of the Analysis Block (Fig. 18) are parameters used for calculation of hydraulic conductivity for underdamped aquifer responses. These include the Time Correction Factor (modulation or **t*d/t***) and the damping coefficient (**Cd**) determined on the Interval Page. Another parameter included here is the **K-Correction for Small Diameter Wells**. For underdamped responses in smaller diameter wells (less than 2-inches/50mm ID) frictional losses due to the small diameter of the well must be considered. This factor corrects for any frictional loss due to use of smaller diameter DP tools or wells for slug testing in the higher K formations (Butler 2002).

The compartment in the upper right corner of the Analysis Block (Fig. 18) includes the well geometry parameter **Le/Rb** that should be evaluated when using the Bouwer & Rice model. If the ratio of Le/Rb is less than 6 a value of 6 should be substituted or another analysis method should be considered. The **A**, **B** and **C** parameters reported here are the empirical Bouwer and Rice parameters used to calculate the ln(Re/Rw) parameter used in this model. The A and B parameters are used for partially penetrating wells and the C parameter is used for fully penetrating wells.

The lower left compartment of the Analysis Block (Fig. 18) reports parameters used for calculation of K for overdamped slug test (log) responses. The intercept of the best-fit line (**Amplitude**) and the slope of the best-fit line (**D-Coeff**) are reported here along with the $\mathbf{T_o}$ value. An **R-squared** value is reported here to provide an indication of the "goodness of fit" of the line to the test data. The closer R-squared is to 1.00 the better the fit of the line to the test data. R-squared values above 0.95 are very good, values of 0.99 or higher indicate an excellent fit to the test data.

The lower right corner of the Analysis Block (Fig. 18) provides the results of the hydraulic conductivity (**K**) calculation based on the curve fitting, parameter data, and other inputs and choices you have made in the analysis process. The quality of the result here is dependent on the quality of the slug test conducted in the field, quality of the data obtained, and the input parameters and option selections you have made in the software. The hydraulic conductivity is reported both in feet per day (ft/day) and centimeters per second (cm/sec).

The lower right compartment of the Parameter Screen (Fig. 19) provides access to a figure that gives graphical definition of the well construction parameters and a list of definitions for these parameters. As noted previously, these files are in pdf format and are opened using Adobe® Reader®. Clicking on the Print This Page icon will print the complete Parameter Page on the system default printer. This is the simplest way to generate documentation of the well construction parameters, slug test results, and calculated hydraulic conductivity for reporting.

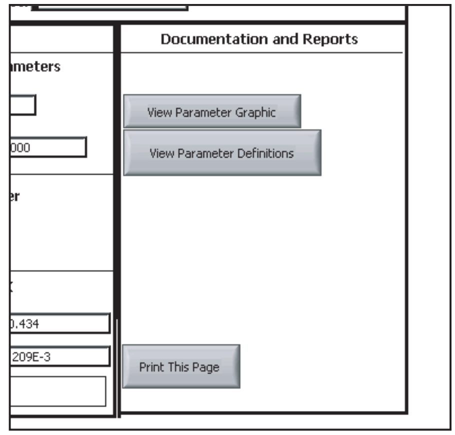


Figure 19: Close-up view of the Parameter screen showing the buttons available in the Documentation and Reports box.

3.4 INF Screen

Clicking on the INF tab brings up the SITE INFORMATION file (*.inf extension) generated as each slug test data file is created (Fig. 20). The *.inf file must be in the computer memory for it to be accessed. This file saves basic information about data file acquisition such as date and time the test started and ended. The *.inf files may be edited to add site specific and user specific information through Word Pad or other word processing software. The INF file is included here to provide complete documentation of the slug test acquisition process.

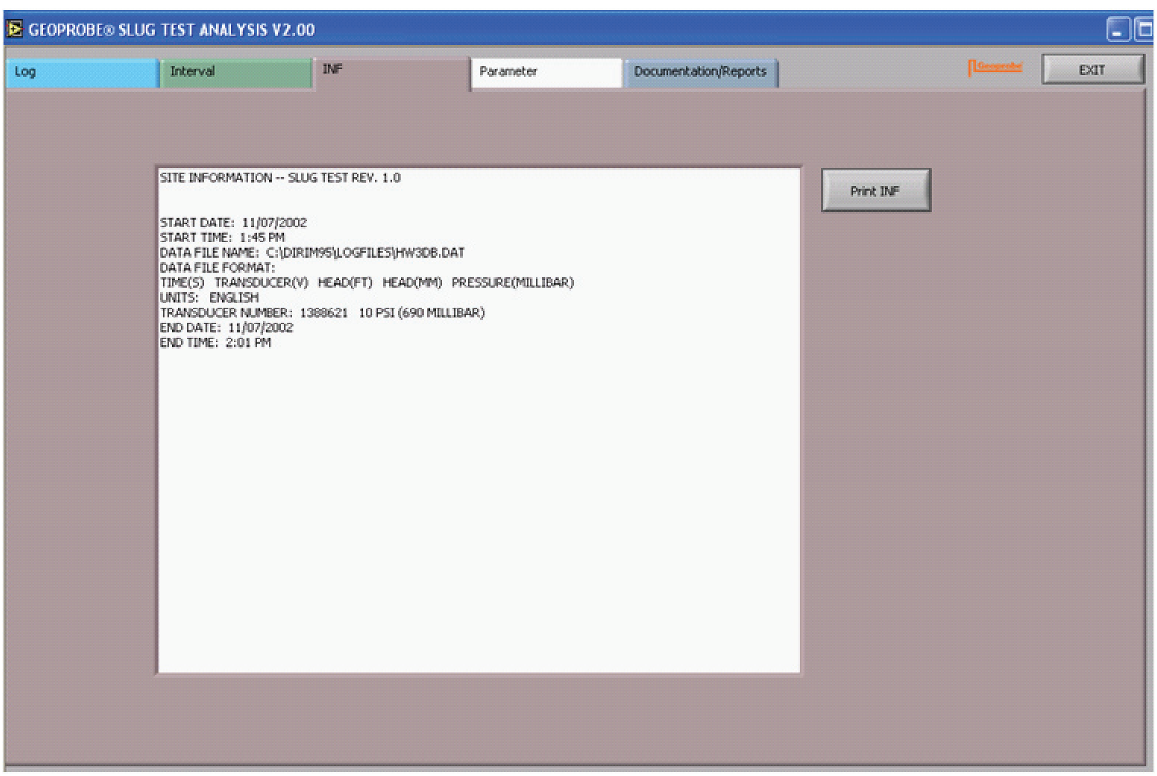


Figure 20: Slug test acquisition information file screen.

3.5 Documentation/Reports Screen

The last page of the STA package allows you to select the graphs and other documentation pages for printing from one convenient location (Fig.21). Simply click on the box adjacent to the desired items and then click on the Print icon. Additionally, you may open a pdf version of the Slug Test SOP document to review or print a copy. The instruction sheet for use of the Test Jig to test the data logger (A to D converter) is included for easy access and printing. The STA User's Guide also may be opened for review or printing from this page.

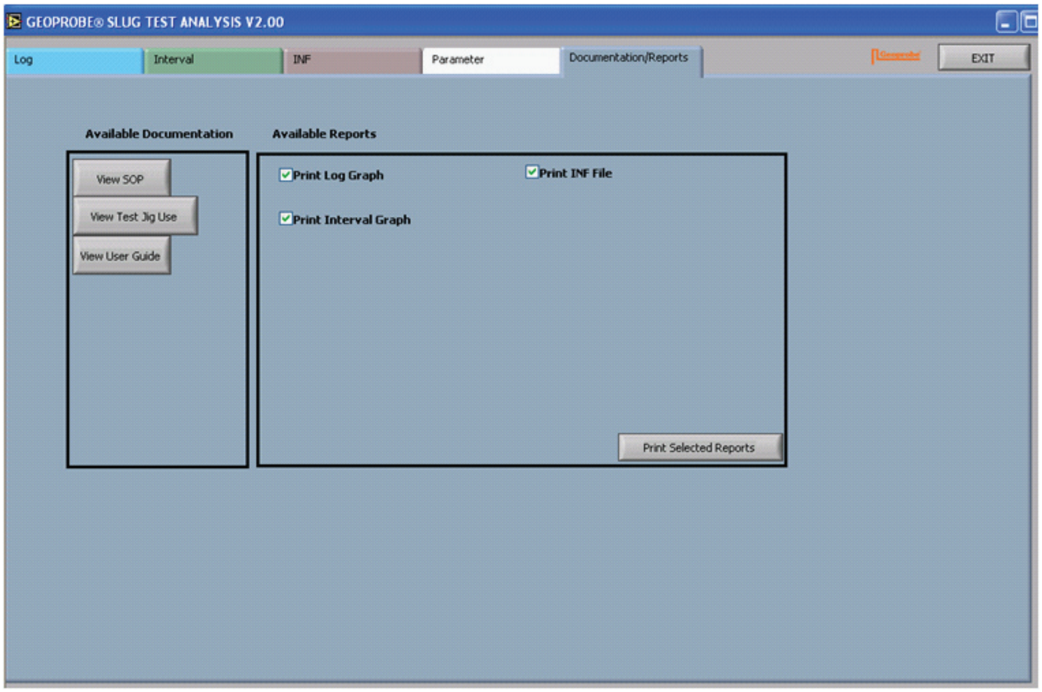


Figure 21: Documentation and Reports screen.

Section 4.0
RECOMMENDED READING

The purpose of this User's Guide is simply to provide you with guidance on how to use this software package to model slug test data obtained with the GW1600 Pneumatic Slug Test kit. This Guide is not intended to explain hydrology, hydrogeology, geology nor the mathematics used to model the aquifer responses observed from a slug test. A multitude of text books, books, peer reviewed journal articles and consensus standards have been written about slug testing and the calculation of hydraulic conductivity from slug test data. A recent book, *The Design, Performance, and Analysis of Slug Tests* (Butler 1997) provides a thorough review of slug testing methods and detailed discussion of the various models used in analysis of the results. For a more general background in hydrogeology the reader may wish to review a text such as *Applied Hydrogeology* (Fetter 1994) or similar books. Several consensus standards relating to slug test methods and analysis have been published by the American Society of Testing and Materials (ASTM). Current ASTM standards on these topics are available from the ASTM web site (*www.astm.org*) and include but are not limited to the following standards D 4043, D 4044, D4104, and D 5785. Some recent peer reviewed journal articles (Butler et al. 2002, McCall et al. 2002, Butler 2002, Sellwood et al. 2004) that address slug testing with direct push equipment may prove useful to the reader.

Section 5.0
EQUATIONS USED TO CALCULATE HYDRAULIC CONDUCTIVITY (K)

The specific equations used in the STA software to calculate hydraulic conductivity (K) are shown on the following three pages. The first set of equations are for confined aquifers and utilize the Hvorslev Method to estimate K. Beginning on Page 20, the second set of equations are for unconfined aquifers and utilize the Bouwer & Rice Method to estimate K. Note that the variables and references listed on Page 21 apply only to the unconfined aquifer equations.

Confined Aquifer
(Hvorslev Method)

Oscillatory Response (Underdamped)		Log Response (Overdamped)	
Partially Penetrating[1]	**Fully Penetrating**[1]	**Partially Penetrating**[2]	**Fully Penetrating**[3]
$K = \left(\frac{t_d^*}{t^*}\right)\left(\frac{r_c^2 \ln\left[b/(2r_w) + (1+(b/2r_w)^2)^{1/2}\right]}{2\,b\,C_d}\right)$	$K = \left(\frac{t_d^*}{t^*}\right)\left(\frac{r_c^2 \ln\left[b/(r_w) + (1+(b/r_w)^2)^{1/2}\right]}{2\,b\,C_d}\right)$	$K = \frac{r_c^2 \ln(L_e/R_e)}{2\,L_e\,T_0}$	$K = \frac{r_c^2 \ln(R_e/r_w)}{2\,B\,T_0}$ Where: $\ln(R_e/r_w) = \ln(200)$
b = screen length r_c = corrected casing radius r_w = effective radius of screen C_d = damping parameter t^* = time t_d^* = dimensionless time parameter K = hydraulic conductivity		r_c = radius of casing L_e = effective length of screen R_e = effective radius of slug test T_0 = time it takes water level to rise or fall 37% of the initial change r_w = effective radius of screen B = thickness of aquifer	

References

[1] Butler, James J. Jr., and Elizabeth J. Garnett. 2000. Simple Procedures for Analysis of Slug Tests in Formations of High Hydraulic Conductivity Using Spreadsheet and Scientific Graphics Software. Kansas Geological Survey, Open-file Report 2000-40, 23 pages. www.kgs.ku.edu

[2] Fetter, Charles W. 1994. Applied Hydrogeology, Third Edition. Prentice-Hall, Inc. Upper Saddle River, NJ. 691 pages.

[3] Butler, James J. Jr. 1997. The Design, Performance, and Analysis of Slug Tests. Lewis Publishers, Boca Raton, FL. 252 pages.

Unconfined Aquifer

(Bouwer & Rice Method)

Oscillatory Response① (Underdamped)

Partially Penetrating

$$K = \left(\frac{t_d^*}{t^*}\right)\left(\frac{r_c^2 \ln\left[R_e/r_w\right]}{2\,b\,C_d}\right)$$

Where:

$$A = 1.4720 + \left[3.537x10^{-2} * (b/R_w)\right] - \left[8.148x10^{-5} * (b/R_w)^2\right] + \left[1.028x10^{-7} * (b/R_w)^3\right] - \left[6.484x10^{-11} * (b/R_w)^4\right] + \left[1.573x10^{-14} * (b/R_w)^5\right]$$

$$B = 0.2372 + \left[5.151x10^{-3} * (b/R_w)\right] - \left[2.682x10^{-6} * (b/R_w)^2\right] - \left[3.491x10^{-10} * (b/R_w)^3\right] + \left[4.738x10^{-13} * (b/R_w)^4\right]$$

$$\ln(R_e/r_w^*) = \left[\frac{1.1}{\ln((d+b)/r_w^*)} + \frac{A+B\left(\ln\left[(B-(d+b))/r_w^*\right]\right)}{b/r_w^*}\right]^{-1}$$

Fully Penetrating

$$K = \left(\frac{t_d^*}{t^*}\right)\left(\frac{r_c^2 \ln\left[R_e/r_w\right]}{2\,b\,C_d}\right)$$

Where:

$$C = 0.7920 + \left[3.993x10^{-2} * (b/R_w)\right] - \left[5.741x10^{-5} * (b/R_w)^2\right] + \left[3.858x10^{-8} * (b/R_w)^3\right] - \left[9.659x10^{-12} * (b/R_w)^4\right]$$

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

Log Response② (Overdamped)

Partially Penetrating

$$K = \frac{r_c^2 \ln(R_e/r_w^*)}{2\,b\,T_0}$$

Where:

$$A = 1.4720 + \left[3.537x10^{-2} * (b/R_w)\right] - \left[8.148x10^{-5} * (b/R_w)^2\right] + \left[1.028x10^{-7} * (b/R_w)^3\right] - \left[6.484x10^{-11} * (b/R_w)^4\right] + \left[1.573x10^{-14} * (b/R_w)^5\right]$$

$$B = 0.2372 + \left[5.151x10^{-3} * (b/R_w)\right] - \left[2.682x10^{-6} * (b/R_w)^2\right] - \left[3.491x10^{-10} * (b/R_w)^3\right] + \left[4.738x10^{-13} * (b/R_w)^4\right]$$

$$\ln(R_e/r_w^*) = \left[\frac{1.1}{\ln((d+b)/r_w^*)} + \frac{A+B\left(\ln\left[(B-(d+b))/r_w^*\right]\right)}{b/r_w^*}\right]^{-1}$$

Fully Penetrating

$$K = \frac{r_c^2 \ln(R_e/r_w^*)}{2\,b\,T_0}$$

Where:

$$C = 0.7920 + \left[3.993x10^{-2} * (b/R_w)\right] - \left[5.743x10^{-5} * (b/R_w)^2\right] + \left[3.858x10^{-8} * (b/R_w)^3\right] - \left[9.659x10^{-12} * (b/R_w)^4\right]$$

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

$\frac{t_d^*}{t^*}$ = match point ratio of dimensionless time to measured time

t_d^* = dimensionless time

t^* = measured time

r_c = radius of casing

$\ln\left[R_e/r_w\right]$ = empirical parameter for Bouwer & Rice method used to estimate radius of influence

r_w = effective radius of screen

b = effective screen length

C_d = damping parameter

T_0 = time it takes water level to raise or fall 37% of the initial change

R_e = effective radius of slug test

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①Butler, James J. Jr., and Elizabeth J. Garnett. 2000. Simple Procedures for Analysis of Slug Tests in Formations of High Hydraulic Conductivity Using Spreadsheet and Scientific Graphics Software. Kansas Geological Survey, Open-file Report 2000-40, 23 pages. www.kgs.ku.edu

②Butler, James J. Jr. 1997. The Design, Performance, and Analysis of Slug Tests. Lewis Publishers, Boca Raton, FL. 252 pages.

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