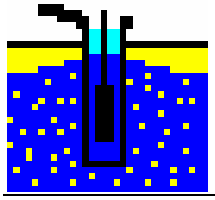
Evaluation and representation of slug tests

GGU-SLUGTEST

VERSION 6



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1 Preface

The **GGU-SLUGTEST** program allows the evaluation and graphical representation of slug tests.

Data input is in accordance with WINDOWS conventions and can therefore be learned almost entirely without the use of a manual. Graphics output supports the true-type fonts supplied with WINDOWS, so that excellent layout is guaranteed. Colour output and any graphics (e.g. files in formats BMP, JPG, PSP, TIF, etc.) are supported. PDF and DXF files can be imported by means of the integrated **Mini-CAD** module (see the "**Mini-CAD**" manual).

The program has been thoroughly tested. No faults have been found. Nevertheless, liability for completeness and correctness of the program and the manual, and for any damage resulting from incompleteness or incorrectness, cannot be accepted.

2 Licence protection

GGU software is provided with the WIBU-Systems CodeMeter software protection system. For this purpose the GGU-Software licences are linked to a USB dongle, the WIBU-Systems CmStick, or as CmActLicense to the respective PC hardware.

It is required for licence access that the CodeMeter runtime kit (CodeMeter software protection driver) is installed. Upon start-up and during running, the **GGU-SLUGTEST** program checks that a licence on a CmStick or as CmActLicense is available.

3 Language selection

GGU-SLUGTEST is a bilingual program. The program always starts with the language setting applicable when it was last ended.

The language preferences can be changed at any time in the "**Info**" menu, using the menu item "**Spracheinstellung**" (for German) or "**Language preferences**" (for English).

4 Starting the program

After starting the program, you will see two menus at the top of the window**:**

- File
- Info

After clicking on the "**File**" menu, you can load a previously analysed system by means of the "**Load**" menu item, or a new one created using "**New**". Seven menus then appear at the top of the window:

- File
- Edit
- Hvorslev, ...
- Type curves
- Test design
- Graphics preferences
- Info

After clicking one of these menus, the so-called menu items roll down, allowing you access to all program functions.

The program works on the principle of ***What you see is what you get***. This means that the screen presentation represents, overall, what you will see on your printer. In the last consequence, this would mean that the screen presentation would have to be refreshed after every alteration you make. For reasons of efficiency, and as this can take several seconds for complex screen contents, the **GGU-SLUGTEST** screen is not refreshed after every alteration.

If you would like to refresh the screen contents, press either [**F2**] or [**Esc**]. The [**Esc**] key additionally sets the screen presentation back to your current zoom, which has the default value 1.5, corresponding to an A4 sheet in landscape format.

5 Theoretical principles

5.1 Slug tests - a brief introduction

The fundamental aim of hydraulic tests is to determine the hydraulic parameters of the system under investigation.

When carrying out such tests a precisely defined signal is applied to the unknown system, e.g. the submersion of a defined body below the at-rest water level of a well.

The reaction of the system - the change in water level with time - is a function of the hydraulic parameters and the geometry (*FLOPETROL, 1983; KARASAKI, 1986*). The solution to this inverse problem requires the definition and formulation of a theoretical model, the reaction of which to an identical input signal must correspond as precisely as possible to that of the real system (*GRINGARTEN, 1980*).

The solution is often ambiguous: differently configured models can react identically to an identical input signal.

The more information available on geological strata, hydrologic conditions and on the borehole or well geometry, the lower the number of possible solutions (*GRINGARTEN, 1980*).

5.2 Evaluation by COOPER et. al.

5.2.1 Basic differential equation

The slug test was originally derived with mathematical precision by *COOPER et al. (1967)* on the basis of the differential equation for transient, radial-symmetric flow into a confined, homogeneous and isotropic aquifer. One of the principal boundary conditions taken into consideration by them is the finite well radius and thus the wellbore storage of the well.

The approach used is:

$$\frac{\partial^2 h}{\partial r^2} + \frac{1}{r}\frac{\partial h}{\partial r} = \frac{S}{T}\frac{\partial h}{\partial t}$$

where:

h : Head [m]

r : Radial distance from well [m]

t : Time [s]

T : Transmissivity [m²/s]

S : Storage coefficient [-]

The differential equation is derived from a combination of the law of mass conservation, Darcy's Law and, optionally, a description of state (*MATTHEWS & RUSSEL, 1967*). The conditions for this are constant radial flow, a confined, homogeneous and isotropic medium of infinite extent, and a single fluid phase with small and constant compressibility.

Here, the transmissivity indicates the volumetric flow of a fluid of defined viscosity in a hydraulic gradient of 1 through a 1 m section of aquifer, encompassing the complete thickness (m) of the aquifer and which is arranged perpendicular to the direction of flow (*LANGGUT & VOIGT, 1980*).

The relationship between the transmissivity and the permeability (k_f), then, is

$$T = k_f \cdot m.$$

The storage coefficient is a parameter describing the quantity of water stored or released from an aquifer per surface unit of the aquifer for a unit change in water level (*KRUSEMANN & DE RIDDER, 1973*). Strictly speaking, the storage coefficient only applies to confined aquifers and is a function of the elasticity (or compressibility) of the grain skeleton and the fluid. The volume of the single grains is assumed to be constant because their compressibility is substantially smaller than that of the grain skeleton and smaller than the fluid (*MATTHESS & UBELL, 1983, p. 159*). The storage coefficient can thus be defined as (*KRUSEMANN & DE RIDDER, 1990*):

$$S = m \cdot n \cdot c_w \cdot y_w \cdot \left(1 + \frac{c_A}{n\, c_w}\right)$$

where:

S : Storage coefficient [-]

m : Aquifer thickness [m]

n : Aquifer porosity [-]

c_w : Compressibility of fluid [m²/N]

c_A : Compressibility of aquifer [m²/N]

γ_w : Unit weight of fluid [N/m³]

5.2.2 Further boundary conditions

For a generally valid approach to the solution, applicable to numerous boundary conditions, the above differential equation introduces dimensionless variables in place of dimensioned variables. The dimensionless pressure or water level (h_D) can be formulated as a function of time, location, system geometry and other influencing factors, and the dimensionless time (t_D) as a function of the well radius, for example (*EARLOUGHER, 1977*):

h_D = f (time, location, geometry,...)

t_D = f (well radius, time,....).

This model has the advantage that the dimensionless variables are directly proportional to the dimensioned variables and can thus be mutually converted by simple transformations.

The complete description of the solution also consists of specification and formulation of boundary conditions. The type of input signal (e.g. the pressure impulse for a slug test) can be seen as one of the inner boundary conditions.

In addition, the influence of the borehole or the well itself must be considered. For a free groundwater level the wellbore storage of a well or borehole is defined as:

$$C = \frac{\pi \, r_B^2}{\rho_w \, g}$$

and

$$C = c_w \cdot V_w$$

for an enclosed volume of water.

Where:

C : Storage constant [m³/m]

r_B : Well radius [m]

ρ_w : Density of groundwater [kg/m³]

g : Gravitational acceleration [m/s²]

c_w : Compressibility of water [m²/N]

V_w : Volume of water column [m³]

5.2.3 Skin effect

Often, a zone with altered hydraulic properties to those of the surrounding rocks can be observed in the immediate vicinity of a borehole or a well. This is chiefly caused by the penetration of drilling mud and additives or by the swelling of existing clay minerals. The drilling process can also lead to decompaction of the rock mass. The resulting change in pressure is known as the skin effect (*HURST, 1953*).

Mathematically, the skin effect can be described in two ways, either as an infinitesimally small zone without inherent storage capacity (*VAN EVERDINGEN, 1953*) or as a finite zone of given dimensions with inherent storage capacity (*MOENCH & HSIEH, 1985 a; KARASAKI, 1986*).

For an infinitesimally small skin zone the following applies:

$$s \left(\frac{k}{k_s} - 1\right) \ln\left(\frac{r_s}{r_B}\right)$$

where:

s : Skin factor [-]

k : Permeability of aquifer [m/s]

k_s : Permeability of skin zone [m/s]

r_s : Radius of skin zone [m]

r_B : Well/borehole radius [m]

For practical application an infinitesimal skin can be described using the concept of the effective borehole radius (r_{eff}) (*EARLOUGHER, 1977*):

$$r_{eff} = r_B \cdot e^{-s}$$

This means that for a skin factor different to zero, the hydraulically effective radius no longer corresponds to the actual well radius. For a skin factor greater than zero, the effective radius is smaller than the well radius, and for a skin factor smaller than zero, the effective radius becomes greater than the well radius. The skin factor lies between infinite for completely sealed boreholes and -5 for stimulated, i.e. fractured boreholesof (*EARLOUGHER, 1977*). After *HAWKINS (1956)*, the pressure loss or increase for an infinitesimal skin zone is:

$$h_s = s \cdot \frac{Q}{2\pi T}$$

where:

h_s : Pressure loss [m]

s : Skin factor [1]

Q : Pumping rate [m³/s]

T : Transmissivity [m²/s]

A skin effect (pseudo skin) can also be evoked by an imperfect well, turbulent flow, an inclined borehole or by the entry resistance of a well screen (*DA PRAT, 1981; 1990*).

5.2.4 COOPER et al. approach to the solution

For the water level in a well, *COOPER et al. (1967)* arrived at the following solution:

$$h(t) = \frac{8 h_0 \, a}{\pi^2} \int_0^{\infty} e^{\left(-\beta u^2 / a\right)} \frac{du}{u \cdot f(u)}$$

where:

$a = \frac{r_s^2 S}{r_c^2}$: Wellbore storage [-]

$\beta = \frac{T t}{r_c^2}$: Dimensionless time [-]

and

h_0 : Water level in well at time t = 0 [m]

h(t) : Water level in well at time t [m]

T : Transmissivity [m²]

S : Storage coefficient [-]

u : Integration constant [-]

f(u) : $[uJ_0(u)-2\alpha J_1(u)]^2+[uY_0(u)-2\alpha Y_1(u)]^2$ [-]

$J_{0,1}$: Bessel functions 0^{th}, 1^{st} order 1^{st} degree [-]

$Y_{0,1}$: Bessel functions 0^{th}, 1^{st} order 2^{nd} degree [-]

r_s : Radius of well screen [m]

r_c : Radius of casing [m]

By numerical integration, *COOPER et al. (1967)* compiled five tables with $h(t)/h_0$ and ß for varying α. If the table values are graphically represented in a semi-logarithmic format, one arrives at type curves which allow the transmissivity to be determined in a similar manner to that using the Theis type curve method.

5.3 Type curves methods - several approaches

An expansion of the solution after *COOPER* by five additional type curves was presented by *PAPADOPULOS et al. (1973)* once they had recognised that the existing values for α were only sufficient for the evaluation of tests in layers of high permeability. PAPADOPULOS et al. (1973) also commented on the relatively large uncertainty of the method when determining the storage coefficient.

With the ***pressurised slug test***, *BREDEHOEFT & PAPADOPULOS (1980)* introduced an alternative to the classical slug tests. The borehole being investigated is filled to the top with water and then a pressure impulse applied. The head of the borehole is closed by a valve and the subsequent pressure loss registered. This procedure is suitable for very low permeability layers because it allows the test duration to be substantially reduced. The storage capacity of the borehole is now no longer determined by the free water column, but by the compressibility of the enclosed volume of water.

However, this model assumes that the rock and the testing equipment are incompressible. But this is not very realistic. In reality, the compressibility of the whole system, consisting of the enclosed water volume, the rock and the measuring equipment must be known.

The skin effect was considered by *RAMEY et al. (1975)*, adopting the *COOPER et al. (1967)* approach. They showed that it is possible to combine the storage constant and the skin factor to a single fingerprint parameter $C_D e^{2s}$ for recalculation of type curves. However, their solution only applies to an infinitesimal skin zone and for curve parameters $C_D e^{2es} \geq 10$ (*MOENCH & HSIEH, 1985 a,b*).

FAUST & MERCER (1984) investigated the influence of a finite skin zone on the determination of transmissivity in layers of low permeability, with the aid of a numerical model. According to their calculations, a positive skin factor, caused by a zone of lower permeability than the surrounding rock, can lead to an incorrect appraisal of the true transmissivity. There is a hazard here of measuring not the transmissivity of the rock mass, but that of the skin zone.

This assessment was nevertheless cast in doubt by *MOENCH & HSIEH (1985 b)*. On the contrary, they are of the opinion that the transmissivity would be correctly determined despite a positive skin factor.

An imperfect well with wellbore storage is the subject of a model by *DOUGHERTY (1989)*. A skin is not taken into consideration in the analytical solution.

5.4 Approaches for slug tests in double-porosity media

The slug test in double-porosity media (matrix and joints) is comprehensively dealt with by *MATEEN (1983)* and *MATEEN & RAMEY (1984)*. Besides the fundamentals after *COOPER et al.(1967)*, they also consider both wellbore storage and an infinitesimal skin zone. The pseudo-stationary and transient interactions between matrix and joints were dealt with.

Beside the transmissivity and the skin factor, this allows the ratio of the storage capacity of joints to the total storage capacity - matrix and joints - and the fluid transfer (ratio of permeabilities) between matrix and joints to be assessed.

The pressure in a slug test in double-porosity media can thus be described as follows: during the initial stage, only the joints are effective. The matrix then begins to feed the joints, a transition phase is initiated. At the end of the test the fluid originates in the complete system of matrix plus joints.

GRADER & RAMEY (1988) developed further the solutions for double porosity. Using this approach, the range of a test can be up to 1000 times the borehole radius under favourable conditions.

KARASAKI et al. (1988) show that the duration of a slug test does not depend on the water volume inserted or extracted, or from the size of the impulse, but is directly proportional to the storage constant and inversely proportional to the transmissivity.

5.5 Evaluation by HVORSLEV

5.5.1 Basic assumption

All of these models assume a transient, radial-symmetric flow in a confined aquifer.

The *HVORSLEV (1951)*, *BOUWER & RICE (1976)* and *BOUWER (1989)* methods, on the other hand, employ Thiem's (*THIEM, 1906*) well equation for stationary flow. These methods are also suitable for use with a free groundwater level. *HVORSLEV (1951)* uses six different, empirically determined equations, employed according to well and aquifer geometry, for determining permeability.

The basic assumption is that the water level increases or decreases exponentially during a slug test. In contrast to all other authors, *HVORSLEV (1951)* differentiates between a horizontal, a vertical and a mean permeability. Where necessary, this allows due consideration of rock mass anisotropy.

5.5.2 General equation of HVORSLEV

A general derivative of the *HVORSLEV* equation can be formulated as follows:

With:

q : Percolation [m³/s]

t : Time [s]

A : Flow cross-section [m²]

y : Increase in water level [m]

y_0 : At-rest water level [m]

k_f : Permeability [m/s]

L : Flow path [m]

the differential equation

$$q \cdot dt = A \cdot dy$$

and Darcy's Law

$$q = A \cdot k_f \frac{y - y_0}{L} \quad ,$$

after introducing F = A/L [m], substituting and integrating, becomes

$$k_f = \frac{A}{F(t_2 - t_1)} \ln (h_1 / h_2) \, ,$$

where h_1 and h_2 are the gauge levels at the subsequent times t_1 and t_2.

5.5.3 Determination of shape factor and k_f value

F is known as the shape factor and takes into consideration the idealised flow path L, according to the well configuration and aquifer geometry. Because L cannot be exactly calculated, *HVORSLEV (1951)* determined empirical shape factors for six different test arrangements, which are used in the k_f value equation.

The most frequently used equation is valid for an open, imperfect well in a free aquifer of infinite thickness. The following then applies for the shape factor:

$$F = \frac{2\pi L}{\ln(2m\,L/D)}$$

This leads us to the horizontal coefficient of permeability:

$$k_f\ h = \frac{d^2 \ln(2m\,L/D)}{8L(t_2 - t_1)} \ln\left(h_1 / h_2\right) \text{ , if m L/D > 4}$$

or

$$k_f\ h = \frac{d^2 \ln\left(m\,L/D\sqrt{1+(m\,L/D)^2}\right)}{8L(t_2 - t_1)} \ln\left(h_1 / h_2\right) \text{ , if m L/D} \le 4$$

where:

d : Casing diameter [m]

D : Well screen diameter [m]

L : Length of screen [m]

m : $\sqrt{k_f h / k_f v}$ [1]

By modification of the general equation for k_f and using

$h_1 = H_0$ $\quad t_1 = t_0 = 0$

$h_2 = h(t)$ $\quad t_2 = t$

we receive:

$$k_f = \frac{A}{f \cdot t} \ln\left(H_0 / h(t)\right)$$

Because the parameters A, F and k_f are constant for any given well or aquifer, they can be converted to form:

$$c \cdot t = \ln\left(H_0 / h(t)\right)$$

where

$$c = k_f \cdot F / A \text{ ,}$$

giving:

$$h(t) = H_0 \cdot e^{-c \cdot t}$$

The function represented by the final equation describes the sinking water level in the well in a slug test after *HVORSLEV (1951)*.

5.6 Evaluation by BOUWER & RICE

5.6.1 Basic approach

The *BOUWER & RICE (1976)* method is closely related to the *HVORSLEV (1951)* method. Because the Thiem equation includes the range of the drawdown cone, but this is not known, it was determined with the aid of an electro-analogue model for a variety of aquifer and well geometries.

The approach used is:

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

where:

Q : Inflow rate [m³]

k_f : Permeability [m/s]

L_e : Length of screen [m]

$h-h_w$: Gradient [1]

R_e : Range [m]

r_w : Borehole radius [m]

For the change in water level in the well:

$$\frac{dy}{dt} = -\frac{Q}{\pi\ r_c^2}$$

where:

r_c : Radius of riser pipe [m]

The relationships given assume that the water level is within the blank casing and fluctuates in this region. If, however, the at-rest or the altered water level is within the well filter region, the hydraulic effectiveness of the filter gravel must be taken into consideration (*BOUWER, 1989*). Instead of r_c, an equivalent radius in accordance with

$$r_{c\ new} = \sqrt{(1 - n)\, r_c^2 + n\, r_w^2}$$

where:

$r_{c\ new}$: Effective standpipe radius [m]

r_c : Radius of screen/blank casing [m]

r_w : Radius of well [m]

n : Porosity of filter gravel [1]

must be adopted.

5.6.2 Solvation of the equations

By substituting and solving from the previous equations we get:

$$y_t = y_0 \exp\left(-\frac{2k_f\, L_e\, t}{r_c^2 \ln\left(R_e / r_w\right)}\right)$$

and

$$k_f = \frac{r_c^2 \ln\left(R_e / r_w\right)}{2L_e\, t} \ln \frac{y_0}{y_t}$$

where:

y_0 : Drawdown in well at t = 0 [m]

y_t : Drawdown in well at t > 0 [m]

t : Time [s]

R_e : Range [m]

The range R_e of a slug or bail test was determined with the aid of an electro-analogue model. The following relationship applies for a perfect well ($H = L_w$):

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

The following equation is used for an imperfect well:

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

where H is defined as the distance between the groundwater base and the at-rest water level in metres. The coefficients A, B and C are determined from a diagram as a function of L_e / r_w.

We can write:

$$k_f = \frac{D}{t} \ln \frac{y_0}{y_t}$$

where:

$$D = \frac{r_c^2 \ln\left(R / r_w\right)}{2L_e}$$

Because D is known for each well, the result for the water level history as a function of the value of k_f is:

$$y_t\,(k_f) = y_0\, e^{-\frac{k_f\, t}{D}}$$

On the basis of this derivative, the principle of an evaluation after *BOUWER & RICE (1976)* rests upon finding a value for k_f which minimises the deviation between the measured and the calculated water levels.

6 Program concept

For the type curve method the program employs published solutions in Laplace space for the differential equations used to describe the slug test. Using to the model adopted by *COOPER et al. (1967)* and $C_D = {}^1/_2\alpha$ the solution for the dimensionless water level in Laplace space is:

$$h_D(p) = \frac{K_0\sqrt{p}}{p\,K_0\sqrt{p} + \frac{1}{C_D}\sqrt{p}\,K_1\left(\sqrt{p}\right)}$$

where:

h_D : Laplace transform [-]

p : Laplace variable [-]

C_D : Dimensionless wellbore storage [-]

K_0 : Bessel function of the second kind, Order 0 [-]

K_1 : Bessel function of the second kind, Order 1 [-]

The real solutions that can be derived from this can be calculated using analytical methods, but they require much more effort and often lead to unsatisfactory results. The Laplace transform is therefore inverted numerically by the **GGU-SLUGTEST** program.

The Laplace transform of a function $h_D(t)$ is defined as:

$$h_D(p) \;:=\; L\left\{h_D(t)\right\} = \int_0^\infty e^{-pt}\,h_D(t)\,dt$$

The numerical inversion can be formulated after *STEHFEST (1970 a,b)* as:

$$h_D(t) = L^{-1}\left\{h_D(p)\right\} = \frac{\ln 2}{t}\sum_{i=1}^{N} W_i\,h_D\left(\frac{i\ln 2}{t}\right)$$

where:

N : Even number [-]

W : Weighting factor [-]

In theory, h(t) is all the more precisely approximated the larger N is (*STEHFEST, 1970 a*). However, because the calculation precision depends on the number of digits processed by the computer used, rounding off errors increase with increasing N. N should therefore be selected in accordance with the precision of the computer.

The best results are obtained from the **GGU-SLUGTEST** program with N = 12 to N = 16, depending on the function to be inverted for the Laplace transform (dimensionless water level).

On this basis, you can use the **GGU-SLUGTEST** program to generate any type curves for evaluation of the implemented slug test models. Adjustment of the measured data to the type curves can then be carried out either in the conventional manner, i.e. by hand on the screen, or by an automatic fit. If required, a second fit routine even generates the optimum type curve for your data.

7 Explanation of menu items

7.1 File menu

7.1.1 "New" menu item

All current data will be deleted. You can import new data.

The data entered in "**Edit/General**", "**Edit/Result text**" and "**Edit/Company**" (see Sections 7.2.11 to 7.2.13) are retained.

7.1.2 "Load" menu item

You can load a file with test data, which was created and saved at a previous sitting, and then edit the test data.

7.1.3 "Save" menu item

You can save data entered or edited during program use to a file, in order to have them available at a later date, or to archive them. The data is saved without prompting with the name of the current file. Loading again later creates exactly the same presentation as was present at the time of saving.

7.1.4 "Save as" menu item

You can save data entered during program use to an existing file or to a new file, i.e. using a new file name. For reasons of clarity, it makes sense to use "**.sbt**" as file suffix, as this is the suffix used in the file requester box for the menu item "**File/Load**". If you choose not to enter an extension when saving, "**.sbt**" will be used automatically.

7.1.5 "Info" menu item

When you go to this menu item, the program gives you information on the data used. You will see whether the data are imported from a datalogger or determined using the "**Test design**" menu. Additionally, the number of values and the evaluation range, you have chosen, is indicated.

7.1.6 "Read datalogger" menu item

With **GGU-SLUGTEST** you can process data imported from a W.A.S., Braunschweig, datalogger (e.g. MDS II). The data is exported to a file and imported using this menu item; it can then be processed further.

7.1.7 "Import ASCII data" menu item

Because you will probably receive most of your data in the shape of files on storage media (disk), this menu item represents a vital interface for accessing your data. To facilitate reading the ASCII file you will see a dialog box.

The current line of the ASCII file is shown at the top. You can move through the file using the arrow buttons on the right. In the "**Time column:**" and "**Value column:**" you enter the column number for the corresponding information contained in the file. If all the information is correct, the result for the row is shown in the box below each column. Otherwise, "**Error**" appears.

You may need to change the column delimiter.

If the time is given as clock time, please ensure the correct "**time delimiter**" is used.

If the file contains invalid as well as valid rows, the invalid rows will simply be skipped during reading.

After the "**Read data**" button has been pressed and the data successfully read, you will see a message box with the number of values and character strings read, and the value at the start of the test.

Directly after clicking "**OK**" you will be given the option of adjusting the data. You confirm your choice in a prompt and can then adjust the data immediately in a dialog box, depending on your test configuration; this dialog box can also be accessed by going to "**Edit/Test data**" (please note the description in Section 7.2.1).

7.1.8 "Export ASCII data" menu item

This menu item allows the current values and corresponding times to be saved as an ASCII file. For example, it is thus possible to save MDS data imported from a datalogger as an ASCII file.

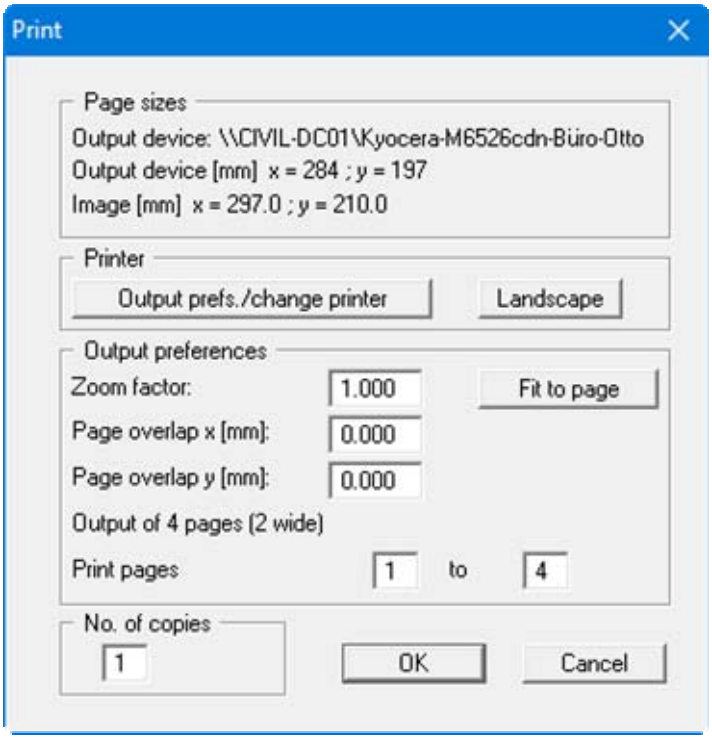
7.1.9 "Output preferences" menu item

You can edit output preferences (e.g. swap between portrait and landscape) or change the printer in accordance with WINDOWS conventions.

7.1.10 "Print and export" menu item

You can select your output format in a dialog box. You have the following possibilities:

- "**Printer**"
  allows graphic output of the current screen to the WINDOWS default printer or to any other printer selected using the menu item "**File/Output preferences**". But you may also select a different printer in the following dialog box by pressing the "**Output prefs./change printer**" button.



  In the upper group box, the maximum dimensions which the printer can accept are given. Below this, the dimensions of the image to be printed are given. If the image is larger than the output format of the printer, the image will be printed to several pages (in the above example, 4). In order to facilitate better re-connection of the images, the possibility of entering an overlap for each page, in x and y direction, is given. Alternatively, you also have the possibility of selecting a smaller zoom factor, ensuring output to one page ("**Fit to page**" button). Following this, you can enlarge to the original format on a copying machine, to ensure true scaling. Furthermore, you may enter the number of copies to be printed.

- "**DXF file**"
  allows output of the graphics to a DXF file. DXF is a common file format for transferring graphics between varieties of applications.

- "**GGU-CAD file**"
  allows output of the graphics to a file, in order to enable further processing with the **GGU-CAD** program. Compared to output as a DXF file this has the advantage that no loss of colour quality occurs during export.

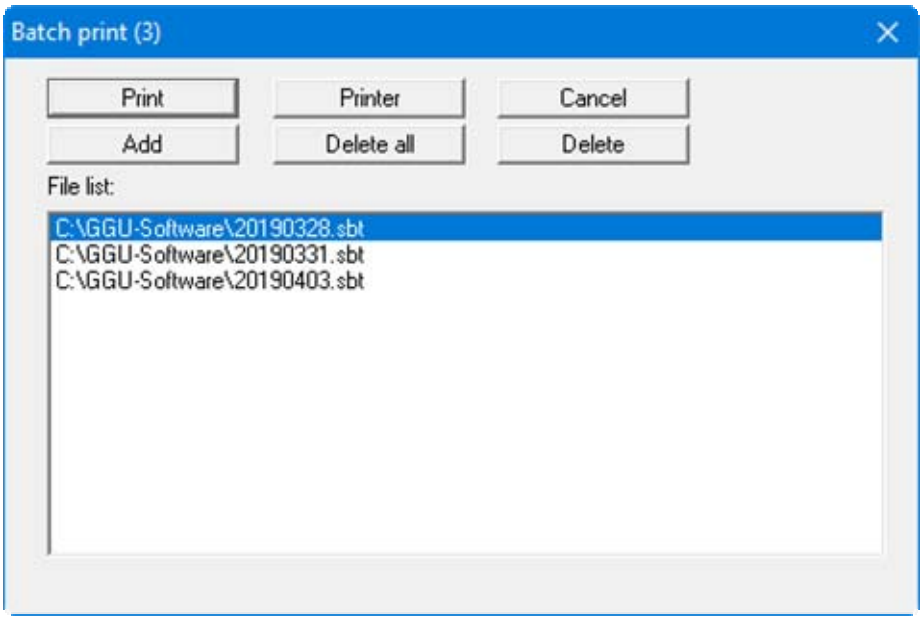
- "**Clipboard**"
  The graphics are copied to the WINDOWS clipboard. From there, they can be imported into other WINDOWS programs for further processing, e.g. into a word processor. In order to import into any other WINDOWS program you must generally use the "*Edit/Paste*" function of the respective application.
- "**Metafile**"
  allows output of the graphics to a file in order to be further processed with third party software. Output is in the standardised EMF format (Enhanced Metafile format). Use of the Metafile format guarantees the best possible quality when transferring graphics.

> If you select the "**Copy/print area**" tool from the toolbar, you can copy parts of the graphics to the clipboard or save them to an EMF file. Alternatively you can send the marked area directly to your printer (see "**Tips and tricks**", Section 8.4).
>
> Using the "**Mini-CAD**" program module you can also import EMF files generated using other GGU applications into your graphics (see Section 7.6.8).

- "**Mini-CAD**"
  allows export of the graphics to a file in order to enable importing to different GGU applications with the **Mini-CAD** module.
- "**GGUMiniCAD**"
  allows export of the graphics to a file in order to enable processing in the **GGUMiniCAD** program.
- "**Cancel**"
  Printing is cancelled.

7.1.11 "Batch print" menu item

If you would like to print several appendices at once, select this menu item. You will see the following dialog box:



Create a list of files for printing using "**Add**" and selecting the desired files. The number of files is displayed in the dialog box header. Using "**Delete**" you can mark and delete selected individual files from the list. After selecting the "**Delete all**" button, you can compile a new list. Selection of the desired printer and printer preferences is achieved by pressing the "**Printer**" button.

You then start printing by using the "**Print**" button. In the dialog box which then appears you can select further preferences for printer output such as, e.g., the number of copies. These preferences will be applied to all files in the list.

7.1.12 "Exit" menu item

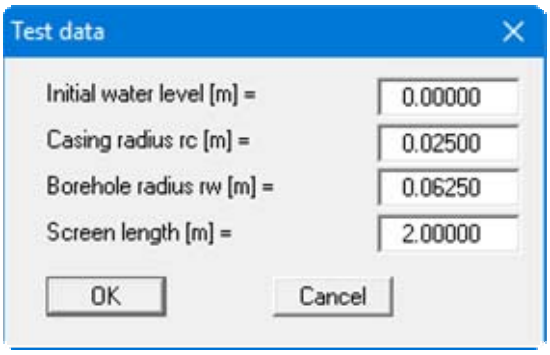
After a confirmation prompt, you can quit the program.

7.1.13 "1, 2, 3, 4" menu items

The "**1, 2, 3, 4**" menu items show the last four files worked on. By selecting one of these menu items the listed file will be loaded. If you have saved files in any other folder than the program folder, you can save yourself the occasionally onerous ***rummaging*** through various sub-folders.

7.2.1 "Test data" menu item

Enter the principal test data required for slug test evaluation.

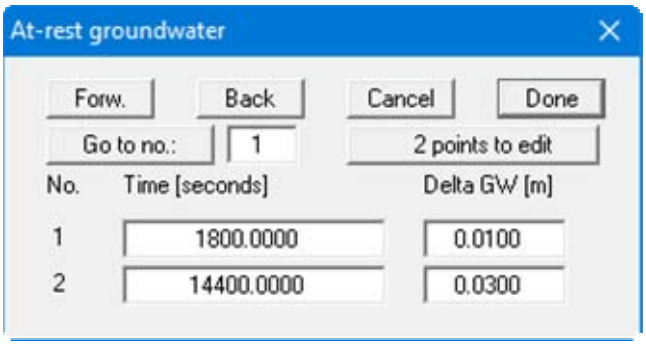


> If your dataset contains the pure elevations above the at-rest groundwater level, enter **0** for the initial water level.

7.2.2 "At-rest groundwater" menu item

Whilst processing the at-rest groundwater level, you can take into consideration that the at-rest groundwater level fluctuates during a slug test. To make this practicable, data must be available form relatively close observation gauges.

First, enter the number of value pairs you need to enter using "**x points to edit**". In the list that follows this you can enter the time and corresponding groundwater level.



The individual values are then connected to a polygon. The program automatically takes these changes in the at-rest groundwater level into consideration when evaluating the slug test.

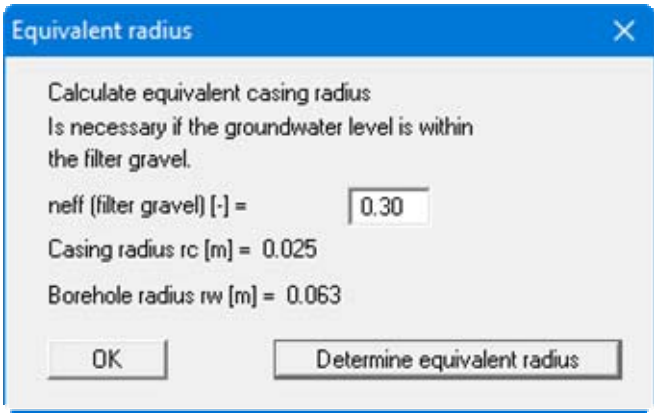
7.2.3 "Equivalent radius" menu item

Normally, we assume for a slug test that the water level fluctuates in the region of the blank casing. However, there is one exception when the at-rest water level is within the region of the screen or the filter gravel. The porosity of the filter gravel must then be taken into consideration. Together with the well development details, a new, so-called equivalent radius results in accordance with

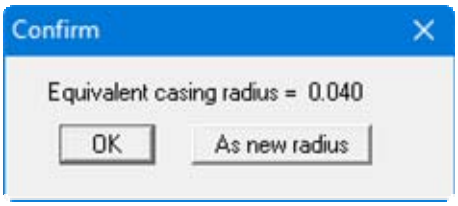
$$r_{c\,neu} = \sqrt{(1-n)\,r_c^2 + n\,r_w^2}$$

where ***n*** is the porosity of the filter gravel.

If this configuration corresponds to that of the test you are evaluating, enter the porosity "**neff**" of the filter material using this menu item. This input must be as a decimal, not a percentage!



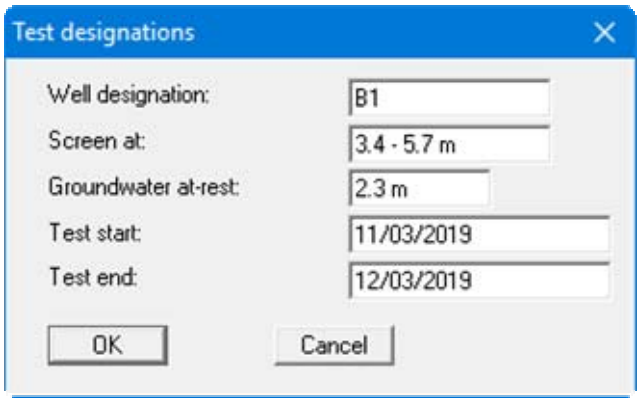
You can view the new value for the casing radius r_c by pressing the "**Determine equivalent radius**" button.



If you would like to evaluate your test using the equivalent radius, click "**As new radius**". The newly determined equivalent casing radius is then used in the test data. If you click the "**OK**" button the value is not accepted and then serves information purposes only.

7.2.4 "Test designations" menu item

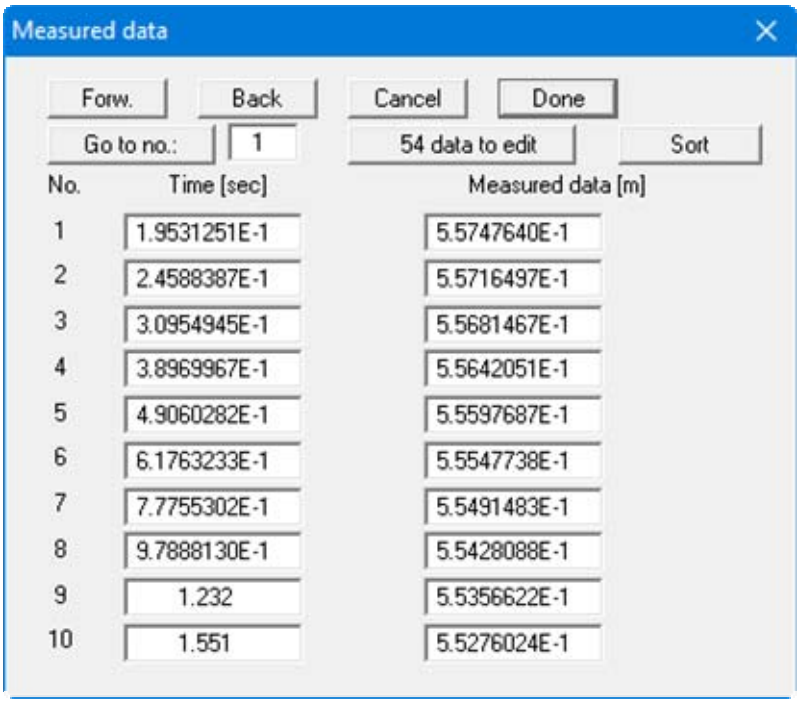
You can annotate the output sheet with additional, descriptive information concerning the test being evaluated. Just enter the required data into the following dialog box.



The texts in the first three input boxes in the dialog box can be edited in Section 0 using the menu item "**Graphics preferences/Output sheet**".

7.2.5 "Edit measured data" menu item

You can edit your measured data in a dialog box.



- "**Forw.**", "**Back**"
  If you have more than 10 data pairs you can navigate through them using these buttons.
- "**Go to no.:**"
  You can advance to the specified data pair.

- "**54 values to edit**"
  In the example shown here there are 54 data pairs. By pressing this button a dialog box opens in which the number of data pairs can be edited.

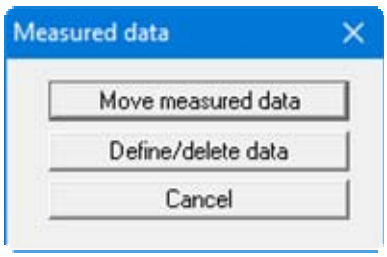
  If no data are present (new test), the box will contain a **0**. Data pairs can be appended by increasing the number; by reducing the number, existing data pairs can be deleted from the end of the list.

> To delete pairs from an existing list, enter a time that is greater than the greatest actual time.
>
> The "**Sort**" button moves this line to the end of the list and it can then be deleted by appropriately reducing the number of data.

- "**Sort**"
  If you have appended data pairs using the previously described button, you can have the data correctly sorted by time using this button.
- "**Cancel**" or "**Done**"
  You will leave the dialog box without accepting the changes.

7.2.6 "Graphically" menu item

You can comfortably edit the imported data graphically on the screen. This saves a lot of time and tedious typing or correcting of numbers. You can also view the changes in the graph immediately on the screen. First, select the required action:

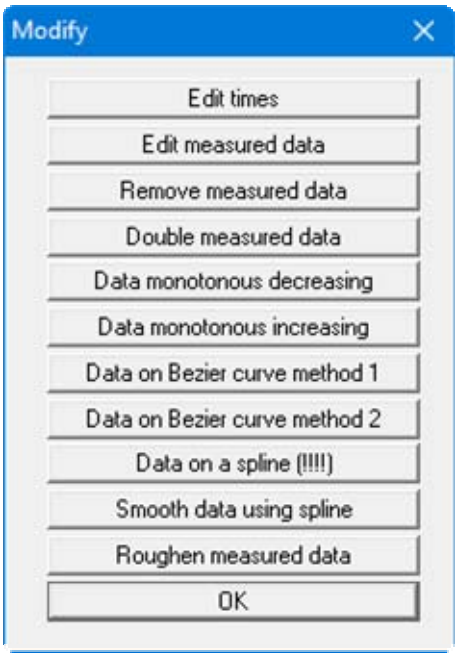


- "**Move measured data**"
  Move the required data point by drag and drop using the left mouse button. The last move can be undone by pressing the [**Backspace**] key.
- "**Define/delete data**"
  Define a new point by clicking the left mouse button at the desired position.

  An existing point is deleted by clicking it with the right mouse button. The last delete can be undone by simultaneously pressing the [**Backspace**] and [**Alt**] keys.

7.2.7 "Modify" menu item

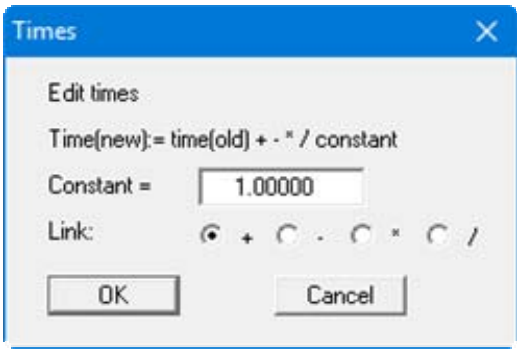
This menu item offers numerous options for processing your data.



These actions directly alter your measured data. No "**undo**" is available for any actions with the exception of "**Edit times**" and "**Edit measured data**", i.e. you cannot reset any of the editing performed on the data.

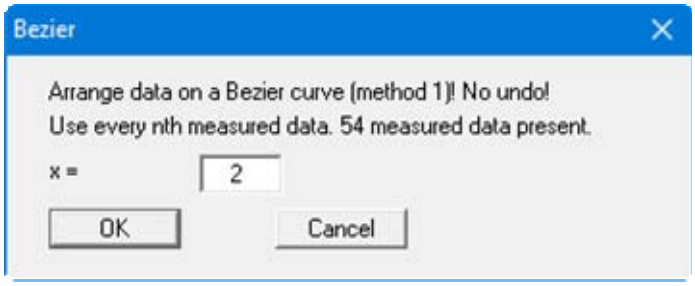
Before you carry out any irreversible manipulations on your data, you should save the file under a different name in order to retain the original data.

- "**Edit times**"
  By linking to a constant, you can convert the times associated with your values, e.g. from [seconds] to [minutes].

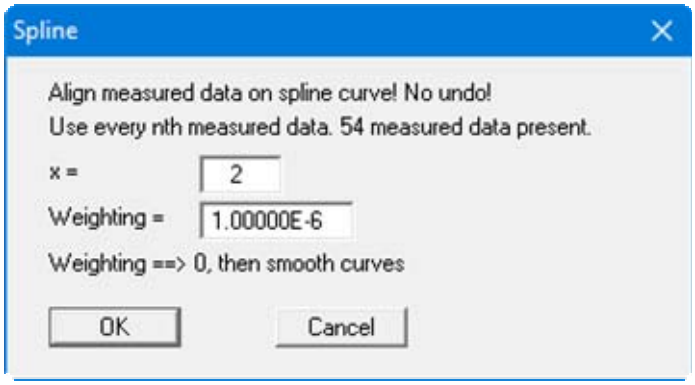


- "**Edit measured data**"
  You can edit your data by linking to a constant. This makes it very simple to correct reading errors for all data.

- "**Remove measured data**"
  You can decrease the number of data by deleting every n^{th} value. This kind of data reduction is recommended for particularly large records, where the evaluation would otherwise be extremely time intensive.
- "**Double measured data**"
  If the number of data is very small, you can append a new value between two existing ones. This is done by means of linear interpolation.
- "**Data monotonous decreasing**"
  The measured data can be arranged monotonous decreasing.
- "**Data monotonous increasing**"
  The measured data can be arranged monotonous increasing.
- "**Data on Bezier curve method 1**"
  You can connect the data points with the help of a Bezier spline curve. The algorithm employed here adheres strictly to the data points (= method 1). The number of data points to be considered for the curve can be entered in a dialog box.

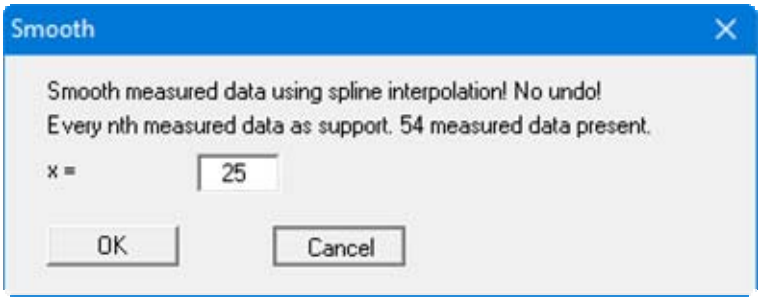


- "**Data on Bezier curve method 2**"
  The data points are connected by a Bezier spline, whereby the curve is smoothed out (= method 2). You enter the number of data to be used, just as in the previous action.
- "**Data on a spline (!!!!)**"
  You can arrange the data points on a spline curve. After using this action a dialog box opens, in which you can specify the number of data to be included.



  The weighting factor entered here influences the curve smoothing. The smaller the weighting, the smoother the curve.

- "**Smooth data using spline**"
  With the help of this action you can generate an orderly, evaluable curve from noisy data using a compensation spline. A dialog box opens, in which you specify the data points to be included as model points.



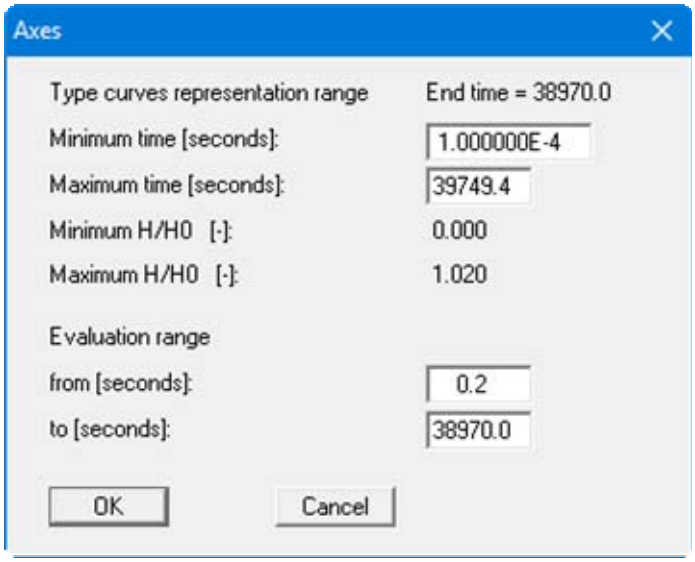
  Depending on the precise condition of the dataset you must select a more or less large separation of the model points to achieve a relatively smooth curve.

- "**Roughen measured data**"
  This point was included to facilitate testing of the smoothing out methods described above. For example, if you have simulated a slug test according to your specifications using the "**Test design**" menu, i.e. calculated the data for a given permeability, you can make these data ***noisy*** by any figure. Enter a maximum roughening value in metres into the dialog box and specify whether the roughening is proportional to the respective measured data.

- "**OK**"
  You will leave the menu item.

7.2.8 "Data range via editor" menu item

You can define ranges to be taken into consideration, or represented, for both the screen presentation and for your evaluation. If, for example, your dataset contains data from a slug and bail test, you can select either the slug or the bail test for evaluation using this menu item. This function can also be accessed using the [**F7**] key.



In the dialog box you will see the minimum and maximum values for times and values automatically determined by the program for the representation range. For the evaluation range you will see times only. You can enter your own values into the corresponding input boxes and thus redefine the representation and evaluation ranges.

> The program compares your times for the evaluation range with those for the existing data points. For the "**from**" time, the value of the next lowest data point is used and for the "**to**" time that of the next highest data point.
>
> The times for the evaluation range must always form a subset of the times for the representation range. You will otherwise see a warning message and the times for the evaluation range will be automatically adjusted by the program.

You can also redefine the evaluation range only to achieve the optimum screen display, using the "**Edit/Fit in selected data**" menu item (see Section 7.2.10).

7.2.9 "Auto-display all data" menu item

If you have altered the presentation on the output sheet using "**Edit/Data range via editor**", "**Edit/Fit in selected data**" or "**Edit/Data range graphically**", this menu item will take you back to a presentation that includes all measured data with the automatically determined minimum and maximum time and height values. This function can also be accessed using the [**F8**] key.

7.2.10 "Fit in selected data" menu item

The range selected using the"**Edit/Data range via editor**" menu item is displayed using the space available on the output sheet to its optimum. This function can also be accessed using the [**F9**] key.

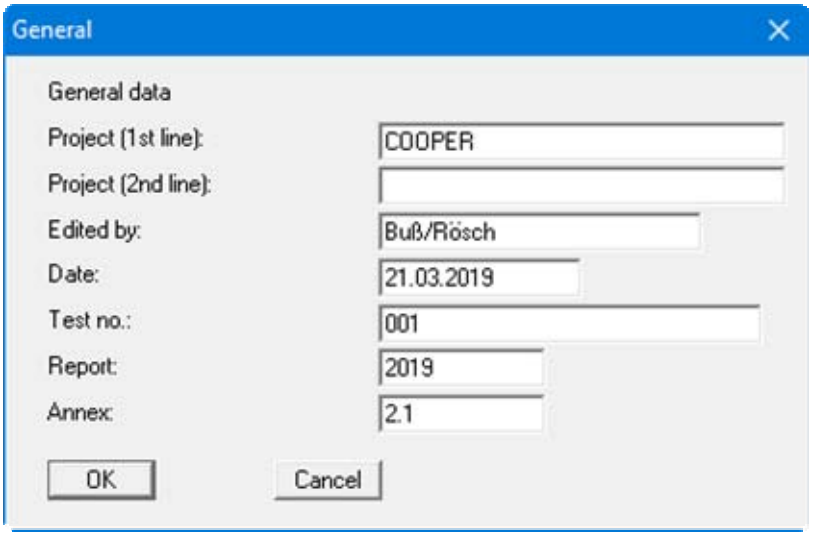
7.2.11 "Data range graphically" menu item

In principal, this is the same option as described in Section 7.2.8, the difference being that you can comfortably define the data range graphically. All you have to do is simultaneously hold the [**Shift**] and [**Ctrl**] keys together with the left mouse button to define the required window.

If you activate the check box "**Apply to time axis only**" in the message box, only the new time coordinates are accepted; the y-axis with the height data remains unchanged (the diagram is stretched in x-direction).

7.2.12 "General" menu item

You can annotate the output sheet with general information on the evaluated test. Enter the information into the following dialog box.



Some of the texts in front of the input boxes can be edited in Section 0, using the menu item "**Graphics preferences/Output sheet**", e.g. "**Edited by:**" and "**Date:**".

7.2.13 "Result text" menu item

At the bottom right of the output sheet a text box contains the results of the evaluation or simulation. The program default result text (see Section 7.3.6, menu item "**Hvorslev, .../Permeability**") can be edited and complemented in a total of 6 lines of input in the dialog box. This editor can be opened directly by double-clicking with the right mouse button above the text box on the output sheet.

7.2.14 "Company" menu item

In the top left box of the output sheet you can display your company's name and address in 4 lines of text. Input is by means of the corresponding dialog box. The information then appears centred in the text box. This editor can be opened directly by double-clicking with the right mouse button above the text box on the output sheet.

If you would like to include company logos use the **Mini-CAD** module (see Section 7.6.8 and the "**Mini-CAD**" manual).

7.3.1 "Height log" menu item

Use this menu item to display the y-axis (height) logarithmically.

Select this option if you would like to check whether your data approximately adhere to a descending e-function. With a logarithmic y-axis the result should be a straight line.

7.3.2 "Hvorslev" menu item

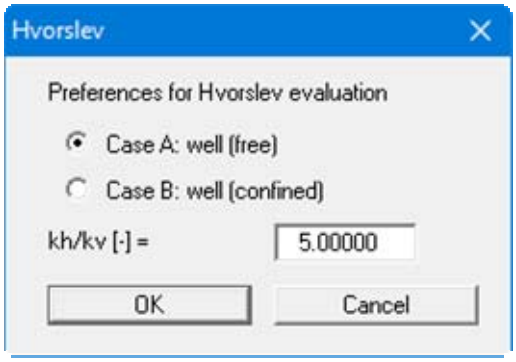
You can evaluate your slug test using the *HVORSLEV (1951)* method. However, you should have first defined your preferences for this evaluation method as described in the next menu item.

A linear data curve appears on the screen. In addition, after selecting this menu item, the best-fit curve (e-function) is drawn using the *HVORSLEV (1951)* model approach. After pressing [**F12**] you will see the result of the evaluation for the best-fit curve.

> You can achieve a clear presentation of the data curve and the best-fit curve by going to the menu items "**Graphic preferences/Preferences**" and "**Graphic preferences/Pen colour and width**" (Sections 7.6.1 and 7.6.4) and specifying presentation preferences.

7.3.3 "(Hvorslev) - preferences" menu item

If you want to evaluate using the *HVORSLEV* method, you must first select an evaluation equation after *HVORSLEV* to suit your problem. In the dialog box which then opens, you are presented with the well configurations. The ***variable head method*** after *HVORSLEV* is implemented in the program.



Case A applies to a perfect well in a free aquifer. Case B applies to a perfect well in a confined aquifer.

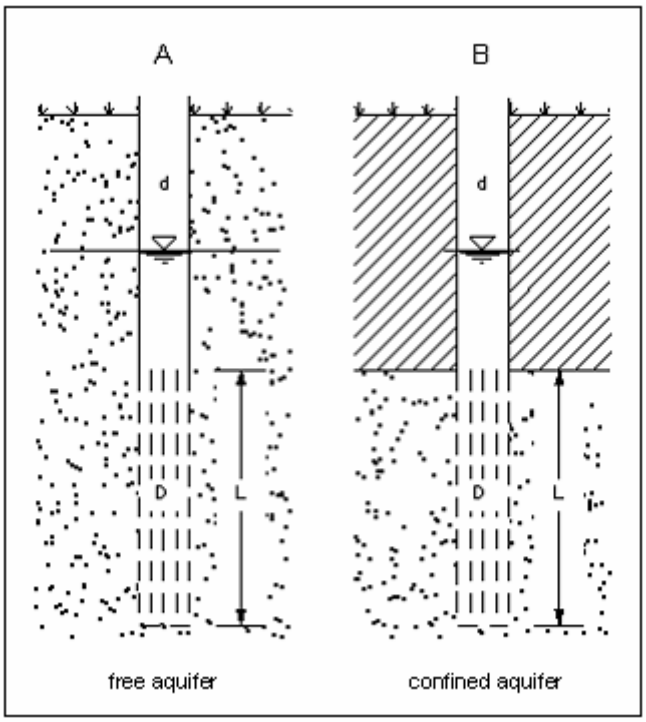


Figure 1: Well configurations for HVORSLEV evaluation

In addition, you can enter a value to represent the ratio of horizontal to vertical permeability. Internally, the program uses the root of this ratio. This allows due consideration of anisotropy.

After confirming your input with "**OK**" you will be automatically presented with the data and best-fit curves after *HVORSLEV*.

7.3.4 "Bouwer + Rice" menu item

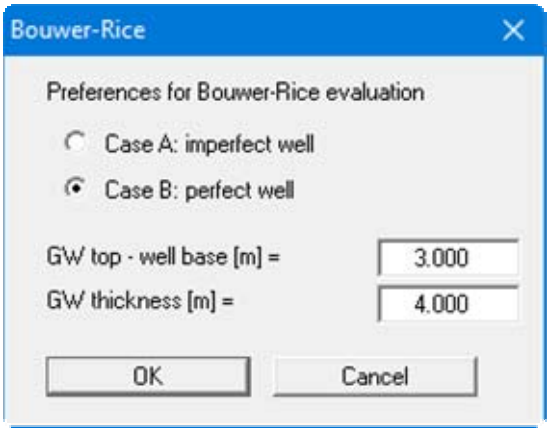
This menu item allows you to adopt the evaluation method after *BOUWER & RICE (1976)*. However, you should have first defined your preferences for this evaluation method as described in the next menu item.

The best-fit curve (e-function) is drawn beside the data curve using the *BOUWER & RICE* model approach. After pressing [**F12**] you will see the result of the evaluation for the best-fit curve.

> You can achieve a clear presentation of the data curve and the best-fit curve by going to the menu items "**Graphic preferences/Preferences**" and "**Graphic preferences/Pen colour and width**" (Sections 7.6.1 and 7.6.4) and specifying presentation preferences.

7.3.5 "(Bouwer + Rice) - preferences" menu item

For an evaluation after *BOUWER & RICE* you must also first select a well configuration to suit your problem from the following dialog box.



You can choose from an imperfect well (Case A) and a perfect well (Case B). The *BOUWER & RICE* evaluation model can be adopted for both a free and a (semi-) confined aquifer.

You must then enter the distance between the groundwater table (at-rest water level) and the base of the well (well toe), and the thickness of the layer filled by the groundwater.

> The depth of the groundwater must always be greater than the distance between the well toe and the groundwater table.

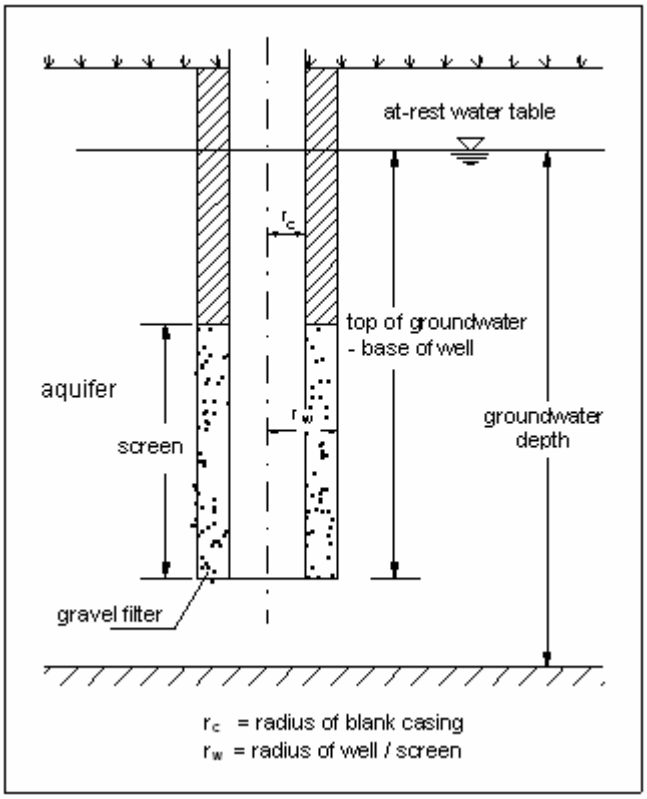
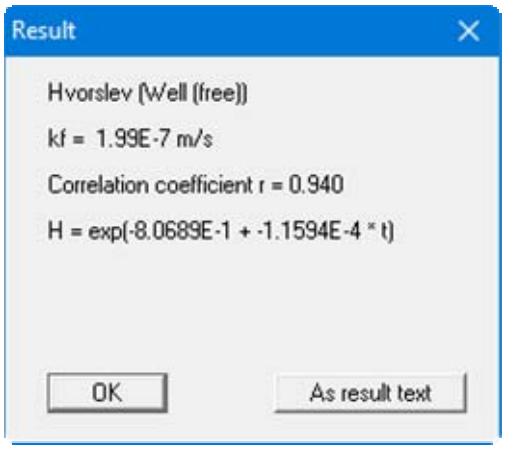


Figure 2: Well configuration for BOUWER & RICE evaluation

After confirming your input with "**OK**" you will be automatically presented with the data and best-fit curves after *BOUWER & RICE*.

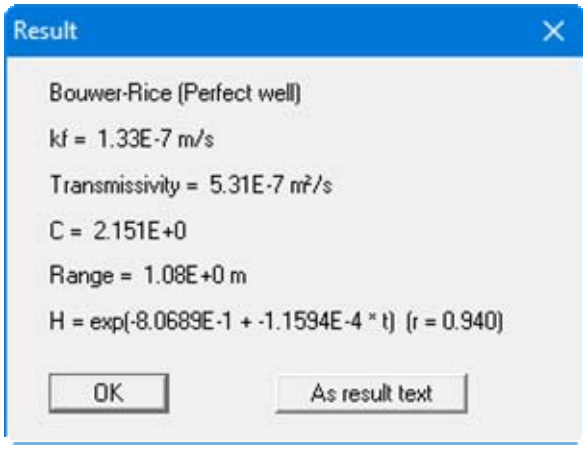
7.3.6 "Permeability" menu item

In order to get a result from an evaluation after *HVORSLEV* or *BOUWER & RICE*, you must go to this menu item after selecting one of the two methods and defining your preferences. A small text window then opens, containing the principal evaluation results.



The first line indicates the evaluation method with the corresponding well and aquifer configuration. For *HVORSLEV*, k_f then follows, together with the correlation coefficient and the calculated e-function.

For the evaluation after *BOUWER & RICE*, k_f is followed by the transmissivity and then the parameter C. This parameter is required internally for the calculation of certain quantities involved in the *BOUWER* model and is intended as a control mechanism for advanced users.

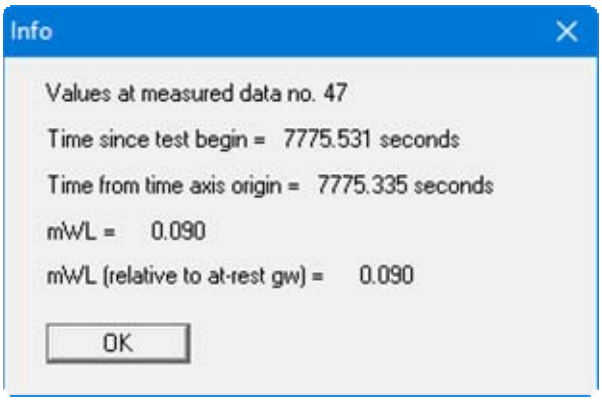


The range of the slug tests follows this. Finally, the equation for the adapted e-function is given, followed by the correlation coefficient as a measure of the agreement between the measured data and the calculated course.

You confirm the results with "**OK**" and close the result window. The "**As result text**" button sends the content of the result window to your output sheet. The complete text then appears in the lower right box of the output sheet. The text can be processed further using the "**Edit/Result text**" menu item (see Section 7.2.13).

7.3.7 "Individual values" menu item

Use this menu item to study a point on your curve in more detail. Click on the data point with the left mouse button. A message window opens, as shown in the following example for point no. 415. Close the window using the "**OK**" button.

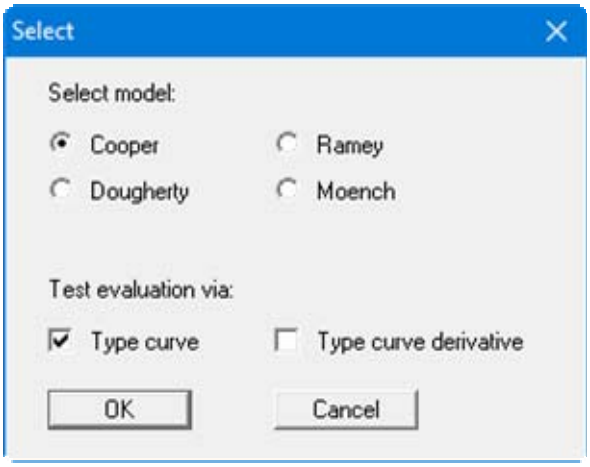


7.4 Type curves menu

The **GGU-SLUGTEST** program allows the evaluation of slug tests employing the model approaches after *COOPER et al.(1967)*, *DOUGHERTY (1989)*, *MATEEN (1983)*, *RAMEY et al. (1975)* and *MOENCH & HSIEH (1985 a)*.

7.4.1 "Cooper (Ramey/Dougherty/Moench)" menu item

In the program's default setting, the first menu item in the "**Type curves**" menu is "**Cooper**". Select the required model here, as shown in the following dialog box. The name of the menu item will be adjusted in the further course of the program, depending on the model selected, e.g. "**Type curves/Ramey**".



When selecting a model, the well geometry, the aquifer configuration and the data itself should be taken into consideration.

You can select from:

- **Cooper** (perfect well with wellbore storage in a homogeneous, isotropic, confined aquifer)
- **Dougherty** (imperfect well with wellbore storage in a homogeneous, isotropic, confined aquifer)
- **Ramey** (perfect well with wellbore storage and infinite skin in a homogeneous, isotropic, confined aquifer)
- **Moench** (perfect well with wellbore storage and finite skin in a homogeneous, isotropic, confined aquifer)

In addition, you can choose to have the test evaluated by means of normal type curves or the derivative of the type curves.

> The evaluation by means of the type curve derivative makes sense if you want to perform a "**hand fit**".

If the type curves are represented as derivatives, they are generally easier to differentiate from one another than the normal representation. This helps when selecting by hand the best-fitting derivative and thus the type curve.

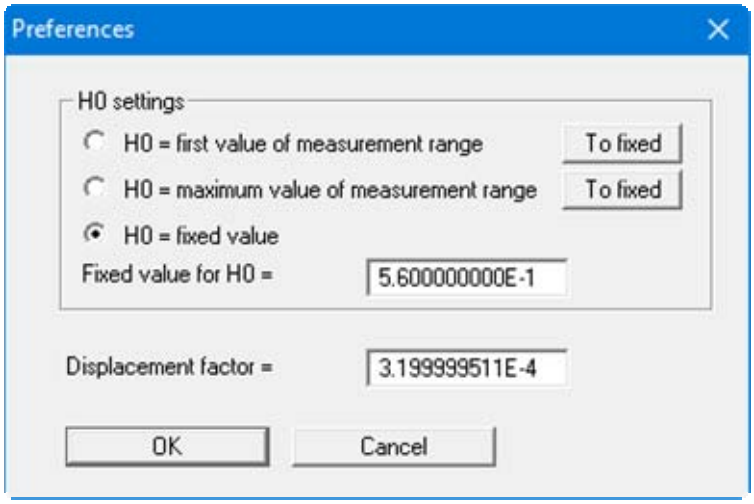
The name of the following menu item is adjusted according to the selected test evaluation, e.g. "**Type curves/Cooper preferences**".

Confirm the model selection and test evaluation using "**OK**". If you have already loaded a dataset, the standard type curves are presented on the output sheet corresponding to the evaluation models and your data curve.

7.4.2 "Cooper preferences"/"Cooper deriv. preferences" menu item

> This menu item applies equally to the model approaches after *RAMEY*, *DOUGHERTY* and *MOENCH*, and the derivatives of the various type curves.

A dialog window for defining H_0 preferences opens when you go to this menu item.



You can select:

- the first value of your selected measurement range,
- the maximum of the measurement range or
- any fixed value.

The "**To fixed**" buttons allow you to assign the first value or the greatest value of the measurement range as fixed H_0. The value is then transferred to the input box.

> Please note that H_0 has a decisive influence on the curvature of the data, particularly at the start of the curve, because in a *COOPER* graph the quotient H/H_0 is represented.
>
> The value chosen for H_0 can therefore have a critical influence on your result.

In the dialog box above you can also define a displacement factor (> 0!) for the data curve. Initially, a factor of 1 is shown for the undisplaced curve. By horizontal displacement along the time axis the data curve is brought to congruence with the best fitting type curve. The displacement factor is used in the calculation of the transmissivity and permeability.

Your input is accepted after you leave the dialog box via the "**OK**" button and the adapted representation drawn on the output sheet .

In the following figure the model approach after *COOPER* is shown with the relevant parameters.

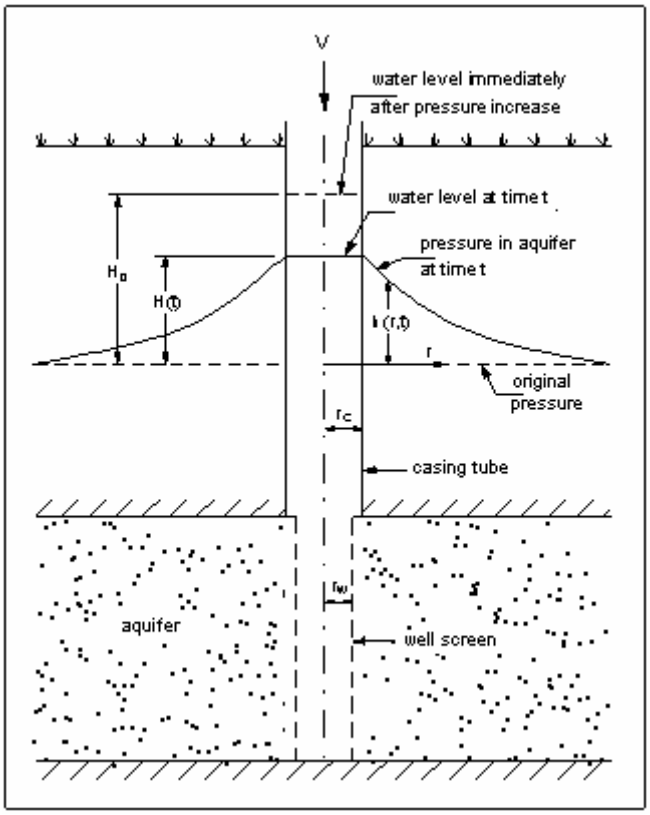
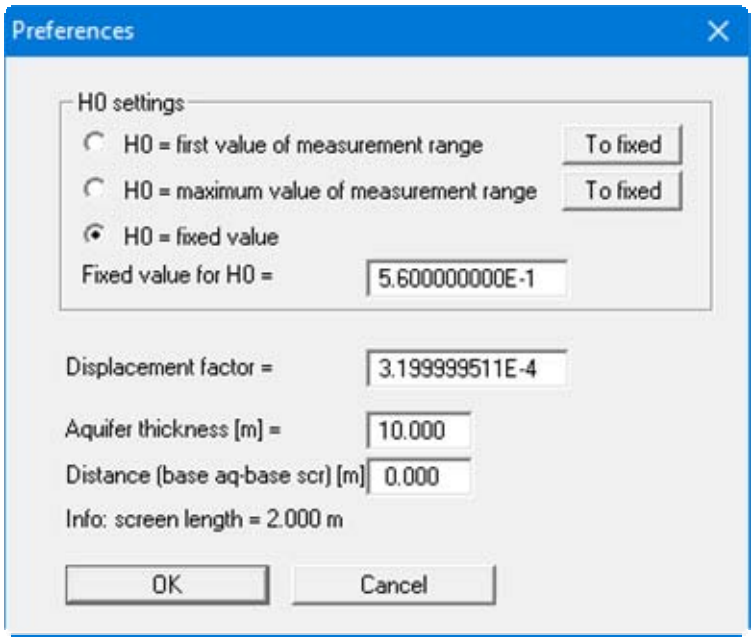


Figure 3: Aquifer configuration after COOPER

If you have chosen "**DOUGHERTY**" (the same as *COOPER*, but for an imperfect well) as evaluation model, you will see an expanded dialog box.



Here, you must also enter the "**Aquifer thickness**" and the "**Distance**" (base of aquifer - base of screen)" (see Figure 4: UKAq - UKF). This information is required to produce a pertinent model configuration.

This means that new values must be entered for each new aquifer configuration.

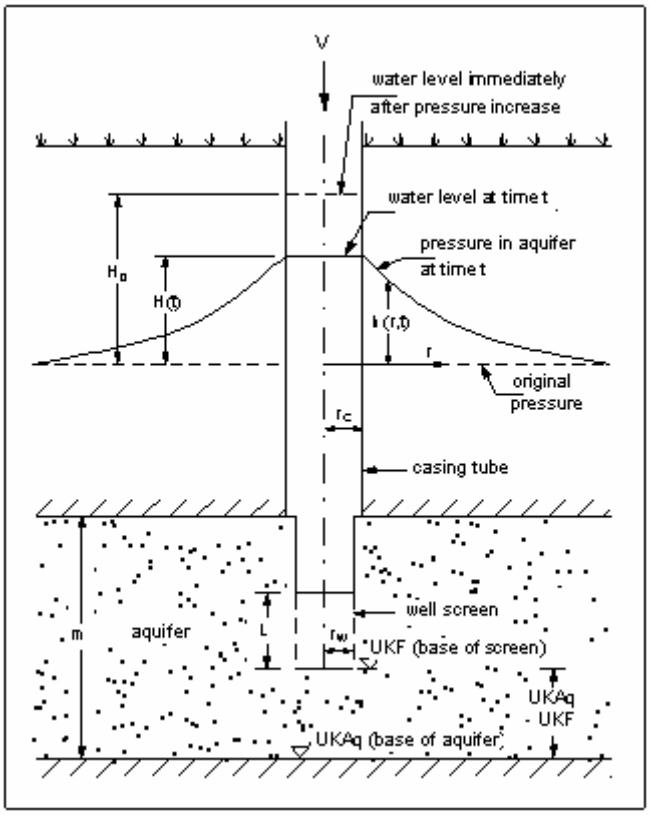


Figure 4: Aquifer configuration after DOUGHERTY

The "**RAMEY**" evaluation model corresponds to the configuration of the *COOPER* model (see Figure 3, Page 41).

For the "**MOENCH**" evaluation model, which includes a finite skin zone around the well, you must additionally enter

- the ratio of the permeabilities of the aquifer to the skin zone,
- the ratio of the storage coefficient of the skin zone to the aquifer and
- a radius for the skin zone.

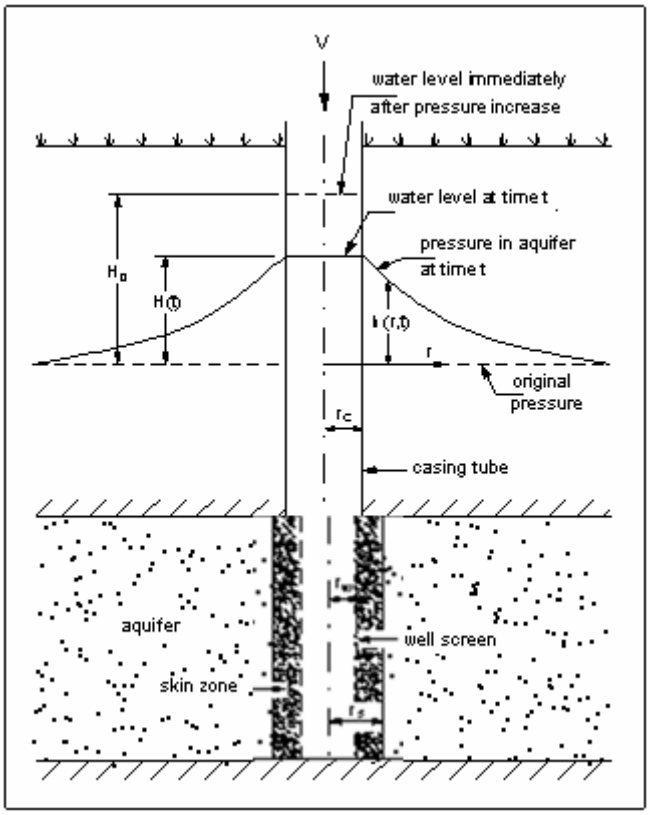


Figure 5: Aquifer configuration after MOENCH

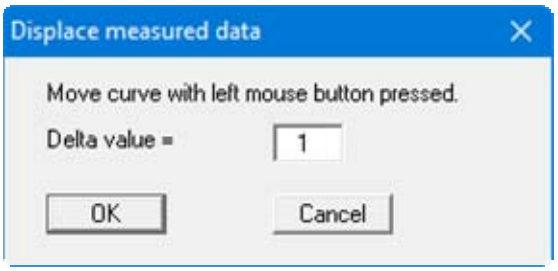
7.4.3 "Derivative preferences" menu item

If you have decided on an evaluation by means of the derived type curves you can define the following parameters using this menu item:

- a scaling factor for the y-axis (h/H_0) for the data curve and the derived type curve and
- a displacement factor for the derived data curve in the x-direction (time axis).

7.4.4 "Hand fit" menu item

For an initial overview it is often sufficient to evaluate ***manually***. "**Hand fit**" allows you to bring the data curve to congruence with one of the type curves using the mouse. Before doing this you must specify from which value the curve is displaced. A small dialog window opens.



Data curve displacement is faster the greater the selected "**Delta value**". You will have to show a little patience for especially large datasets.

As long as you hold the left mouse button the data curve can be horizontally displaced by any amount. Height displacement is possible if the measured data deviate correspondingly.

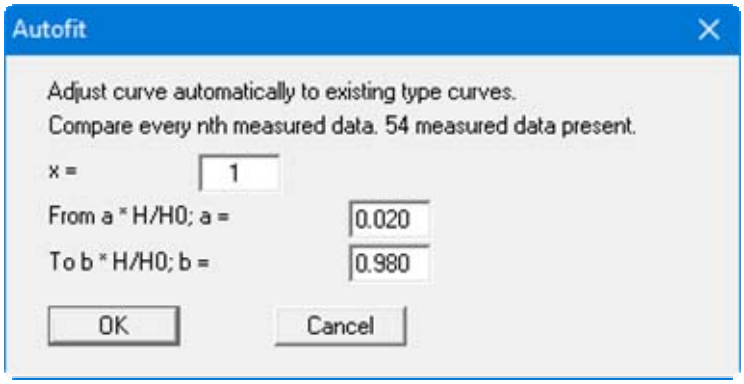
> Take note of the status bar at the bottom of the program window:
> k_f is shown here in real time.
>
> This will help to give you a ***feeling*** for how the permeability varies for a "**fit**" from type curve to type curve.

7.4.5 "Autofit 1" menu item

If the "**Type curves/Autofit 1**" menu item is selected the program automatically compares the data with the existing type curves and searches for the best fitting type curve using the ***least squares method***.

> Please ensure that you do not have only a very few type curves in your type curves file, because the program will always find a type curve that fits best.

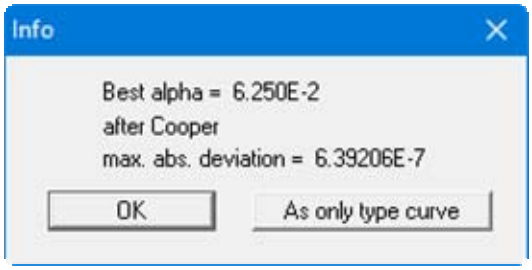
Before you can perform an "**Autofit 1**" you must specify in a dialog window which n^{th} data points of the data curve are to be compared to the type curves. Normally, you can work with the default setting "**x = 1**", i.e. every data point is included in the comparison. You can reduce the number of data points for very large datasets, by entering 10, for example. This makes things a little faster.



In addition, you can specify the range for H/H_0, that is, the region of the y-axis for which the ***fit*** is performed. The default range is from 0.02 to 0.98. The data often become noisy towards the end of a measuring campaign. This area can also be blanked out.

Confirm your input using the "**OK**" button. The program then searches without further ado for the best fitting type curve.

When the analysis is complete a window opens displaying the selected type curve parameter for your evaluation model. The maximum absolute deviation between the data curve and the type curve is calculated for this purpose. If you close the window with "**OK**", the type curve fit is drawn on the output sheet .



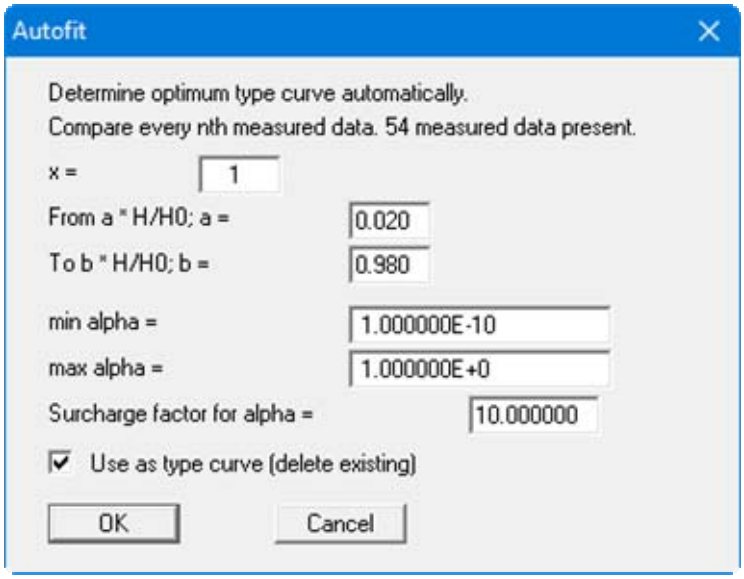
If, on the other hand, you press the "**As onlytype curve**" button, only the best fitting type curve is drawn on the output sheet with the data curve. Any existing type curves will be deleted.

When employing the "**DOUGHERTY**" and "**MOENCH**" models you must ensure that you really have generated the type curves most suitable for your aquifer and well geometry, using the menu item "**Type curves/Generate**" (see Section 7.4.10).

If the type curves do not fit your geometry you will see an error message; you should not ignore this. Otherwise you will begin an evaluation with type curves unsuitable for your current configuration and the results may well be nonsense.

7.4.6 "Autofit 2" menu item

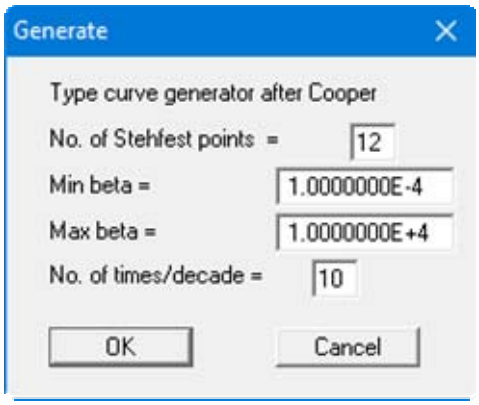
Using this ***fit*** method, the best fitting type curve is not selected from an existing set of type curves, but the ***optimum type curve*** is calculated. This means that the program generates the optimum fit type curve by systematic variation of the type curve parameter. If you have decided on "**Autofit 2**" the following dialog box opens:



In the dialog box you can specify which n^{th} data points of the data curve are considered for "**Autofit 2**". Here, once again, you can limit the range of H/H_0. Moreover, you can define a minimum and a maximum type curve parameter, between which the type curve parameter varies. You must also specify a surcharge factor for the type curve parameter. Do not make this factor too small at first, or go for a coffee afterwards.....

Finally, you have the option of notifying the program whether to accept the newly calculated, optimum type curve. If you activate this check box, the existing type curves are deleted.

Once you have specified all preferences and concluded input with "**OK**", a further dialog box opens with the heading "**Type curve generator after Cooper**" (the name corresponds to the evaluation model selected).



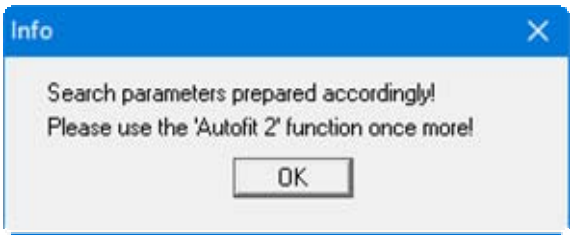
Because a type curve is calculated by means of the ***Stehfest algorithm***, you can edit the number of Stehfest weighting factors here. In principle, the calculation of a type curve is more precise the more Stehfest points (even number!) are used. However, computing time also increases with an increase in the number of Stehfest points. The program achieves good results with 8,10,12,14,16 and 18 Stehfest points. You should generally leave this at 12 points. Nevertheless, it is still possible that given parameter combinations, in conjunction with a given number of Stehfest points, may lead to an unrealistic type curve.

In addition, you can specify the start ("**Min beta**") and end time ("**Max beta**"), and the number of times per logarithmic decade for the optimised type curve. If these parameters are cleverly selected the computation time can be greatly reduced.

> With regard to the times, please note that these are dimensionless type curve times.

Once you have entered all the required values, close the window with "**OK**" and "**Autofit 2**" finds an optimum type curve. You can follow the variation of the type curve parameter in the status bar at the bottom of the program window. After computation of the optimum type curve an info box opens showing the found optimum type curve parameter and the maximum absolute deviation between the type curve and the measured data. After confirming with "**OK**" you are asked whether the type curve parameter should be further delineated.

If you answer "**No**" then "**Autofit 2**" is complete and you see the type curves on your output sheet . If you answer the question with "**Yes**", you will next see the following info box; close it by clicking "**OK**".



The program now offers you the opportunity of defining all required parameters. Generally, you should simply leave the values proposed automatically by the program. However, you are free to enter your own values. In this manner you can further delineate the type curve parameters in several computation runs.

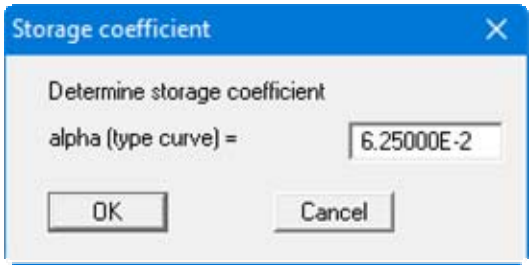
> Ensure that the maximum absolute deviation between the type curve and the measured data really does decrease.

7.4.7 "Permeability" menu item

After a completed ***fit*** the hydraulic parameters derived from it will be of interest. Various dialog boxes will open, depending on the evaluation model selected (see Section 7.4.1).

7.4.7.1 Evaluation model after COOPER

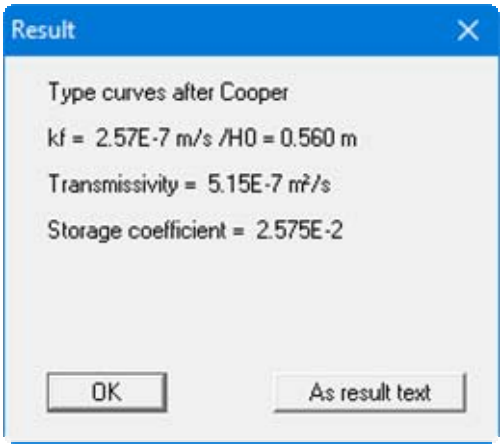
If you have chosen to use the "**COOPER**" evaluation model and go to the "**Type curves/Permeability**" menu item, the following dialog box opens:



In this box the type curve parameter, together with the well data from which the storage coefficient is calculated, is proposed for an ***automatic fit***.

> **ATTENTION:** If you have previously performed a "**Hand fit**", you must enter the correct type curve parameter yourself.

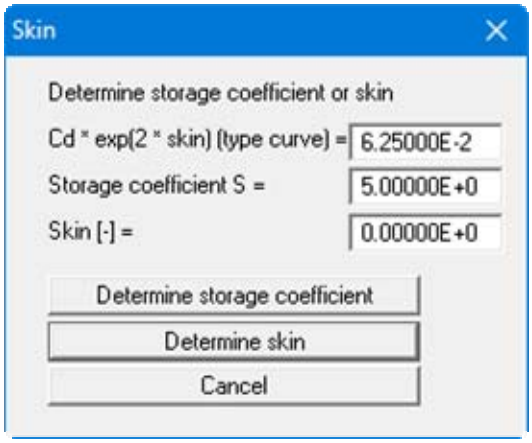
If you confirm the proposed value or the value determined by means of "**Hand fit**" with "**OK**", the storage coefficient is shown. After confirming the storage coefficient with "**OK**" a new box opens, presenting you with the result of your evaluation.



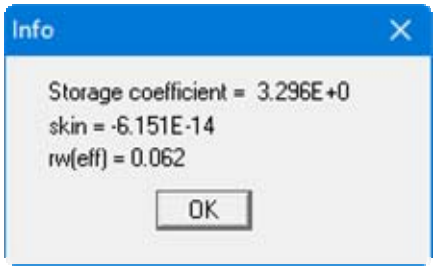
In the first line you are reminded of the selected evaluation model. Below this are k_f and the user-defined H_0, the transmissivity and the storage coefficient once again. Close this info box with "**OK**". If you would like to transfer the results to your output sheet , click the "**As result text**" button. The results are then displayed in the lower right box of the output sheet (also see the "**Edit/Result text**" menu item, Section 7.2.13).

7.4.7.2 Evaluation model after RAMEY

If you selected the "**RAMEY**" model for your ***fit*** and you activate the "**Type curves/Permeability**" menu item, a window opens with the heading "**Determine storage coefficient or skin**" and showing the type curve parameters and the storage coefficient. Furthermore, a value for the skin is proposed.



Because the *RAMEY* method can calculate either only the storage coefficient or only the skin, one of the two variables must already be known in order to calculate the other. You therefore have the option of having either the storage coefficient calculated for a user-defined skin value or having the skin calculated for an estimated storage coefficient. When you have done this a small window opens displaying the values.

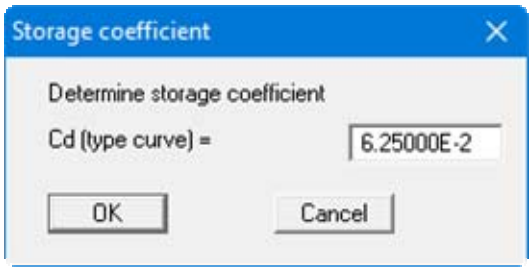


In addition, the hydraulically effective well radius is calculated from the skin and displayed here. If you confirm the values with "**OK**" a new window opens with the heading "**Type curves after Ramey**", showing all evaluation results.

These results consist of the permeability k_f, the initial height H_0, the transmissivity, the storage coefficient, the skin and the effective well radius. If desired, you can use this result as the result text in the lower right box of the output sheet .

7.4.7.3 Evaluation model after DOUGHERTY

Using the "**DOUGHERTY**" model, the type curve parameter is displayed in a "**Determine storage coefficient**" dialog box.



You can accept this parameter for the autofits.

> **ATTENTION:** If you have previously performed a "**Hand fit**", you must enter the correct type curve parameter yourself.

If you confirm the proposed value or the value determined by means of "**Hand fit**" with "**OK**", the storage coefficient is shown. After confirming the storage coefficient with "**OK**" a "**Type curves after Dougherty**" result window opens with all relevant evaluation values.

If required, the contents of the result window can be transferred to the output sheet . This is done by pressing the "**As result text**" button.

7.4.7.4 Evaluation model after MOENCH

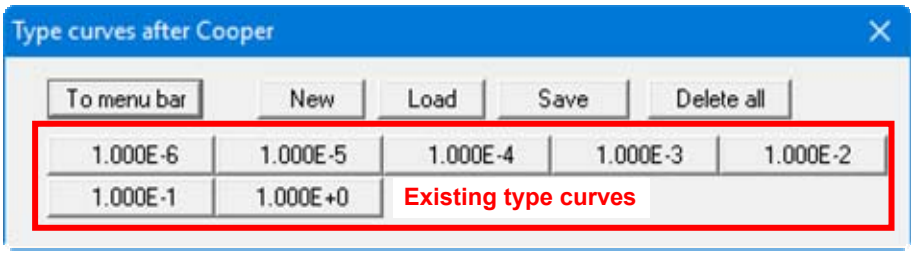
The "**MOENCH**" model applies accordingly. A type curve parameter for calculation of the storage coefficient is proposed. Following a hand-fit you must enter the correct type curve parameter yourself.

Once you have accepted or entered the value, click on "**OK**" and the storage coefficient will be displayed. Another click on "**OK**" opens a window with the heading "**Type curves after Moench**".

Here, you can see all evaluation parameters, such as k_f, H_0, the transmissivity and the storage coefficient. Furthermore, the user-defined ratios of aquifer permeability to skin zone permeability and skin storage coefficient to aquifer storage coefficient, and the ratio of skin radius to well radius, are given. If required, the contents of the result window can be transferred to the output sheet using the "**As result text**" button.

7.4.8 "Edit type curves" menu item

Using this menu item you can manage the type curves in the system for the currently selected evaluation model. After clicking, a dialog box with the heading "**Type curves after Cooper**", similar to the following example, opens.



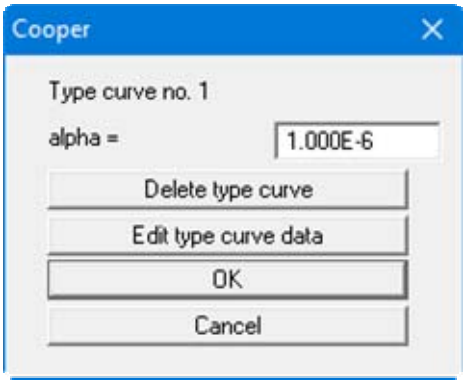
There are already seven type curves in this example. The buttons are automatically labelled with the alpha value of the respective type curve. The following actions are possible:

- "**To menu bar**"
  You will return to the menu bar
- "**New**"
  You can enter a new type curve.

> **NOTE:** New type curves cannot be calculated using this menu item!

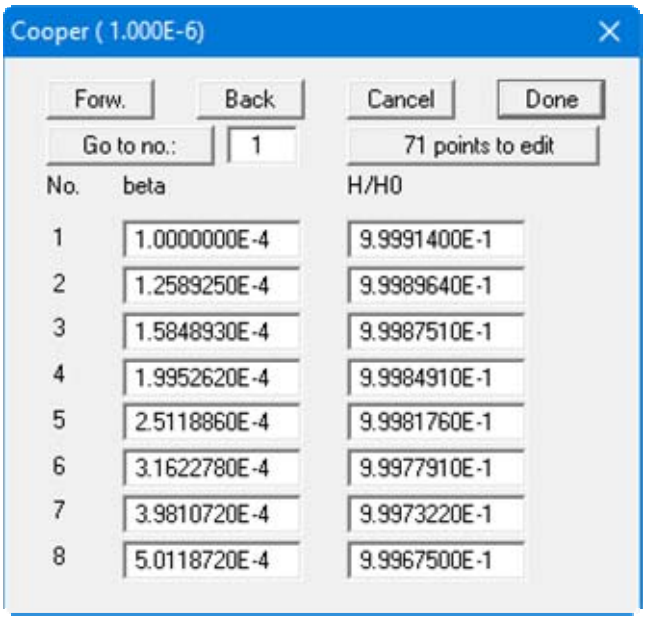
- "**Load**"
  You can load a dataset with previously saved type curves.
- "**Save**"
  You can save existing type curves together in a dataset.
- "**Delete all**"
  You can delete all existing type curves, in order to generate new type curves, for example.
- "**1.000E-6**", "**1.000E-5**", **.....**
  You can view and edit the respective type curve data, if required, by clicking on each button.

After clicking "**New**", or the button of an existing type curve, a dialog box opens allowing you to enter or edit the type curve parameter and additional parameters, depending on the model.



This allows you to append new type curves acquired, for instance, by copying from publications or other sources. If you choose "**New**" but close the box using "**Cancel**", any alterations made will be rejected, but the type curve itself will be retained (new button with the alpha value labelling). Individual curves can be deleted using the "**Delete type curve**" button.

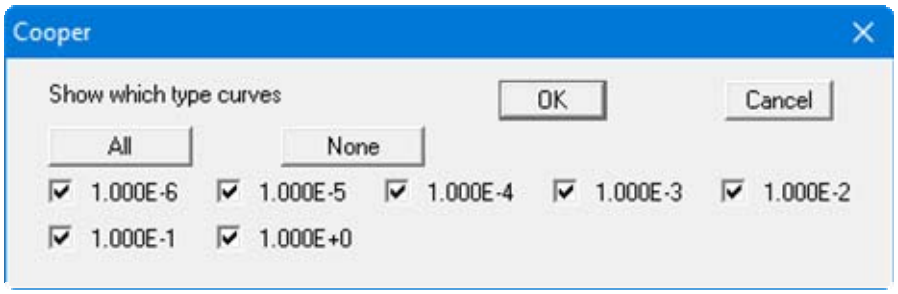
If you clicked the "**Edit type curve data**" button, you can enter or edit individual type curve values in a dialog box. In the title bar of the dialog box the evaluation model is shown and, in brackets, the type curve parameter of the selected type curve.



No points exist for a new type curve. First, click on the "**x points to edit**" button (in the example above 71 points already exist) and enter the required number. You can navigate through the list using "**Forw.**" and "**Back**" or jump directly to the required point by entering the number and clicking "**Go to no.:**" To conclude your entry or edit click "**Done**".

7.4.9 "Select" menu item

Using this menu item you have the option of comfortably selecting any type curves for representation.



Activate the check boxes in front of the required type curves. You can quickly select "**All**" or "**None**" with the corresponding buttons. After selection, close the dialog box with "**OK**".

> In order to make the type curves appear on the output sheet , press either [**Esc**] or [**F2**] after selecting them and closing the box.

7.4.10 "Generate" menu item

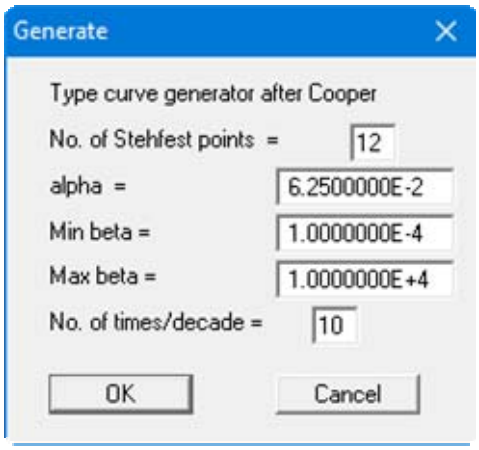
The type curve generator can generate any number of type curves for the models *COOPER*, *DOUGHERTY*, *RAMEY* and *MOENCH*. You can define the respective parameters according to your own requirements. However, you should be aware of which parameter combinations are sensible and which are not.

The models *COOPER* and *RAMEY* are universal models: beside the type curve parameters, no other data is utilised for the calculation.

The models *DOUGHERTY* and *MOENCH* are special models. This means that the type curves are valid only for special aquifer and well geometries.

7.4.10.1 Type curves after COOPER

A dialog box with the heading "**Type curve generator after Cooper**" opens.



First, you enter the "**No. of Stehfest points**". This correlates directly to the numerical method used for calculating the type curves. Generally, you should leave this at the 12 point default. In principle, however, the type curve would be more precise the higher the number of Stehfest model points. Nonetheless, because of the limited precision of your computer, the results may be rather strange for values above 18.

> The number of Stehfest points must always be even.

Next, you enter the type curve parameter alpha. A useful range here is between 1e-1 and 1e-10, approximately. You can now enter the dimensionless start and end time for the type curve. A useful range for beta here is between 1e-4 und 1e+4. Finally, you are asked for the number of time steps per logarithmic decade. The default value is ten steps.

> The higher the number of steps, the greater the number of data pairs included in the type curve. The computation time increases accordingly.

Once you have defined everything as you require, confirm your input with "**OK**", or abort the process with "**Cancel**".

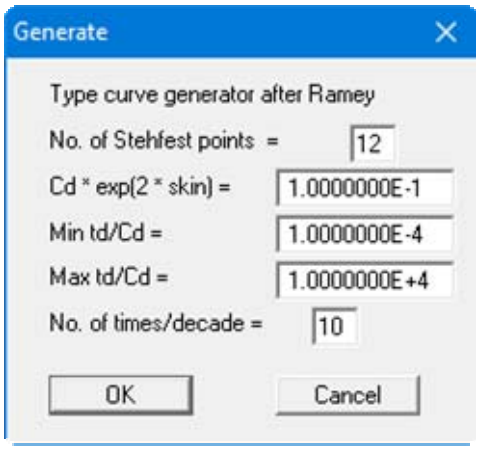
When the program has concluded computations you are asked whether you want to save the type curve. If you answer this by pressing the "**Yes**" button a Windows dialog box opens where you can use "**Save file as**" to save the type curve. The program suggests "**.tku**" as the extension for the type curve file name.

If you have saved the type curves or replied to the previous question with "**No**", you will be asked whether the type curve should be included in the list of available curves. The program then stores the curve.

If you want the calculated type curves to be permanently saved, you must save them using "**Type curves/Edit type curves**" button "**Save**", as described in Section 7.4.8. The default file is called "**GGU-SLUGTEST.tkv**".

7.4.10.2 Type curves after RAMEY

In principle, generating type curves according to the *Ramey* evaluation model is exactly the same as the *COOPER* model. The only difference for *Ramey* is the type curve parameter $C_D e^{2s}$.

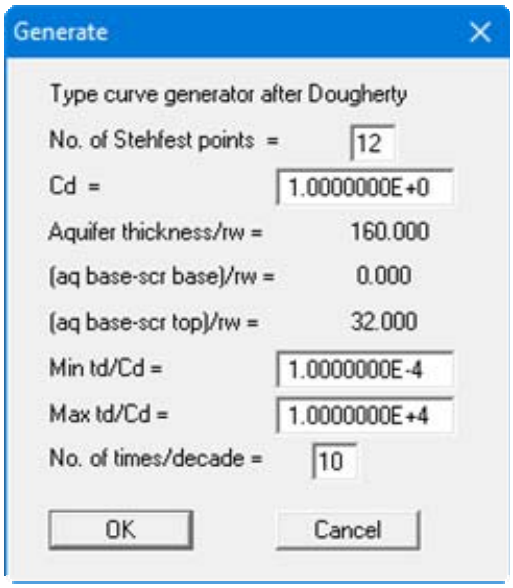


7.4.10.3 Type curves after DOUGHERTY

In the *DOUGHERTY* model you must know the well and aquifer geometry, beside input of the previously mentioned parameters, or at least enter plausible estimates. You should have the following parameters ready:

- the aquifer thickness,
- the distance between the base of the aquifer and the base of the screen,
- the distance between the base and the top of the screen (length of screen).

These values must be respectively divided by the borehole radius.



The information corresponds to the information entered in the menu item "**Edit/Test data**" (see Section 7.2.1). So you see, the type curves for an imperfect well after *DOUGHERTY* are precisely adapted to your respective system.

You then enter the start and end time (dimensionless type curve time) and the number of times per decade.

When you are ready to start the computation click "**OK**". The computation may take some time if you have a ***slow*** computer.

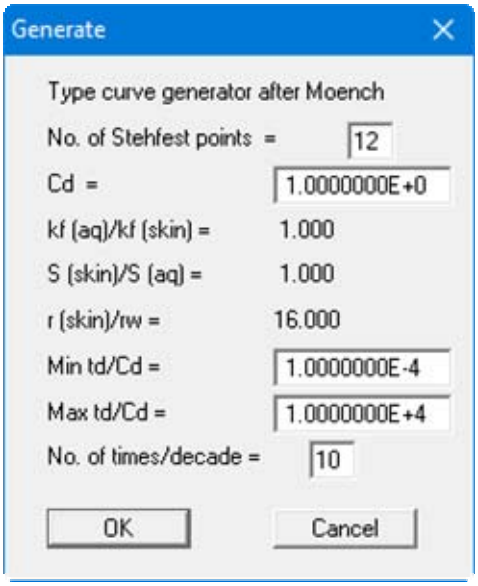
Once the computation is complete you can once again decide whether the type curve should be saved and/or placed in the list of available curves.

7.4.10.4 Type curves after MOENCH

In contrast to the *RAMEY* model, the model approach after *MOENCH* takes into consideration a skin zone of limited extent around the well (finite skin). Accordingly, this skin zone possesses a radius (measured from the borehole centre), a permeability and a storage coefficient.

Beside the Stehfest points and the type curve parameters, you must tell the program

- the ratio of the permeability of the aquifer to the permeability of the skin zone,
- the ratio of the storage coefficient of the skin zone to the storage coefficient of the aquifer and
- the ratio of the radius of the skin zone to that of the borehole or the well



Here, too, it is advisable to carefully consider the configuration for the type curve calculation. For example, for a well in a relatively impermeable rock, the permeable filter gravel fill can be taken into consideration as a skin zone.

All further steps have already been described.

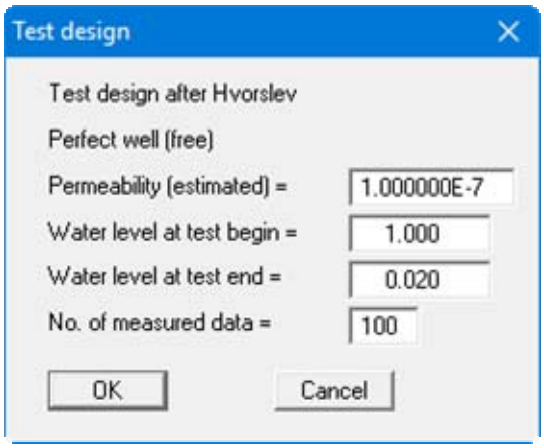
7.5.1 General note for the Test design menu

This menu allows the simulation of a slug test for all implemented models.

This is particularly useful for planning upcoming tests. You should use this option extensively in order to acquire a feel for the possible changes in water levels for varying aquifer and well types.

7.5.2 "Hvorslev" menu item

After selecting this item a "**Test design after Hvorslev**" dialog box opens. The same configuration (Case A/B) appears that you previously selected in the menu item "**Hvorslev/ - preferences**" (see Section 7.3.3).



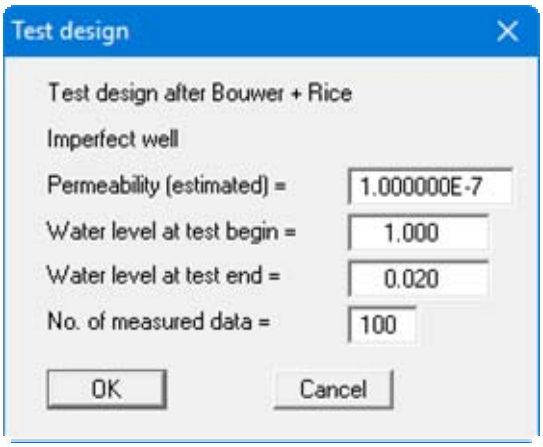
Enter an estimate for the permeability in the dialog box. In addition, you must enter a water level at the start of the test (the increase for a slug test) and the end of the test. Finally, you can enter the number of data pairs ("**No. of measured data =**") for the simulated curve.

> Well data input is carried out via the menu item "**Edit/Test data**" (see Section 7.2.1).

After confirming the data with "**OK**", the data graph is immediately displayed on your output sheet according to the *HVORSLEV* model.

7.5.3 "Bouwer + Rice" menu item

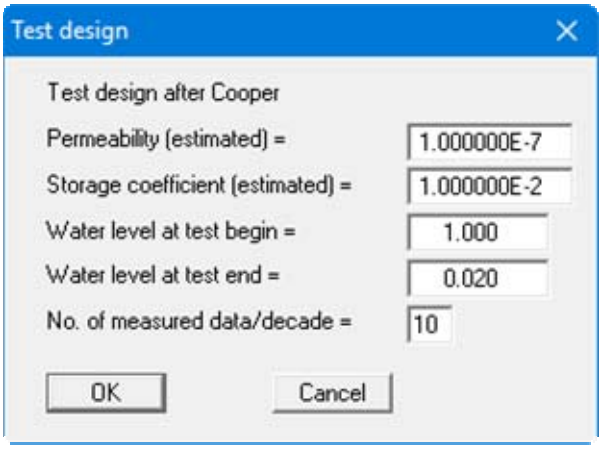
You will see the same dialog box as in the previous menu item, but with a different heading. Input is the same as for "**Test design/Hvorslev**".



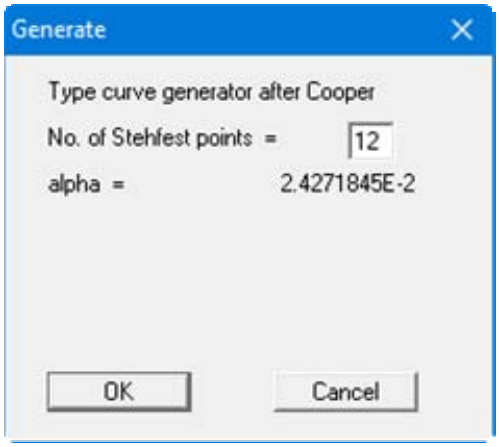
7.5.4 "Cooper (Ramey/Dougherty/Moench)" menu item

The title of this menu item reflects the evaluation model selected in "**Type curves/Cooper (Ramey/Dougherty/Moench)**" (see Section 7.4.1).

The "**Test design after Cooper**" dialog window that opens when "**COOPER**" is selected asks for the permeability and the storage coefficient. In addition, you can enter the increase for a fictitious test, as well as the water level at the end of the test. Finally, you enter the number of data per logarithmic decade.



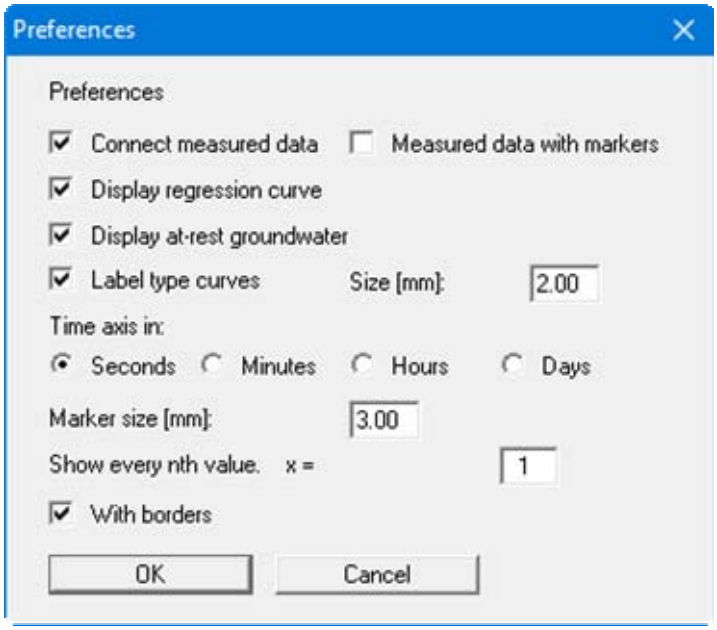
After confirming with "**OK**" a new dialog box opens, where you enter the number of Stehfest points. The type curve parameter alpha shown on the screen was determined by the program from your well data (menu item "**Edit/Test data**", Section 7.2.1) and the storage coefficient.



After confirmation with "**OK**" the simulated graph is displayed together with the *COOPER* type curves. For test design using one of the other evaluation models *RAMEY*, *DOUGHERTY* or *MOENCH* operate in a similar way.

7.6.1 "Preferences" menu item

In a dialog box you can define preferences and alter the appearance of the graph and the type curves.



You can connect the data points to a curve and have the data points marked by a circle. The number and size of the markers can be specified at the bottom of the dialog box.

By activating the appropriate check box you can display the regression curve (*HVORSLEV*, *BOUWER & RICE*) in the graphics. You can also choose to display the at-rest water level.

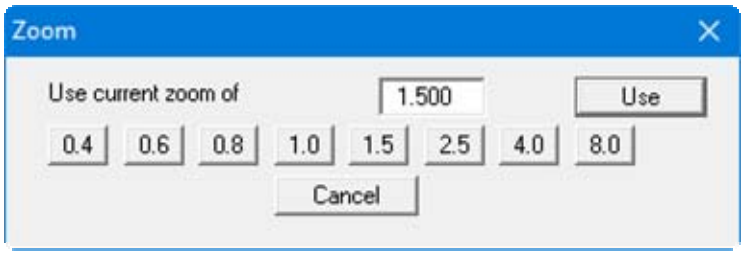
If you wish to have the type curves annotated, activate the corresponding check box and, if necessary, enter a different text size. By activating the required dimension for the time axis the representation can be displayed in seconds, minutes, hours or days.

After confirming your input with "**OK**" the graph is redrawn according to your preferences.

7.6.2 "Refresh and zoom" menu item

The program works on the principle of ***What you see is what you get***. This means that the screen presentation represents, overall, what you will see on your printer. In the last consequence, this would mean that the screen presentation would have to be refreshed after every alteration you make. For reasons of efficiency and as this can take several seconds for complex screen contents, the screen is not refreshed after every alteration.

If, e.g., after using the zoom function (see below), only part of the image is visible, you can achieve a complete view using this menu item.



A zoom factor between 0.4 and 8.0 can be entered in the input box. By then clicking on "**Use**" to exit the box the current factor is accepted. By clicking on the "**0.4**", "**0.6**", etc. buttons, the selected factor is used directly and the dialog box closed.

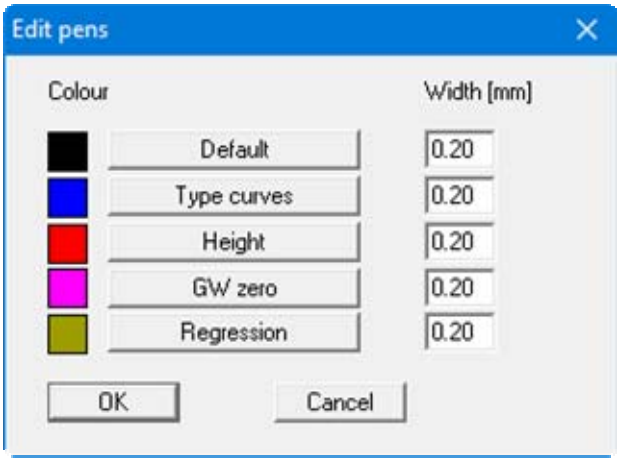
It is much simpler, however, to get a complete overview using [**Esc**]. Pressing [**Esc**] allows a complete screen presentation using the zoom factor specified in this menu item. The [**F2**] key allows screen refreshing without altering the coordinates and zoom factor.

7.6.3 "Zoom info" menu item

By clicking two diametrically opposed points you can enlarge a section of the screen in order to view details better. An information box provides information on activating the zoom function and on available options.

7.6.4 "Pen colour and width" menu item

For reasons of clarity, different colours are used as default for graphic presentation of the graphs. Using this menu item you can alter the preferences to suit your wishes.



The pen width can be edited for the different graphs and, after clicking the buttons with the appropriate designation, the pen colours be adapted. The pen preferences can be saved in the "**GGU-SLUGTEST.alg**" file (see Section 0).

On ***monochrome printers*** (e.g. laser printers), colours are shown in a corresponding grey scale. Graphic elements employing very light colours may be difficult to see. In such cases it makes sense to edit the colour preferences.

7.6.5 "Legend font selection" menu item

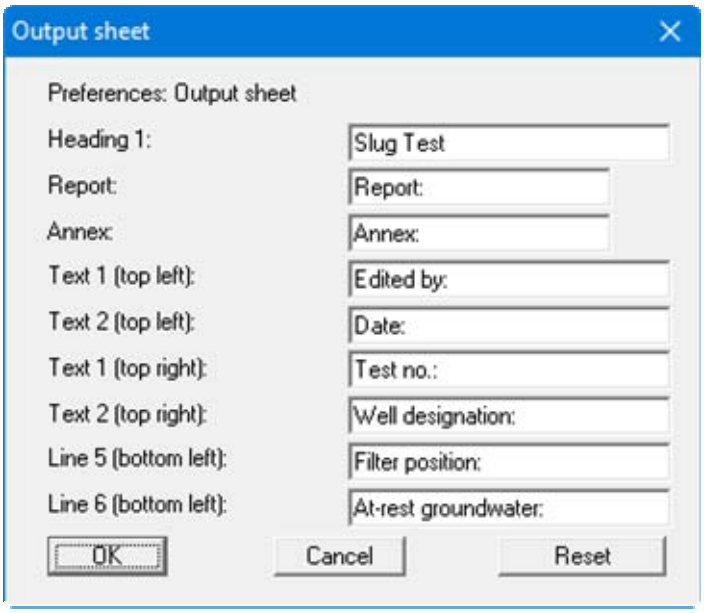
With this menu item you can switch to a different true-type font. All available true-type fonts are displayed in the dialog box.

7.6.6 "Font size selection" menu item

You can edit font sizes of texts [in mm] within the various input areas.

7.6.7 "Output sheet" menu item

Using this menu item you can enter or edit the default text on your output sheet. If you save the "**GGU-SLUGTEST.alg**" file containing the preferences at the same level as the program, they will be used automatically when the program is started.



Your input in the fields "**Text 1**" to "**Line 6**" of the above dialog box, as well as the input for "**Report:**" and "**Annex:**" also represent the designations for the appropriate input boxes in the "**Edit/Test designations**" (see Section 7.2.4) and "**Edit/General**" (see Section 7.2.12) menu items dialog boxes. Use "**Reset**" to restore the default labelling settings.

7.6.8 "Mini-CAD toolbar" menu item

Using this menu item you can add free text to the graphics and add lines, circles, polygons and images (e.g. files in formats BMP, JPG, PSP, TIF, etc.). PDF files can also be imported as images. A pop-up menu opens, the icons and functions used are described in more detail in the **Mini-CAD** manual saved in the '**C:\Program Files (x86)\GGU-Software\ Manuals**' folder during installation.

7.6.9 "Toolbar preferences" menu item

After starting the program a horizontal toolbar for menu items appears below the program menu bar. If you would rather work with a popup window with several columns, you can specify your preferences using this menu item. The smart icons can also be switched off.

At the bottom of the program window you find a status bar with further information. You can also activate or switch off the status bar here. The preferences will be saved in the "**GGU-SLUGTEST.alg**" file (see menu item "**Graphics preferences/Save graphics preferences**") and will be active at the next time the program is started.

By clicking on the tools (smart icons) for menu items you can directly reach most of the program functions. The meaning of the Smart icons appears as a text box if you hover with the mouse pointer over the tools. Some of the tool functions can be activated from the normal menu items.

"**Zoom out**"
If you have previously ***zoomed in***, this tool returns to a full screen display.

"**Zoom (-)**"/"**Zoom (+)**"
With the zoom functions you can zoom in or out of parts of the image, by clicking the left mouse button.

"**Copy/print area**"
Use this tool to copy only parts of the graphics in order to paste them, e.g. to a report. You will see information on this function and can then mark an area, which is copied to the clipboard or can be saved in a file. Alternatively you can send the marked area directly to your printer (see "**Tips and tricks**", Section 8.4).

7.6.10 "Save graphics preferences" menu item

Some of the preferences you made with the menu items of the "**Graphics preferences**" menu as well as the inputs using the "**Edit/Company**" menu item can be saved to a file. If you select "**GGU-SLUGTEST.alg**" as file name, and save the file on the same level as the program, the data will be automatically loaded the next time the program is started and need not be entered again.

> If you do not go to "**File/New**" upon starting the program, but open a previously saved file instead, the preferences used at the time of saving are shown. If subsequent changes in the general preferences are to be used for existing files, these preferences must be imported using the menu item "**Graphics preferences/Load graphics preferences**".

7.6.11 "Load graphics preferences" menu item

You can reload a graphics preferences file into the program, which was saved using the "**Graphics preferences/Save graphics preferences**" menu item. Only the corresponding data will be refreshed.

7.7.1 "Copyright" menu item

You will see a copyright message and information on the program version number.

The "**System**" button shows information on your computer configuration and the folders used by **GGU-SLUGTEST**.

7.7.2 "Maxima" menu item

You will see information on the maximum values allowed by the program.

7.7.3 "GGU on the web" menu item

Using this menu item you can access the GGU Software website: www.ggu-software.com.

Get information on updates and modifications on a regular basis from your program module page. You can also subscribe to email notifications, which provide information on all modifications on a monthly basis.

7.7.4 "GGU support" menu item

This menu item takes to the GGU-Software Contact area at www.ggu-software.com.

7.7.5 "Help" menu item

The **GGU-SLUGTEST** help is opened as a PDF document. The help function can also be accessed using the [**F1**] function key.

7.7.6 "What's new?" menu item

You will see information on program improvements in comparison to older versions.

7.7.7 "Language preferences" menu item

This menu item allows you to switch the menus and the graphics from German to English and vice versa. To work in German, deactivate the two check boxes "**Dialoge + Menüs übersetzen (translate dialogues, menus)**" und "**Graphiktexte übersetzen (translate graphics)**".

Alternatively, you can work bilingually, e.g. with German dialog boxes but with graphic output in English. The program always starts with the language setting applicable when it was last ended.

8 Tips and tricks

8.1 Pressurised slug tests

When entering the test data for evaluation of so-called ***pressurised slug tests*** (pulse tests), the casing radius r_c must be replaced by:

$$r_{cnew} = r_c \cdot \sqrt{l \cdot c_w \cdot \rho_w}$$

where:

r_c : Casing radius [m]

l : Test distance [m]

c_w : Compressibility of test zone [m²/N]

ρ_w : Density of water [kg/m³]

If c_w is not precisely known, calculations may be performed using the compressibility of water instead ($4.78 \cdot 10^{-10}$ m^2/N^{-1} at 10 °C).

8.2 Keyboard and mouse

You can scroll the screen with the keyboard using the cursor keys and the [**Page up**] and [**Page down**] keys. By clicking and pulling with the mouse, with [**Ctrl**] pressed, you activate the zoom function, i.e. the selected section will fill the screen. Furthermore you can use the mouse wheel to zoom in/out or scrolling the screen presentation. The following mouse wheel functions are available:

- Mouse wheel up = move screen image up
- Mouse wheel down = move screen image down
- [**Ctrl**] + mouse wheel up = enlarge screen image (zoom in)
- [**Ctrl**] + mouse wheel down = shrink screen image (zoom out)
- [**Shift**] + mouse wheel up = move screen image right
- [**Shift**] + mouse wheel down = move screen image left

By double- clickingthe left mouse button on output sheet elements or **Mini-CAD** objects, the editor for the selected object immediately opens, allowing it to be edited. By double-clicking output sheet elements while holding the [**Shift**] key, the preferences for the position, size and appearance of the element open for editing in the editor.

By double-clicking the left mouse button on output sheet or **Mini-CAD** objects, the editor for the selected object immediately opens, allowing it to be edited.

8.3 Function keys

Some of the function keys are assigned program functions. The allocations are noted after the corresponding menu items. The individual function key allocations are:

- [**Esc**] refreshes the screen contents and sets the screen back to the given format. This is useful, for example, if you have used the zoom function to display parts of the screen and would like to quickly return to a complete overview.
- [**F1**] opens the online-help.
- [**F2**] refreshes the screen without altering the current magnification.
- [**F3**] opens the menu item "**Hvorslev, .../Hvorslev**".
- [**F4**] opens the menu item "**Type curves/Cooper (Ramey/Dougherty/Moench)**".
- [**F5**] opens the menu item "**Type curves/Hand fit**".
- [**F6**] opens the menu item "**Hvorslev, .../Bouwer + Rice**".
- [**F7**] opens the menu item "**Edit/Data range via editor**".
- [**F8**] opens the menu item "**Edit/Auto-display all data**".
- [**F9**] opens the menu item "**Edit/Fit in selected data**".
- [**F11**] opens the menu item "**Type curves/Autofit 1**".
- [**F12**] opens the menu item "**Hvorslev, .../Permeability**" or "**Type curves/Permeability**".

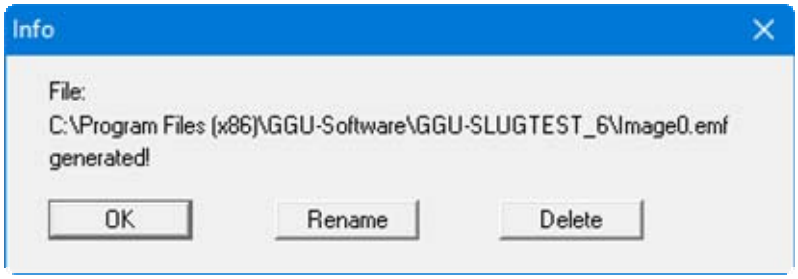
8.4 "Copy/print area" icon

A dialog box opens when the "**Copy/print area**" icon in the menu toolbar is clicked, describing the options available for this function. For example, using this icon it is possible to either copy areas of the screen graphics and paste them into the report, or send them directly to a printer.

In the dialog box, first select where the copied area should be transferred to: "**Clipboard**", "**File**" or "**Printer**". The cursor is displayed as a cross after leaving the dialog box and, keeping the left mouse button pressed, the required area may be enclosed. If the marked area does not suit your requirements, abort the subsequent boxes and restart the function by clicking the icon again.

If "**Clipboard**" was selected, move to the MS Word document (for example) after marking the area and paste the copied graphics using "*Edit/Paste*".

If "**File**" was selected, the following dialog box opens once the area has been defined:



The default location of the file is the folder from which the program is started and, if several files are created, the file is given the file name "**Image0.emf**" with sequential numbering. If the "**Rename**" button in the dialog box is clicked, a file selector box opens and the copied area can be saved under a different name in a user-defined folder. Saving can be aborted by pressing the "**Delete**" button.

If the "**Printer**" button was pressed in the first dialog box, a dialog box for defining the printer settings opens after marking the area. Following this, a dialog box for defining the image output settings opens. After confirming the settings the defined area is output to the selected printer.

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