RSAT 0.2.1

Rising head Slug test Analysis Tool

User Manual

Version 1

Content

List with abbreviations 3

1 Introduction 4

2 Data requirements, possibilities and limitations 4

3 Functionalities 4

4 User manual 5

4.1 Working directory and data file 5

4.2 Preprocessing: splitting raw data and plot normalized head curves 5

4.2.1 Selection of the appropriate data and splitting of multiple measurements 5

4.2.2 Checking for repeatability and quality of the measurements 10

4.3 Calculations 11

4.3.1 Parameters 11

4.3.2 Calculation options 11

4.3.3 Performing calculations and saving results 13

References 14

List with abbreviations

K_r	radial hydraulic conductivity (hydraulic conductivity in horizontal plane) [L/T]
K_z	vertical hydraulic conductivity [L/T]
rc	effective radius well casing [L]
rw	effective radius well screen [L]
Le	effective screen length [L]
d	z-position of end of screen closest to an impermeable boundary in confined formation or to water table in unconfined formation [L]
Re	effective radius parameter [L]
T_0	time at which a normalized head of 0.368 (0.37) is obtained

1 Introduction

The RSAT tool version 0.2.1 is developed for the calculation of the horizontal hydraulic conductivity of aquifers for data from rising head slug tests. It is an extension of the version developed by Ghysels (2018). RSAT is built with Python 3.7. It consists of a user interface to manipulate, visualize and interact with the data. The horizontal hydraulic conductivity is calculated with the Bouwer & Rice (1976) method modified for anisotropy by Zlotnik (1994) and the Hvorslev (1951) method. The guidelines of Butler (1997) are used for the selection of the optimal range of normalized heads: normalized heads in the range of 0.20-0.30 for Bouwer and Rice methods (1976) and 0.15-0.25 for de Hvorslev methods (1951).

2 Data requirements, possibilities and limitations

The observation data files require some general characteristics for importing them in the RSAT tool. These requirements are:

- the delimiter should be one or more space(s)
- data should consist of 5 columns, wherefrom the first is the time in seconds and the fourth is the head expressed in mm
- the data file is not allowed to contain a header nor literals
- the data should not have missing values in certain columns. However, if values are missing over a whole row, for example, certain time moments are not registered, there is no problem

When the delimiter is not the required character, one can change it easily with the 'search and replace' tool implemented in most of the text editors or adapt the program in the function OpenFile() on line 29 by removing 'delim_whitespace=True' and adding the arguments 'sep' or 'delimiter' with the corresponding delimiter.

Data files can have a dot or comma as decimal separator. Data files with different measurement frequencies can be compared and plotted on the same graph.

3 Functionalities

The user interface consists of three main parts which are: (1) working directory and data file selection; (2) preprocessing and (3) calculations. Preprocessing may be needed to perform the calculations correctly. It is used to split data files with multiple slug tests (for example repeated measurements) into individual slug tests. When split, the repeating measurements can be plotted simultaneously to check the repeatability and quality of the measurements. The part where calculations are done consists of entries for the aquifer and slug test characteristics and options for the calculation methods. The output of the tool is a text file with the results and several graphs in pdf format.

4 User manual

In Figure 1 the user interface is displayed. The functionalities and work flow are explained in the following paragraphs.

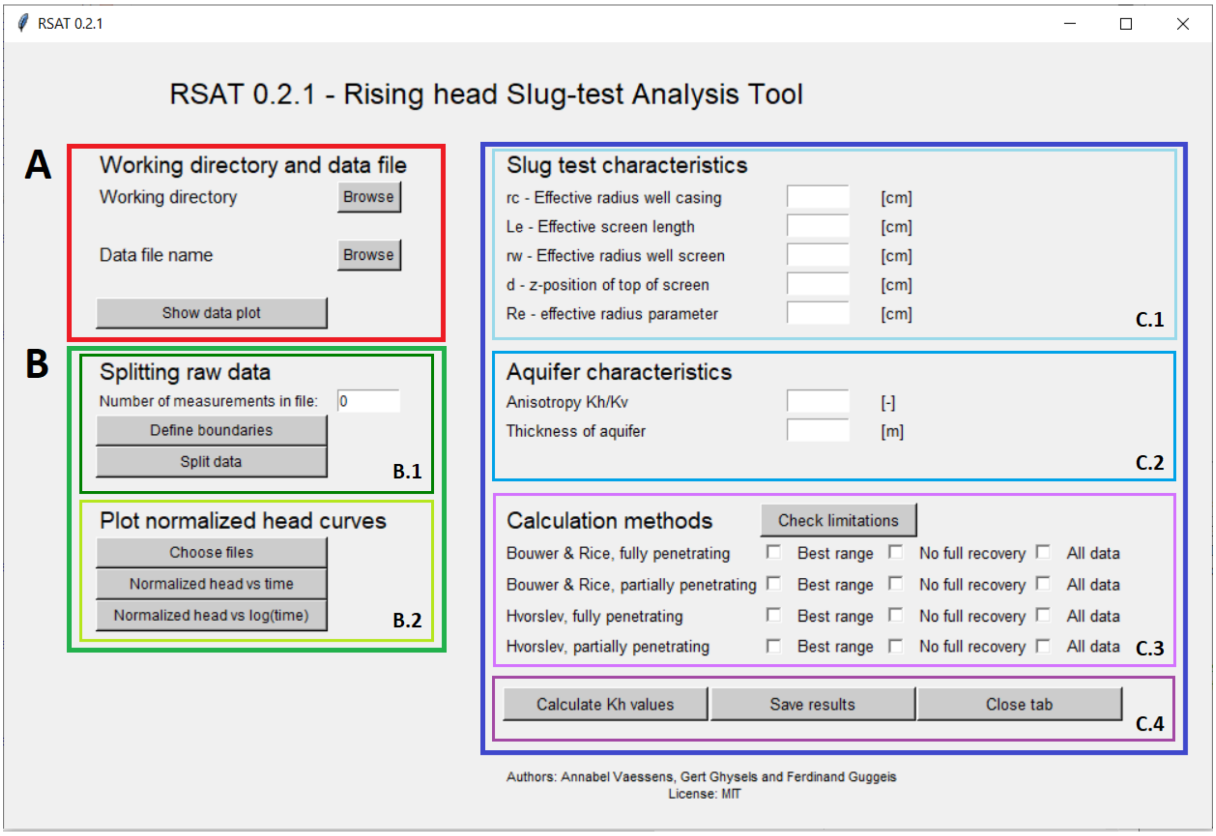

Figure 1: User interface of the RSAT tool.

4.1 Working directory and data file

The first part of the user interface is presented in the red box A on Figure 1. Next to 'working directory', there is a browse button to change the working directory. When selecting data files and saving results, the selected working directory will be the opened location. It is not mandatory to set the working directory, since one can navigate freely through maps when opening/saving a data file, except for saving the individual measurements from the splitting during the preprocessing.

The second browse button opens a window where the user can select a data file. The data will be imported and are used in the parts B.1 and C. There is an option to plot the data on a head-time curve with the button 'Show data plot'. This plot can be saved in pdf format.

4.2 Preprocessing: splitting raw data and plot normalized head curves

The preprocessing is located in the green box B on Figure 1. It consists of two parts: splitting of data and plotting multiple measurements on one graph.

4.2.1 Selection of the appropriate data and splitting of multiple measurements

Raw data files may consist of multiple repeated measurements or may have irregularities that hinder the hydraulic conductivity calculations. One should check the raw data after importing it to determine whether splitting is needed. Two cases are discussed here.

The first case is when there are multiple measurements in one data file. The number of measurements can be count on the plot of part A. This number should be typed in the entry box ‘number of measurements in file’. Next, press the button ‘Define boundaries’.

A new window with the head-time plot will pop up. This plot is clickable. For each measurement, one should click close the beginning and end of each measurement. This should be done in the following order: beginning of first measurement, end of first measurement, beginning of second measurement, end of second measurement , until the end of the last measurement is clicked.

New points are defined with the left mouse click and can be removed with the right mouse click. The previous clicked locations are presented by red crosses. When the last point is clicked, all red crosses will disappear and the user can close the pop-up window. The location of the beginnings is advised to be placed just after the peak before of the measurement. The location of the ends should be placed just before the next peak (or at the end of the data set). Some correct and incorrect examples are in Figure 2, Figure 3, Figure 4 and Figure 5, where there are five measurements indicated with the letters A to E. The resulting individual measurements are saved in the working directory selected in part A. They are saved with the extension ‘.dat’ and with the same filename as the raw data, followed by “_proc” and consecutive letters of the alphabet.

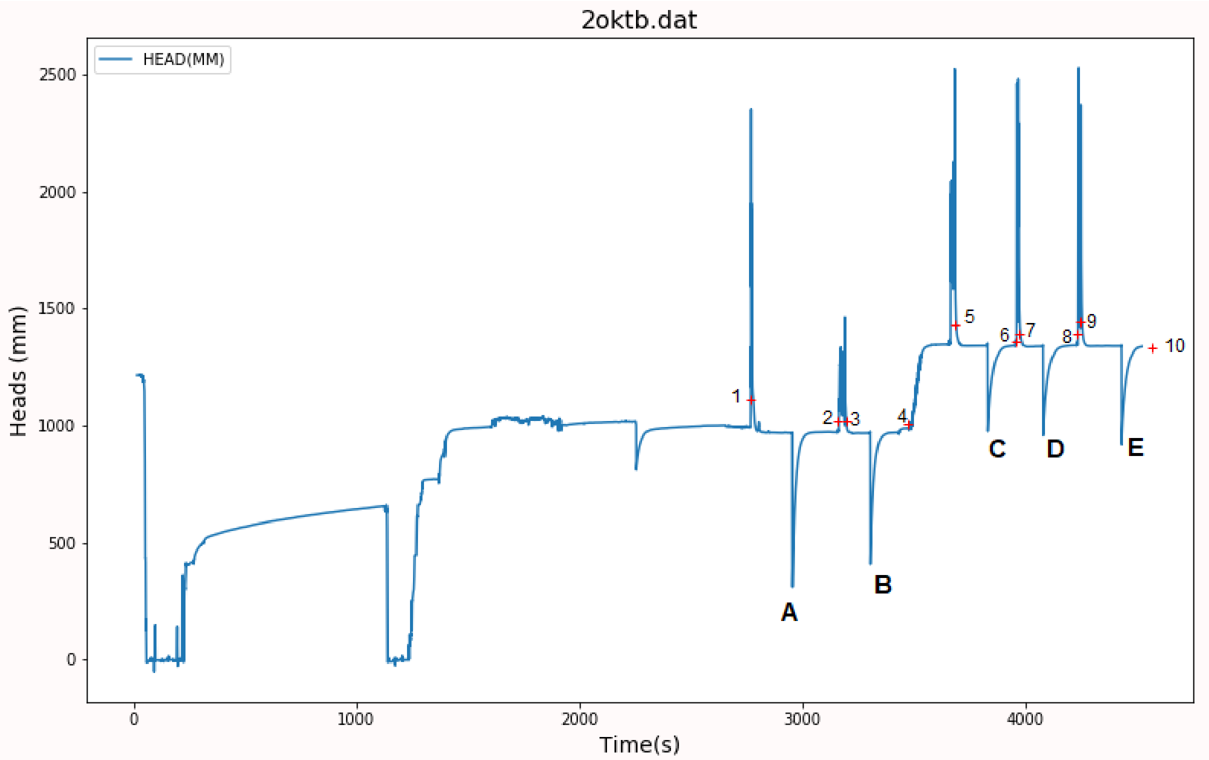

Figure 2: Example of correct splitting. The clicks are placed at the beginning and end of the peaks that represent the insertion of the slug in the well. The clicks are in the following order: beginning of first measurement, end of first measurement, beginning of second measurement etc. The end of the last measurement is placed right of the end of the dataset. This is the best practice, the software will take the last data point as splitting point.

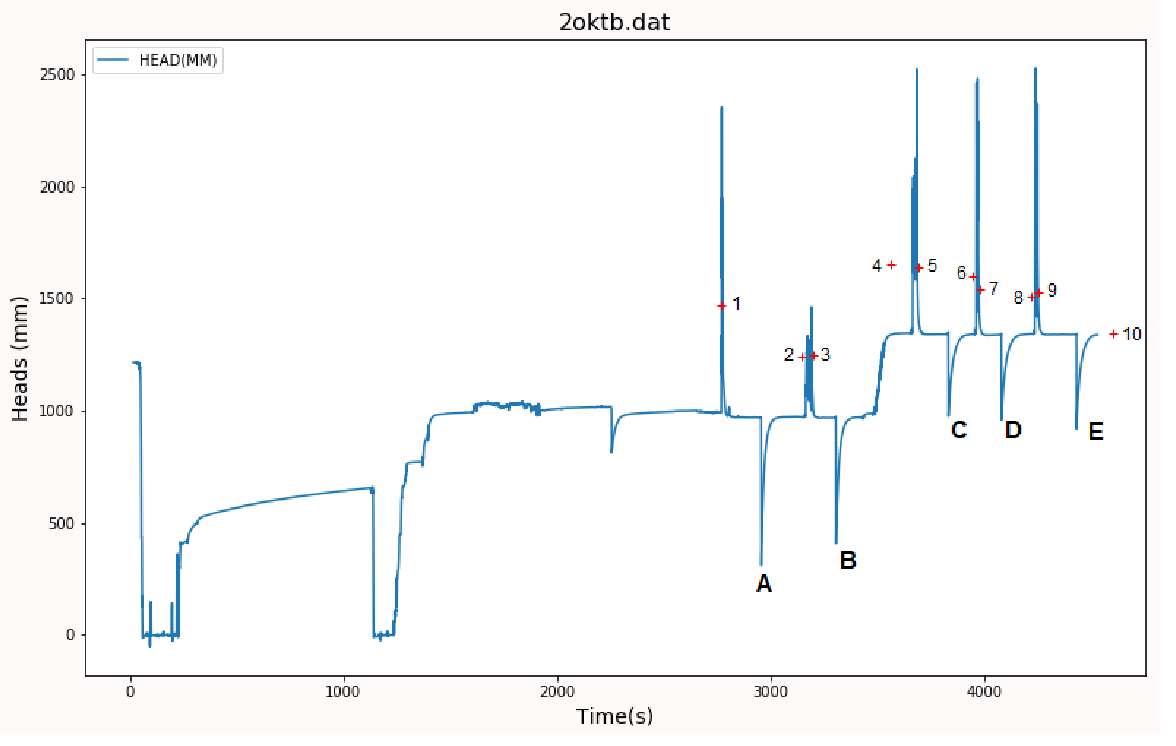

Figure 3: Example of correct splitting. The clicks are placed somewhat higher in the peaks than the previous example. They are placed in the correct order. Remark that point 4 is not placed on the data. This is no problem, since the software automatically snaps to the closest data point. However, it is advised to place the points as close as possible to the desired data point.

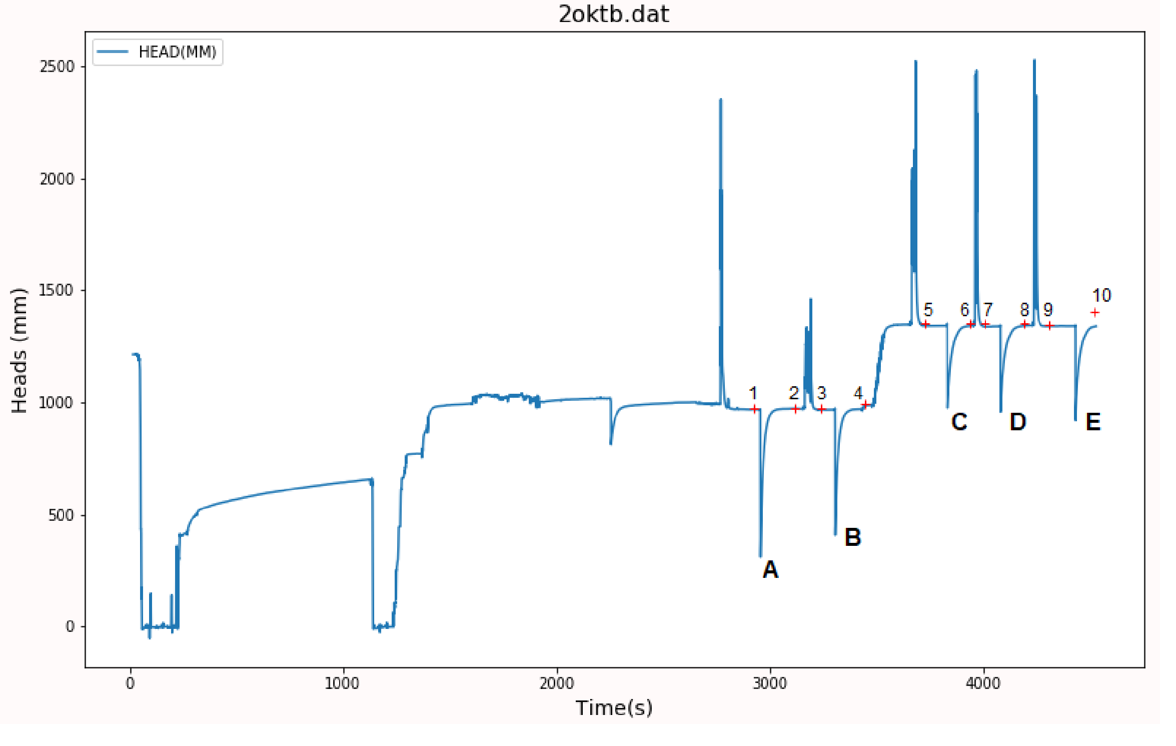

Figure 4: Example of incorrect splitting. The points are placed too narrow: the resulting data sets may comprise not enough values of the base level before the actual measurement nor reach recovery. Point 10 is not placed to the right of the data set, so it might not snap to the last point of the dataset.

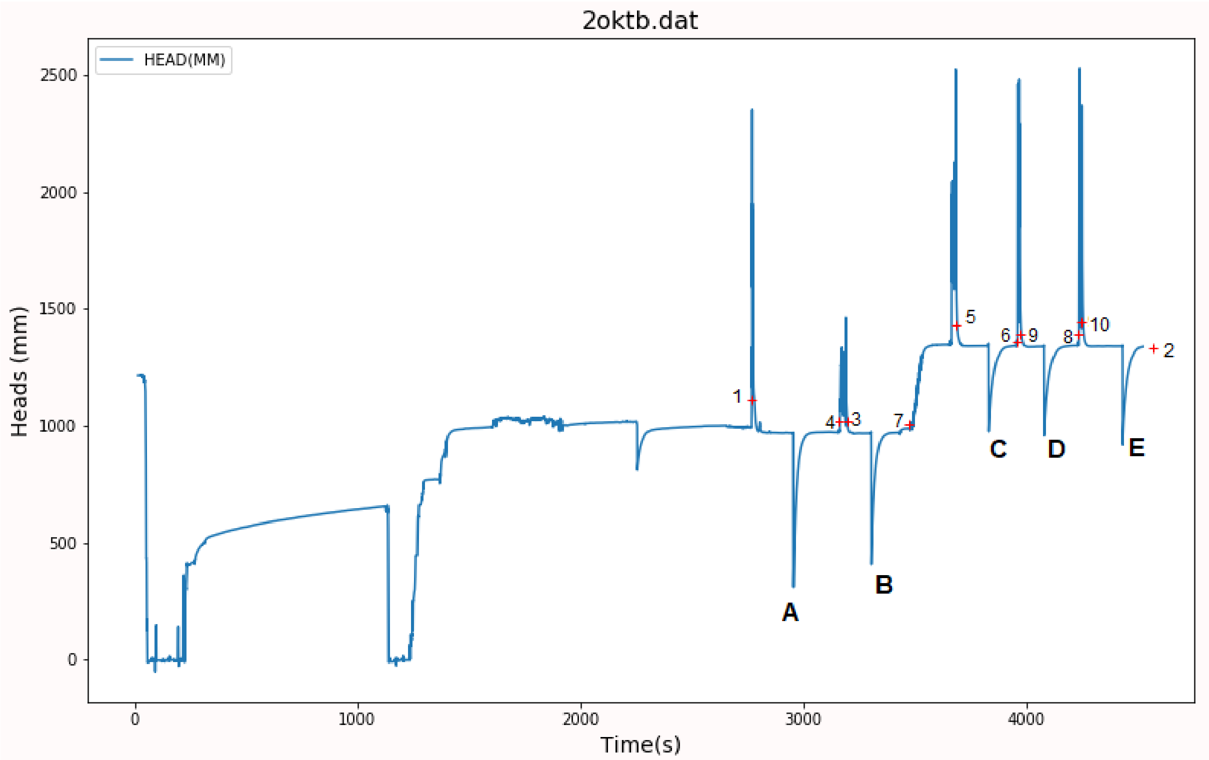

Figure 5: Example of incorrect splitting. The points are not clicked in the correct order.

For this example, the resulting five files will be named like Figure 6:

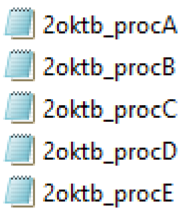

Figure 6: Resulting data files after splitting of the data file 2_oktb.

The second case where the splitting tool should be used is when there is a lot of noise that is not related to the measurement itself. The good part of the measurement can be cut out for further figure display. Especially when there are measurements with lower heads as the minimal head of the actual measurement, the splitting should be performed in order to have a correct identification of the minimum by the software. An example is given in Figure 7.

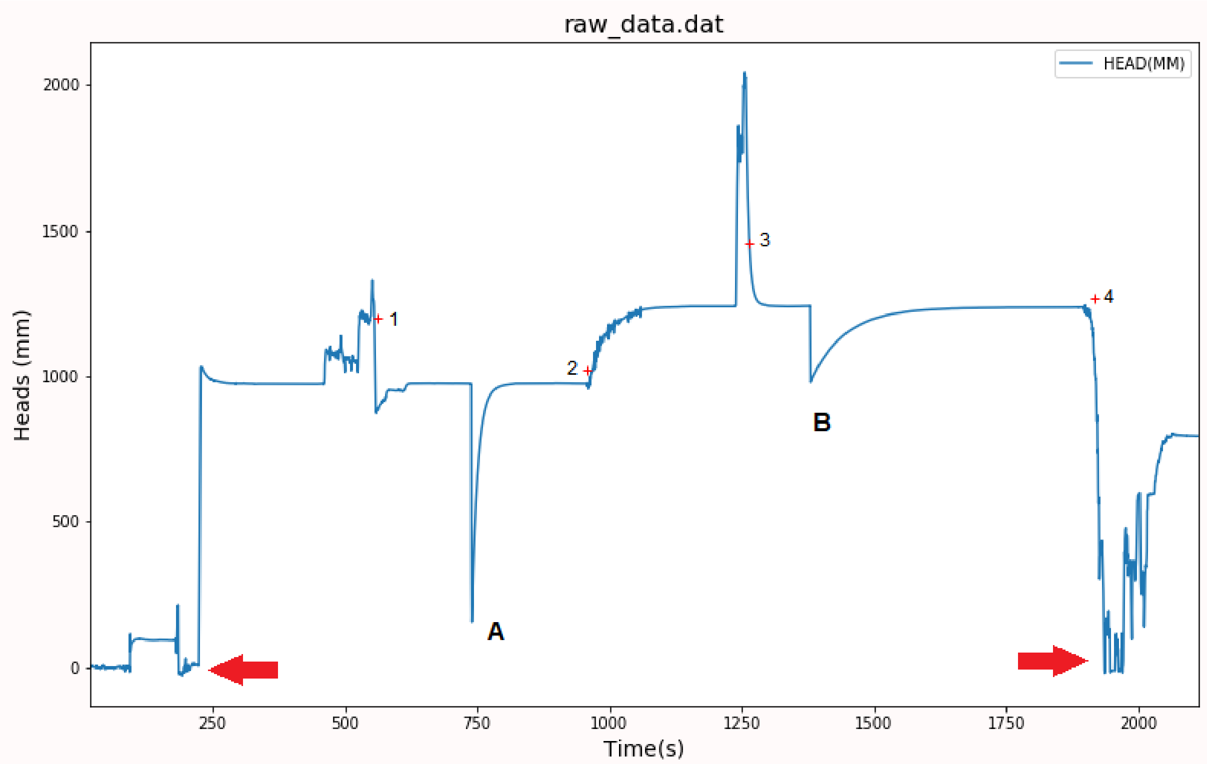

Figure 7: Example of correct splitting when there are data points lower than the minimum of the actual measurement. These points (indicated with red arrows) should be excluded from the data.

4.2.2 Checking for repeatability and quality of the measurements

Once a data file with multiple measurements is split, the quality and repeatability of these measurements can be checked on normalized head versus time and normalized head versus log(time) curves. This functionality is present in part B.2 on Figure 1.

When choosing files, all files should be selected at once on the pop-up window (using the ctrl-key). Once the files are imported, a window will pop-up for each measurement where the user has to indicate the location of the base level. The user can choose to plot the normalized head - time curves or the normalized head - log(time) curves.

There is an option to save the figures in pdf-format at the desired location. Examples are given in Figure 8 and Figure 9.

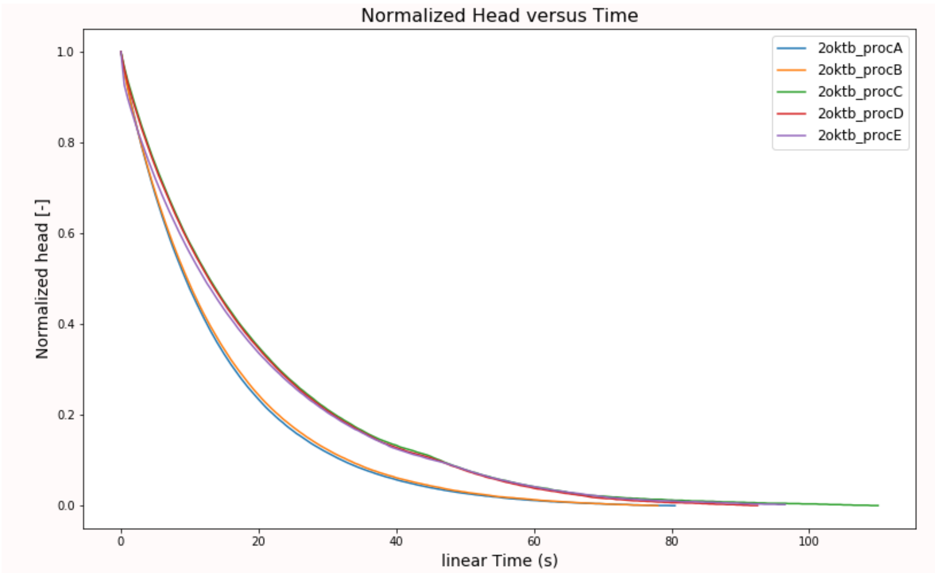

Figure 8: Normalized head - time curves for the split data of 2_oktb. For repeating measurements, the shape of the curves should be similar.

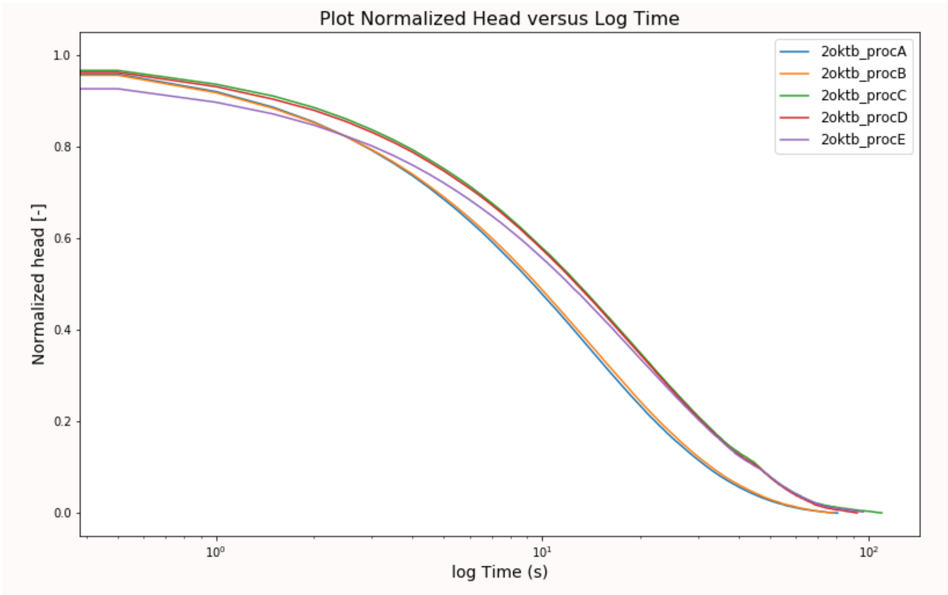

Figure 9: Normalized head - log(time) curves for the split data of 2_oktb.

4.3 Calculations

The main part is the calculation of the horizontal hydraulic conductivity. There are twelve calculation options.

4.3.1 Parameters

The user has to give the parameters summarized in Table 1. R_e and the aquifer thickness are not needed for every calculation method.

Table 1: Parameters for the slug test calculations

Parameter	Unit	Remarks
Slug test characteristics		
r_c	cm	Effective radius well casing
Le	cm	Effective screen length
r_w	cm	Effective radius well screen
d	cm	z-position of end of screen closest to an impermeable boundary in a confined formation or to water table in unconfined formation
R_e	cm	Effective radius parameter. R_e can be assumed to be equal to the length of the well screen for any well, or 200*the effective radius if the well screen for fully penetrating wells (U.S. Department of Navy, 1961). Only needed for the *Hvorslev, fully penetrating* well calculation.
Aquifer characteristics		
anisotropy	-	Hydraulic conductivity anisotropy (K_r/K_z)
Aquifer thickness (AqThick)	m	The aquifer thickness is only needed when performing the *Bouwer-Rice, partially penetrating well* and *Hvorslev, fully penetrating well* calculations. For the other calculations, this entry can be left empty.

4.3.2 Calculation options

Before performing the calculations, it is advised to check the options. The button 'Check limitations' checks in which extent the data reaches the base level (whether the data reaches recovery). Since certain ranges of normalized head are used for different calculation options, some calculations may not be possible when the data does not reach these normalized heads. The software will crash when these options are run anyway.

There are twelve calculations options and four methods are used. The first and second method are for unconfined aquifers and use the equations of Bouwer and Rice. For the Bouwer and Rice methods, the hydraulic conductivity can be calculated based on regression of the following ranges of normalized head: best range (normalized head between 0.30-0.20, Butler 1996), no full recovery range (normalized head between 1.00-0.30) and all data (normalized head between 1.00-0.035).

The equation for the radial (horizontal) hydraulic conductivity of Bouwer-Rice is the following:

$$K_r = \frac{{r_c}^2 * \ln\left(\frac{R_e}{r_w * (K_z/K_r)^{1/2}}\right)}{2 * Le * T_0}$$

Where T_0 is obtained from linear regression of the log(normalized head)-time curve over the corresponding range.

The **first method** of **Bouwer-Rice** is for **fully penetrating** wells in unconfined aquifers. For fully penetrating wells, $\ln\left(\frac{R_e}{r_w*(K_z/K_r)^{1/2}}\right)$ is estimated to be:

$$\ln\left(\frac{R_e}{r_w*(K_z/K_r)^{\frac{1}{2}}}\right) = \left(\frac{1.1}{\ln\left(\frac{d+Le}{r_w*(K_z/K_r)^{1/2}}\right)} + \frac{C}{\frac{Le}{r_w*(K_z/K_r)^{1/2}}}\right)^{-1}$$

with

$$C = 0.7920 + 3.993*10^{-2}*\left(\frac{Le}{r_w*(K_z/K_r)^{\frac{1}{2}}}\right) - 5.743\ *10^{-5}*\left(\frac{Le}{r_w*(K_z/K_r)^{\frac{1}{2}}}\right)^2 + 3.858\ *10^{-8} *\left(\frac{Le}{r_w*(K_z/K_r)^{\frac{1}{2}}}\right)^3 - 9.659*10^{-12}*\left(\frac{Le}{r_w*(K_z/K_r)^{\frac{1}{2}}}\right)^4$$

The **second method** of **Bouwer-Rice** is for **partially penetrating wells** in unconfined aquifers. For partially penetrating wells, $\ln\left(\frac{R_e}{r_w*(K_z/K_r)^{1/2}}\right)$ is estimated to be:

$$\ln\left(\frac{R_e}{r_w*(K_z/K_r)^{1/2}}\right) = \left(\frac{1.1}{\ln\left(\frac{d+Le}{r_w*(K_z/K_r)^{1/2}}\right)} + \frac{A + B*ln\left(\frac{\mathrm{AqThick-d-Le}}{r_w*(K_z/K_r)^{1/2}}\right)}{\frac{Le}{r_w*(K_z/K_r)^{1/2}}}\right)^{-1}$$

with

$$A = 1.4720 + 3.537*10^{-2}*\left(\frac{Le}{r_w*(K_z/K_r)^{\frac{1}{2}}}\right) - 8.148*10^{-5}*\left(\frac{Le}{r_w*(K_z/K_r)^{\frac{1}{2}}}\right)^2 + 1.028*10^{-7} *\left(\frac{Le}{r_w*(K_z/K_r)^{\frac{1}{2}}}\right)^3 - 6.484*10^{-11}*\left(\frac{Le}{r_w*(K_z/K_r)^{\frac{1}{2}}}\right)^4 + 1.573*10^{-14}*\left(\frac{Le}{r_w*(K_z/K_r)^{\frac{1}{2}}}\right)^5$$

$$B = 0.2372 + 5.151\ *10^{-3}*\left(\frac{Le}{r_w*(K_z/K_r)^{\frac{1}{2}}}\right) - -2.682\ *10^{-6}*\left(\frac{Le}{r_w*(K_z/K_r)^{\frac{1}{2}}}\right)^2 - 3.491\ *10^{-10} *\left(\frac{Le}{r_w*(K_z/K_r)^{\frac{1}{2}}}\right)^3 + 4.738\ *10^{-13}*\left(\frac{Le}{r_w*(K_z/K_r)^{\frac{1}{2}}}\right)^4$$

The third and fourth method use the Hvorslev equation for respectively fully and partially penetrating wells, for confined aquifers. The horizontal hydraulic conductivity can be calculated based on regression of the following ranges of normalized head: best range (normalized head between 0.25-0.15, Butler 1996), no full recovery range (normalized head between 1.00-0.30) and all data (normalized head between 1.00-0.035).

The **Hvorslev** equation for the horizontal hydraulic conductivity for **fully penetrating wells** is the following:

$$K_r = \frac{{r_c}^2 * \ln\left(\frac{R_e}{r_w}\right)}{2 * AqThick * T_0}$$

Where T_0 is obtained from linear regression of the log(normalized head)-time curve over the corresponding range.

The **Hvorslev** equation for the horizontal hydraulic conductivity in **partially penetrating wells** is the following:

$$K_r = \frac{{r_c}^2 * \ln\left(\frac{Le}{2 * r_{w*}\sqrt{K_z/K_r}} + \left(1 + \left(\frac{Le}{2r_{w*}\sqrt{K_z/K_r}}\right)^2\right)^{1/2}\right)}{2 * AqThick * T_0}$$

4.3.3 Performing calculations and saving results

The buttons for calculations are in window C.4 (Figure 1). When the button 'Perform calculations' is pressed, a window pops up where the user has to define the base level. The calculated horizontal conductivities will be shown in a pop-up table and the regression results in a separate plot. These windows can be closed. The results (both regression plot and horizontal hydraulic conductivity values and parameters) can be saved in respectively a pdf and a text file with the Save-button.

References

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- Hvorslev MJ, 1951. Time lag and soil permeability in groundwater observations. US Army Bull. 36.
- U.S. Department of Navy, Bureau Yards and Docks, 1961. Design manual: soil mechanics, foundations and earth structures, DM-7, chapter 4.
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