
SlugIn 1.0

USER MANUAL

SLUG TEST ANALYSIS SOFTWARE

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FOREWORD

SlugIn 1.0, a program to **Interpret Slug** tests, is the answer to the requirement of the Instituto Geológico y Minero de España (IGME) (Spanish Geological Service) for a calculation tool for interpreting permeability tests in boreholes and/or wells available in its databases.

The proper evaluation of the hydraulic parameters of an aquifer is the base that supports its hydrogeologic knowledge, and is imperative to face a large number of aspects concerning to the use and preservation of groundwater quality. Proper pumping schedule for an aquifer, optimal distances between pumping wells, sizing of protection perimeters, characterization of groundwater contaminated areas, evolution of contaminant plumes, etc. are daily tasks for hydrogeological studies that find in the lack of knowledge of aquifer formations hydraulic parameters the main obstacle to obtain reliable results.

Slug tests are a very common technique to evaluate aquifer hydraulic parameters. In this regard, it must be stressed that, while not replacing the representativeness of the results achieved with traditional pumping tests, their proper implementation and interpretation allows obtaining the hydraulic parameters of aquifers in media of all kinds of permeability much faster and cheaper than pumping tests.

It is believed that the developed software is of interest for the group of professionals devoted to hydrogeology and geological engineering and this is the reason why it has been made this publication, following the line of many other edited by the IGME. The software has a user-friendly environment, easy to handle for those hydrogeologists without programming background, and there is a version in Spanish both for interface and the user manual which covers lack of codes of this issue in this language.

With the dissemination of the **SlugIn 1.0** application, IGME aims to provide the group of professionals of the area of hydrogeology and geological engineering with a tool to improve and review information about hydraulic parameters of aquifers, integrating it in the national and provincial databases, which will support hydrogeological survey to obtain a better hydrogeological knowledge of a region.

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1.- INTRODUCTION

Slug tests are a widely used technique for “in situ” estimating of the hydraulic properties of the aquifers. These types of tests are performed by measuring the rise and recovery level in an open borehole or well where an instantaneous change of the piezometric level has been induced.

The present document describes the software application **SlugIn 1.0** developed by the Instituto Geológico y Minero de España to facilitate the analysis of hydraulic tests of this kind.

Slug tests have been traditionally used in geological engineering, hydrogeology and, especially, in petroleum engineering, and from the early eighties of the twentieth century slug tests have become a common technique in hydrogeological studies (Todd and Mays, 2005). This fact is coincident both with the rise of characterization studies of contaminated sites (Kruseman and Raider, 1989; Chirlin, 1990), since in some cases it is not advisable to mobilize large amounts of water, as usually happens in pumping tests, and with the low permeability media surveys for storing of toxic waste (Carrera et al. 1987). Nowadays, these tests are also used to obtain hydraulic parameters during water point inventory, with the aim of obtaining spatially distributed information of these parameters for its later use in flow models. Several authors (Butler, 1997; Fetter, 2001) show that the increase in use of this characterization technique is due to the lower costs and the lesser time required to its implementation, compared to traditional pumping tests.

Among the abundant literature which describes the design, implementation and interpretation of slug tests highlights the guide produced by James J. Butler, Kansas Geological Survey (Butler, 1997). Of this paper should be remarked, among other things, a series of advices to run the slug tests correctly. These recommendations are also presented synthetically in Butler et al. (1996) or in classic hydrogeology handbooks such as Fetter (2001) or Todd and Mays (2005).

In essence, in a slug test a sudden change in groundwater head is caused and it is measured the subsequent recovery from preconditions. That disturbance of head can be accomplished by a) sudden incorporation of a solid body under the groundwater level, normally PVC pipes ballasted or sand-filled; b) injection of compressed air into a well with closed head; c) injection or detracting of a small volume of water in a sealed section of the borehole (Butler, 1997).

In connection with the above, it should be noted that when the test is performed in an isolated section the name of the test is different, so that such tests are called pulse tests (when a small volume of water injected) or pumping test (when detracts).

According to Buttler (1997), a) the use of a solid body for the slug test is recommended when the groundwater level is shallow, in large wells in formations

with hydraulic conductivity of moderate to low and when the well screen is entirely under the level of groundwater; b) injection of compressed air to cause a change in the groundwater level is recommended when the level is deep formations and moderate to high permeability; and c) the use of packers for testing by sections recommended in low permeability media, in fractured aquifers, or when you want to study, by sections, the variability of permeability throughout the survey.

The computer application presented aims to facilitate the work of interpretation of slug tests, but have also been incorporated in the code different formulas that allow the interpretation of injection tests at a constant level. Furthermore, as the most widely used analytical solution to both the pulse and slug tests is the one by Cooper et al. (1967), a number of considerations have been made in the program architecture that allow the interpretation of different pulse or slug tests along a survey.

Therefore, it is intended that the computer application SlugIn 1.0 is a tool that allows the user the following utilities:

- ✓ To organize a specific slug test data base structured and with the following hierarchy: *Project* → *Wells* → *Tests* → *Interpretations*.
- ✓ To ease the technician the interpretation of tests with several methods comparing, graphically, the observed heads and the different analytic solutions obtained by directly modifying the hydraulic parameters values.
- ✓ Automated estimation of hydraulic parameters values that best fit observed heads to analytical solutions for different interpretation methods.

Interpretation methods available for the user in the application are:

Variable head tests

- **Cooper, Bredehoeft and Papadopoulos method**
 - To be used in: totally penetrant wells in confined aquifers.
 - Admits Bower correction (unconfined aquifers).
 - Admits the skin effects correction.
 - Variables to calculate: T and S .
 - **Hvorslev method**
 - To be used in: unconfined and confined aquifers.
 - Admits Bower correction (unconfined aquifers).
 - Admits Chapuis correction.
 - Variables to calculate: k and b (cut-off point with ordinate axis).
 - **Bouwer and Rice method**
 - To be used in: unconfined aquifers, with good results in confined aquifers. Total or partially penetrant boreholes.
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- Admits Bower correction (unconfined aquifers).
- Admits Chapuis correction.
- Variables to calculate: k and b (cut-off point with ordinate axis).
- **Slug tests in materials of high hydraulic conductivity**
 - To be used in: unconfined and confined aquifers.
 - Admits Bower correction (unconfined aquifers).
 - Variables to calculate: k and L_e .

Constant head tests

- Variable to calculate: k .
- **Lefranc**
- **Gilg-Gavard**

Finally, it should be noted that the software incorporates the **Mace test** (1999) to determine the reliability of the results obtained when performing slug tests in large diameter wells.

2.- METODOLOGY

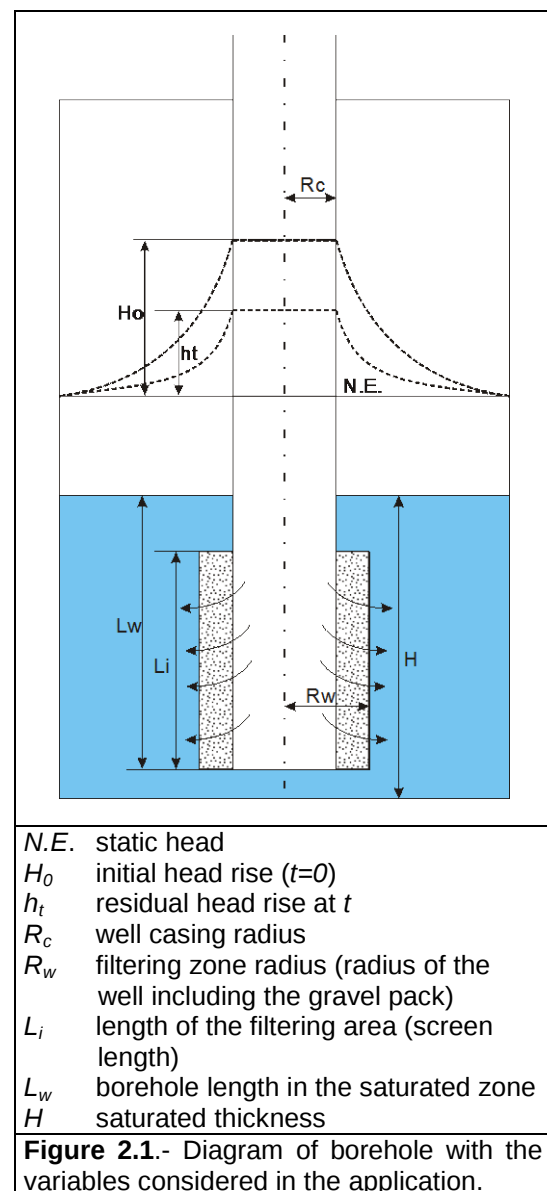
2.1.- VARIABLE HEAD TESTS

As already indicated, variable level test are performed by modifying aquifer static levels instantly afterwards measuring water table head change over time until reaching the static conditions. During the test, it is usually measured, for different time intervals (t), the depth to water table (P_t). The residual head rise (h_t) is the difference between the initial static head (P_0) and the level measured at time t : $h_t = P_0 - P_t$.

Usually all the functions used to interpret variable level tests use a normalized rise (residual head rise), equal to h_t/H_0 , where H_0 is the initial rise for time $t=0$, before starting to recover.

In variable level tests, the software allows to obtain a set of theoretical h_t/H_0 values for the values of hydraulic parameters defined by the user, solving directly with different methods the drawdown function. In this case, the user may interactively calculate, over a graphical representation, which parameters fit better calculated rise to the observed field values. Though, the program also allows the automatic estimate of the hydraulic parameters, solving inversely with different methods the drawdown function. Afterwards, the automatic solution can be modified until a satisfactory one is fixed.

Figure 2.1 shows a scheme of a borehole where all the variables used in the methods included in the application are shown.



2.1.1.- Cooper, Bredehoeft and Papadopoulos method

The aim of using the Cooper et al. (1967) is to obtain two hydraulic parameters: transmissivity (T) and storage coefficient (S).

From the general equation:

$$\frac{h_t}{H_0} = F(\alpha, \beta)$$

where:

h_t , head rise at time t (m)
 H_0 , head rise at time $t=0$ (m)

Function $F(\alpha, \beta)$ has the following expression:

$$F(\alpha, \beta) = \frac{8\alpha}{\pi^2} \int_0^\infty \frac{e^{\left(-\frac{\beta u^2}{\alpha}\right)}}{u \Delta u} du \quad (1)$$

where:

α , integration parameter: $\alpha = \frac{R_w^2 S}{R_c^2}$
 β , integration parameter: $\beta = \frac{T t}{R_c^2}$
 R_c , effective well casing radius (m)
 R_w , effective filtering zone radius (m)
 t , time since the injection or withdrawal (s)
 S , storativity of the aquifer
 T , transmissivity of the aquifer (m^2/s)
 u , integration variable
 Δu , is a complex function: $\Delta u = [uJ_0(u) - 2\alpha J_1(u)]^2 + [uY_0(u) - 2\alpha Y_1(u)]^2$
 J_0, J_1 , Bessel functions of the first kind and zero and first order
 Y_0, Y_1 , Bessel functions of the second kind and zero and first order

Solution in the program

Direct solution of the equation (1) consists in obtaining values $F(\alpha, \beta)$ by introducing α and β values. This solution may be obtained analytically solving that equation.

On the other hand, the inverse solution of the equation (1) is to obtain, given a set of measured h_t vs t values and conditions for the test (R_c , R_w and H_0), the values of the parameters of the function that better fits the distribution. The application calculates these parameters using the gradient method. It allows obtaining

iteratively the value of the parameters that minimize the mean squared error (MSE) between measured and calculated values.

$$FE = \sum_{t=1}^n \sqrt{\left(\frac{h_t}{H_0} - \frac{h_t^*}{H_0} \right)^2}$$

where:

- n , number of measured head values for each time (t)
- h_t , residual head rise observed during the test (m)
- h_t^* , residual head rise calculated by the direct solution (m)

The gradient method is an iterative approach that solves the system of equations resulting from the development, in Taylor series, of the first partial derivative of the function with respect to each of the parameters and equating to zero:

$$\frac{\partial FE}{\partial P_i} = 0$$

In this case, the set of P_i parameters to be estimated are two: transmissivity (T) and the storage coefficient (S). Thus the resulting equation system to be solved in each iteration has the form:

$$\begin{bmatrix} \sum_{t=1}^n \left(\frac{\partial \frac{h_t}{H_0}}{\partial T} \right)^2 & \sum_{t=1}^n \frac{\partial \frac{h_t}{H_0}}{\partial T} \frac{\partial \frac{h_t}{H_0}}{\partial S} \\ \sum_{t=1}^n \frac{\partial \frac{h_t}{H_0}}{\partial S} \frac{\partial \frac{h_t}{H_0}}{\partial T} & \sum_{t=1}^n \left(\frac{\partial \frac{h_t}{H_0}}{\partial S} \right)^2 \end{bmatrix} \begin{bmatrix} \Delta T \\ \Delta S \end{bmatrix} = \begin{bmatrix} \sum_{t=1}^n \frac{\partial \frac{h_t}{H_0}}{\partial T} \left(\frac{h_t}{H_0} - \frac{h_t^*}{H_0} \right)^2 \\ \sum_{t=1}^n \frac{\partial \frac{h_t}{H_0}}{\partial S} \left(\frac{h_t}{H_0} - \frac{h_t^*}{H_0} \right)^2 \end{bmatrix}$$

where:

ΔT and ΔS , increase in transmissivity and storage coefficient to be calculated in each iteration.

As function (1) is not derivable, the partial derivatives are made by numerical methods. Thus, changes in normalized rise produced for small increments in the parameters value ($P_i + 0.01P_i$) are evaluated. The partial derivative can then be approximated to:

$$\frac{\partial \frac{h_t}{H_0}}{\partial P_i} \approx \frac{\frac{h_t}{H_0} - \frac{h_t'}{H_0}}{0.01P_i}$$

where:

h_t/H_0 , normalized rise for P_i

h_t/H_0 , normalized rise calculated $P_i + 0.01P_i$

From a set of initial hydraulic parameters (P_m^0), at the beginning of each iteration k the new value of any parameter i of the set of parameters to optimize is given by:

$$P_i^k = P_i^{k-1} + \Delta P_i$$

As already indicated, the resolution of the h_t/H_0 or $F(\alpha, \beta)$ function can be performed by the program analytically. However, as for the interpretation of field data many iterations may be needed, plus that it has to be solved the derivative to obtain the optimal solution by increments, it has been included in the program the possibility of solving by interpolating between a table of values α vs β previously generated analytically. The limits of the table are α (1E-10 and 8E01) and β (1E-03 and 1E03). This way interpretation and optimization is far faster although somewhat less accurate.

2.1.2.- Hvorslev method (1951)

Hvorslev (1951) solution derives from the general equation:

$$\frac{h_t}{H_0} = \exp\left(\frac{-k t}{\pi R_c^2} F\right) \quad (2)$$

where:

h_t , residual head rise at time t (m)

H_0 , maximum head rise at time $t = 0$ (m)

R_c , effective well casing radius (m)

k , bulk hydraulic conductivity (m/s)

F , shape factor (m)

The most common shape factor expression is that of an ellipsoid of water penetration. It has the following expression:

$$F = \frac{2\pi L_i}{\ln \frac{L_i}{R_w}}$$

By substituting in (2), Hvorslev equation results,

$$\frac{h_t}{H_0} = \exp\left(\frac{-2k L_i t}{R_c^2 \ln \left(\frac{L_i}{R_w^2}\right)}\right)$$

where:

R_w , filtering zone radius (m)
 L_i , screen length (m)

The empirical formula described is developed for ideal conditions of the permeability test, and among others, it is supposed a spherical shape for the injection. Nevertheless, neither the filter is cylindrical, nor permeability is isotropic, etc. Thus, several factors have been developed, called shape factors (F) that formulate the geometry of the area of penetration in the formation.

Generally, the input flow Q_t to the aquifer for a time t can be expressed as (Chapuis, 1989):

$$Q_t = F k h_t \quad (3)$$

where:

Q_t , flow into the aquifer at time t (m³/s)
 k , hydraulic conductivity (m/s)
 F , shape factor (m)
 h_t , hydraulic head at time t (m)

In the case of a test that varies h , a time interval between t_1 and t_2 , $Q_t=S(dh/dt)$, change in h can be written as the integral of the equation (3):

$$Ln\left(\frac{h_1}{h_2}\right) = -C k (t_1 - t_2)$$

where:

C , is equal to $C=F/S$ (m⁻²)
 S , section of the well (m²)

There are many empirical formulas for defining the shape factor dependent of aquifer conditions and borehole tested.

Depending on the test conditions, for applying the Hvorslev method, often the following expressions for the shape factors (**Table 1**) are used.

Table 1.- Shape factors for Hvorslev method. H , aquifer saturated thickness and L_w borehole length in the saturated zone.

No.	Observation	L_i	L_w/H	k_v/k_h	Analytical expression
1	- Isotropic - Recharge from the bottom of the well - Well bottom over the water table	0	0	1	$F = 4 R_w$
2	- Isotropic - Recharge from the bottom of the well - Well bottom in the saturated zone - Partially penetrant	0	<1	1	$F = 5.5 R_w$
3	- Isotropic - Large-diameter wells - Recharge with spherical shape (Schneebeli, 1954) - Partially penetrant	< $8R_w$	<1	1	$F = 4\pi R_w \sqrt{\frac{L_i}{2R_w} + 0.25} \quad (2)$
4 ⁽¹⁾	- Isotropic - Small-diameter wells - Recharge with ellipsoidal shape - Partially penetrant	> $8R_w$	<1	1	$F = \frac{2\pi L_i}{Ln \frac{L_i}{R_w}}$
5 ⁽¹⁾	- Anisotropic $m = \sqrt{k_h / k_v}$ - Small-diameter wells - Recharge with ellipsoidal shape - Partially penetrant	> $8R_w$	<1	$\neq 1$	$F = \frac{2\pi L_i}{Ln \left[\frac{m L_i}{2R_w} + \sqrt{1 + \left(\frac{m L_i}{2R_w} \right)^2} \right]}$
6 ⁽¹⁾	- Anisotropic $m = \sqrt{k_h / k_v}$ - Small-diameter wells - Recharge with semi-ellipsoidal shape - Totally penetrant	> $8R_w$	=1	$\neq 1$	$F = \frac{2\pi L_i}{Ln \left[\frac{m L_i}{R_w} + \sqrt{1 + \left(\frac{m L_i}{R_w} \right)^2} \right]}$

(1) These expressions admit the Chapuis when the have bottom plug: $F_c = F - 5.5 R_w$. Shape factors 5 and 6 are also applied usually in isotropic materials, with $m=1$ in the expression. Between 5 and 6 expressions, 5 is the one usually applied.

(2) In Chapuis (1989) it appears 2π rather than $4\pi R_w$. It seems to be an erratum in Chapuis (Mace, 1999; Sánchez, 2011).

Solution in the program

As for the previous method, the program allows the user to obtain the direct solution for expression (2) so that k can be interactively estimated by comparing calculated versus measured values in the graphical representation.

Automatic estimation for k is obtained in the application from a series of field h_t vs t values and for the test conditions (R_c , R_w , L_i and H_0). The algorithm is outlined below.

Expression (2) may be arranged as:

$$\frac{h_t}{H_0} = e^{-\alpha t} \quad (4)$$

Where:

$$\alpha = \frac{k F}{\pi R_c^2}$$

α can be calculated from field data by fitting a minimum square function to the graph $y = \ln(h_t/H_0)$ vs t . Theoretically, this straight line should cross the origin of coordinates ($\ln(1)$) but, usually, the best fit line intersects the vertical axis at some nonzero point (b). Thus the line usually takes the shape: $y = -\alpha t + b$, and so, two parameters α , and b have to be adjusted.

Least square line is calculated by the classical expressions:

$$-\alpha = \frac{N \sum XY - \sum X \sum Y}{N \sum X^2 - (\sum X)^2}$$

$$b = \frac{\sum Y + \alpha \sum X}{N}$$

With the correlation coefficient:

$$R = \frac{\sum XY - \sum X \sum Y}{\sqrt{[N(\sum X)^2 - \sum X^2][N \sum Y^2 - (\sum Y)^2]}}$$

Once α is calculated, k value is obtained as:

$$k = \frac{\alpha \pi R_c^2}{F}$$

2.1.3.- Bouwer and Rice method

Bower and Rice (1976) formula for obtaining normalized rise is similar to that of the Hvorslev method:

$$\frac{h_t}{H_0} = \exp \frac{-k t}{\pi R_c^2} F$$

But, in this case the shape factor is defined as:

$$F = \frac{2\pi L_i}{Ln \left[\frac{R_i}{R_w} \right]}$$

where:

- R_i , influence radius for the borehole (m). It cannot be estimated
- R_w , radius of the filtering zone (m)
- L_i , length of the filtering area (screen length) (m)

The term $Ln(R_i/R_w)$ can be estimated by means of the following empirical formula:

- Totally penetrant borehole ($L_w=H$): $Ln \frac{R_i}{R_w} = \frac{1}{\frac{1.1}{Ln \frac{L_w}{R_w}} + \frac{C}{\frac{L_i}{R_w}}}$
- Partially penetrant borehole ($L_w < H$): $Ln \frac{R_i}{R_w} = \frac{1}{\frac{1.1}{Ln \frac{L_w}{R_w}} + \frac{A + B Ln \frac{H - L_w}{R_w}}{\frac{L_i}{R_w}}}$

where:

- L_w , water table head from the lower limit of the filter (m)
- H , saturated unconfined aquifer thickness (m)

In these expressions A , B and C are dimensionless parameters that could be obtained by the following analytical expressions:

If $x < 2.554422663$

$$A = 1.638445671 + 0.166908063 x + 0.000740459 \text{Exp}(6.17105281 x - 1.054747686 x^2)$$

If $x \geq 2.554422663$

$$A = 11.00393028 - 170.7752217 \text{Exp}(-1.509639982 x)$$

If $x < 2.596774459$

$$B = 0.174811819 + 0.060059188 x + 0.007965502 \text{Exp}(2.053376868 x - 0.007790328 x^2)$$

If $x \geq 2.596774459$

$$B = 4.133124586 - 93.06136936 \text{Exp}(-1.435370997 x)$$

If $x < 2.200426117$

$$C = 0.074711376 + 1.083958569 x + 0.00557352 \text{Exp}(2.929493814 x - 0.001028433 x^2)$$

If $x \geq 2.200426117$

$$C = 15.66887372 - 178.4329289 \text{Exp}(-1.322779744 x)$$

where $x = \log(L_i/R_w)$.

Solution in the program

For the hydraulic parameters, the application uses the same procedure described when the Hvorslev method is applied. So, it is obtained the coefficients of the line that best fits the distribution $\ln(h_t/H_0)$ vs t .

2.1.4.- Slug tests in materials of high hydraulic conductivity

In slug tests performed in materials of high conductivity, after the initial rise, until the recovery of the initial conditions, a phenomenon of oscillatory damping occurs. This phenomenon can be expressed by the following formula (Kreysing, 1979):

$$\text{If } C_D < 2 \quad \frac{h_t}{H_0} = \exp\left(-\frac{C_D}{2} t_d\right) \left[\cos(\omega_d t_d) + \frac{C_D}{2\omega_d} \sin(\omega_d t_d) \right] \quad (1)$$

$$\text{If } C_D = 2 \quad \frac{h_t}{H_0} = \exp(-t_d) (1 + t_d) \quad (2)$$

$$\text{If } C_D > 2 \quad \frac{h_t}{H_0} = \frac{1}{\beta_1 - \beta_2} [\beta_1 \exp(\beta_2 t_d) - \beta_2 \exp(\beta_1 t_d)] \quad (3)$$

where:

h_t , residual head rise at time t (m)
 H_0 , initial (maximum) head rise at time $t = 0$ (m)

t_d , normalized time (dimensionless): $t_d = t \sqrt{\frac{g}{L_e}}$

g , acceleration of gravity (m/s^2)
 L_e , effective length of water column

ω_d , frequency parameter $\omega_d = \sqrt{1 - \left(\frac{C_D}{2}\right)^2}$

β_1, β_2 , parameters: $\beta_1 = -\frac{C_D}{2} - \omega_d$, $\beta_2 = -\frac{C_D}{2} + \omega_d$

Depending on the type of the aquifer tested, C_D has the following expressions:

a) For unconfined aquifers (Bouwer and Rice method):

$$C_D = \sqrt{\frac{g}{L_e}} \frac{R_c^2 \ln \frac{R_i}{R_w}}{2 L_i k}; k = \sqrt{\frac{g}{L_e}} \frac{R_c^2 \ln \frac{R_i}{R_w}}{2 L_i C_D} \quad (4)$$

b) For confined aquifers (Hvorslev):

$$C_D = \sqrt{\frac{g}{L_e}} \frac{R_c^2 \ln \left[\frac{L_i}{2 R_w} + \sqrt{1 + \left(\frac{L_i}{2 R_w} \right)^2} \right]}{2 L_i k}; k = \sqrt{\frac{g}{L_e}} \frac{R_c^2 \ln \left[\frac{L_i}{2 R_w} + \sqrt{1 + \left(\frac{L_i}{2 R_w} \right)^2} \right]}{2 L_i C_D} \quad (5)$$

where:

- k , hydraulic conductivity (m/s)
- R_c , well casing radius (m)
- R_w , filtering zone radius (m). In anisotropic aquifers should be replaced by $R_w \sqrt{k_v / k_h}$ (Zlonik, 1994). In confined aquifers with the screen on the aquifer should be replaced by $2 R_w$
- R_i , influence radius for the borehole (m). It cannot be estimated.
- L_i , length of the filtering area (screen length) (m)

To estimate $\ln(R/R_w)$ expressions specified in the method Bouwer and Rice may be used.

Solution in the Program

As in the methods described above, the application allows the user to obtain a direct solution of the equation (2), so that you can estimate k interactively on the graph by comparing between calculated and measured values. In this case, besides the test features (R_c , R_w , R_i , L_i) two hydraulic parameters must be provided, hydraulic conductivity (k) and effective length of water column (L_e).

Automatic estimate of parameters k and L_e , from test design and from field values h_t vs t , is performed iteratively by applying the gradient procedure, already described in the method of Cooper, Bredehoeft and Papadopoulos.

2.2.- CONSTANT HEAD TESTS

Constant level tests introduce a constant flow rate that keeps a constant head h in the borehole over the static groundwater level. The interpretation of the test is to calculate the hydraulic conductivity (k) from the test conditions and the input flow by applying different analytical formulas. The methods of interpretation included in the application are described below.

2.2.1.- Lefranc test

The pressure head reached in a borehole in which a constant flow is injected, once stabilized, is given by the following expression:

$$h = \frac{Q}{F k}$$

where:

- Q , injected flow (m^3/s)
- h , hydraulic overload: head in the borehole, above the static level (m)
- k , hydraulic conductivity (m/s)
- F , shape factor (ellipsoid) $F = \frac{2\pi L_i}{\ln \frac{L_i}{R_w}}$
- R_w , filtering zone radius (m)
- L_i , filtering zone length (m)

From the test conditions and the injected flow to stabilize level, the application directly obtains the hydraulic conductivity.

2.2.2.- Gilg-Gavard test

It is similar to the Lefranc test, but another shape factor is applied. The expression is:

$$h = \frac{Q}{F k}$$

where:

- Q , injected flow (m^3/s)
- h , hydraulic overload: head in the borehole, above the static level (m)
- k , hydraulic conductivity (m/s)
- L_i , filtering zone length (m)
- R_w , filtering zone radius (m)
- F , shape factor:
 - if $L_i > 6$, $F = 1.032 L_i + 60 R_w$
 - if $L_i \leq 6$, $F = (1.032 L_i + 60 R_w) (-0.014 L_i^2 + 0.178 L_i + 0.481)$

2.3.- CORRECTIONS AND VALIDATION OF METHODS

2.3.1.- Bouwer correction

Bouwer (1989) correction is applied when heads during the test are oscillating in the well screen. It is almost a must for unconfined aquifers where there is screen in the whole length of the aquifer. This correction applies to the filtering zone radius (casing radius):

$$R_{CA} = \sqrt{(1-\eta) R_C^2 + \eta R_W^2}$$

where:

- R_{CA} , effective casing radius (m)
- η , gravel pack porosity
- R_C , casing radius (m)
- R_W , filtering zone radius (m)

This correction may be applied for variable head methods:

- Cooper, Bredehoeft and Papadapulos
- Hvorslev
- Bouwer and Rice
- High conductivity aquifers

2.3.2.- Chapuis correction

This is a correction to the shape factor. It is to be used for tests in boreholes with bottom plugs. The correction consist of subtracting the value of a shape factor when discharge occurs only in the bottom to the shape factor used (F):

$$F_c = F - 5.5 R_W$$

where:

- F , shape factor
- F_c , corrected shape factor (m)
- R_W , filtering zone radius (m)

This correction may be applied for all the methods that use shape factor:

- Hvorslev
 - Bouwer and Rice
 - Lefranc
 - Gilg-Gavard
-

2.3.3.- Anisotropic aquifers

This correction is to be applied when horizontal conductivity is quite different from the vertical conductivity.

It is implicit in the shape factors indicated for the Hvorslev method (shape factors nº 4, 5 and 6 in **Table 1**), but it also has to be applied for high permeability materials (Zlonik, 1994):

$$R_{WA} = R_w \sqrt{k_v / k_h}$$

where:

- R_{WC} , corrected filtering zone radius (m)
- R_w , filtering zone radius (m)
- k_v , vertical hydraulic conductivity (m/s)
- k_h , horizontal hydraulic conductivity (m/s)

2.3.4.- Skin effect

This effect derives from the anomaly created by different hydraulic conductivities between the rock in the vicinity of the well and the rest of the aquifer formation. This difference, that can be an increase or a decrease, can be due to several causes such as development, clogging, etc. Skin effect is defined by:

$$\sigma = \left(\frac{k_F}{k_S} - 1 \right) L_n \frac{R_{eW}}{R_w}$$

where:

- R_{eW} , filtering zone radius, included the skin (m)
- K_F , formation hydraulic conductivity (m/s)
- K_S , skin hydraulic conductivity (m/s)

If $k_F > k_S$ skin effect (σ) is positive; if $k_F < k_S$ skin effect is negative.

According to Ramey et al. (1975), if the value R_w is replaced in expression (1) by the effective radius $R_{eW} = R_w e^{-\sigma}$, the set of curves $F(\alpha, \beta)$ has the identical shape to those proposed by Cooper et al (1967). Once adjusted, T and S could be calculated if R_{eW} , or σ are known.

The challenge in slug tests is that it is not usual to know σ , and so the interpretation of k or S is ambiguous since the theoretical solution for drawdowns is quite similar considering or not the skin effect. For example, in **Figure 2.2**, which shows the theoretical values of change of h/H_0 with time obtained with the Cooper, Bredehoeft and Papadopoulos method for an skin effect $\sigma = -3$ and without it ($\sigma = 0$), the same variations are obtained; by considering a storage coefficient $S = 5 \times 10^{-4}$ and the skin effect or a value of $S = 1.9 \times 10^{-1}$ without it.

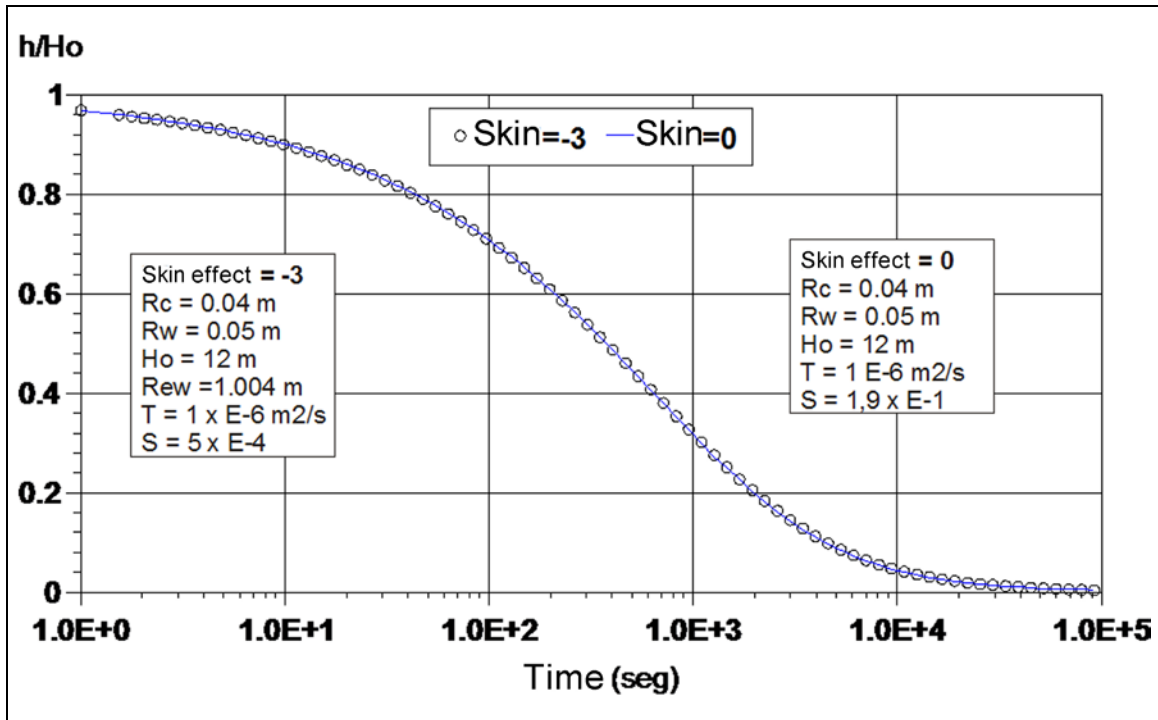


Figure 2.2.- Theoretical change of h/H_0 vs time obtained with Cooper et al. method, for an skin effect $\sigma=-3$ and without skin effect ($\sigma=0$). Both cases show identical results but the first one with $S=5 \times 10^{-4}$ and the second one with $S=1.9 \times 10^{-1}$.

Skin effect has been implemented in **SlugIn 1.0** as the other corrections of the test parameters (i.e. anisotropy or Chapuis). The user may introduce skin effect or may not, to obtain either the analytic solution or the automatic interpretation. Afterwards, it can be interactively modified until an optimal solution is obtained.

The skin effect is included by modifying the radius of the filtering area according to the following expression: $R_{ew}=R_w e^{-\sigma}$. As far as R_w is used for all the interpretation methods in the application, the skin effect can also be included in any of them.

2.3.5.- Validation for large diameter wells

Based on several experiments on large diameter wells, in 1999 Mace developed a test to find the reliability of the results obtained when using slug test in large diameter wells, usually hand built.

The test proposed by Mace is based on defining sectors of greater or lesser reliability of results in diagrams of distribution of shape factor vs length of the filter zone values. The three shape factors used are:

- a) Recharge with ellipsoidal shape (Dachler, 1936 and Hvorslev, 1951), corresponds to No. 4 in **Table 1**:

$$F_a = \frac{2\pi L_i}{\ln \frac{L_i}{R_w}}$$

- b) Recharge with semiellipsoidal shape (Dachler, 1936 and Hvorslev, 1951), similar to No. 6 **Table 1**:

$$F_b = \frac{2\pi L_i}{\ln \left[\frac{L_i}{R_w} + \sqrt{1 + \left(\frac{L_i}{R_w} \right)^2} \right]}$$

This expression is controversial in bibliography. Some publications include $2R_w$ instead of R_w . In the application R_w will be used because it appears this way in the original Mace paper of 1999 in the diagrams to define sectors of reliability.

- c) Recharge with spherical shape (Chapuis, 1989) corresponds to No. 3 in **Table 1**:

$$F_c = 4\pi R_w \sqrt{\frac{L_i}{2R_w} + 0.25}$$

The graphical representations of these factors as a function of L_i and the delimitation of reliability are shown in **Figure 2.3**. These figures were elaborated by Mace empirically applying the Hvorslev method. For the three shape factors used, the sectors are delimited where permeability can be determined with good, medium or poor precision. Sectors have been delimited according to the ratio L_i/R_w . Therefore, depending on the chosen form factor and L_i , the accuracy of the interpretation can be known.

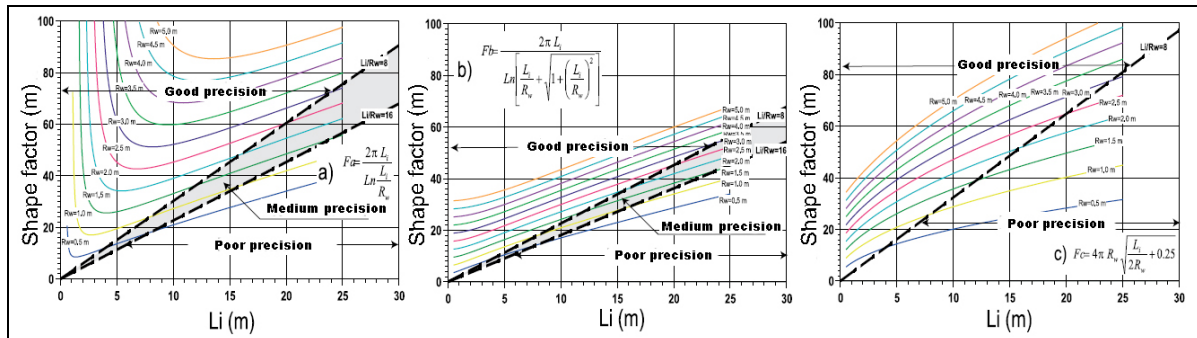


Figure 2.3.- Shape factors vs L_i and delimitation of areas with different expected precisions for the calculation of hydraulic conductivity.

The lines that limit the sectors of better to worse precision have the following expressions:

Shape factor a):	for $L_i/R_w=8$	$F_a = 3.022 L_i$
	for $L_i/R_w=16$	$F_a = 2.266 L_i$
Shape factor b):	for $L_i/R_w=8$	$F_b = 2.263 L_i$
	for $L_i/R_w=16$	$F_b = 1.812 L_i$
Shape factor c):	for $L_i/R_w=8$	$F_c = 3.238 L_i$

The procedure that follows the application to know in which sector would be located the slug test according to the properties of the large diameter well (L_i and R_w) is to calculate in which sector of the diagrams (**Figure 2.3**) is located for each shape factor. This way, the user obtains degrees of precision for the three shape factors by applying the Hvorslev method. The user will choose the most accurate. The location of the point in the diagram is obtained by applying the distance equation of a point to a line passing through the origin:

$$d(A,D) = \frac{a X_A - Y_A}{\sqrt{a^2 + 1}}$$

where:

- $d(A,D)$, distance from point A to line D
- a, slope of the line
- X_A , coordinate X of point A
- Y_A , coordinate Y of point A

If $d(A,D)$ is positive it lies below the line and if negative it lies above. For example, if the well has $L_i=10$ m and $R_w=1.5$ m, the shape factor takes the value of a) 33.1 m, b) 24.2 and c) 35.7. With these values:

Shape factor a):	for $L_i/R_w=8$	$d(A,D)= -0.9$ (negative)
	for $L_i/R_w=16$	$d(A,D)= -4.2$ (negative)
Shape factor b):	for $L_i/R_w=8$	$d(A,D)= -0.6$ (negative)
	for $L_i/R_w=16$	$d(A,D)= -2.9$ (negative)
Shape factor c):	for $L_i/R_w=8$	$d(A,D)= -0.9$ (negative)

In this case, both for the shape factor a) and b) are within the sector of low precision in the estimation, but the shape factor c) is located in the sector of good precision. So the shape factor to use would be c) that simulates a spherical recharge.

In the case of shape factors a) and b) the greater the distance to the line $L_i/R_w = 8$ the greater the precision, but in the case of the shape factor c) the smaller the distance the greater the precision. In this sense, the application indicates the accuracy of the factors and which one provides more precision.

However, it should be noted that there are other limitations that affect the reliability of slug tests in large diameter wells, some of which are noted in the aforementioned Mace (1999) publication. Among other circumstances, it may be noted that the hydraulic conductivity should not be high or that the speed at which filling or depleting occurs should be fast, in large diameter wells the capacity effect can greatly slow down the depleting.

3.- REQUIREMENTS AND INSTALLATION

To install and use the program the following minimum requirements must be met:

- ✓ RAM 512 Mb
- ✓ Monitor with resolution 1024x768 pixels
- ✓ Operating System Windows XP or higher
- ✓ 100 MB available in the hard disk driver
- ✓ .NET framework 4.0 (provided with the application software and available at the Microsoft download page).

As an additional requirement, for some import functionalities, Microsoft Excel and Word must be installed for report writing.

The installation program, as well as the application, are available in Spanish and English and include the following files:

- ✓ **Setup_SlugIn.exe**: Executable file with the installation of **SlugIn 1.0**.
- ✓ **ReadMe.txt** and **ReadMe_eng.txt**: text files (in both languages) with information about the installation, system requirements and/or facts to be considered.
- ✓ **Only if necessary**: folder with the installation files of the .NET Framework 4.0, only if it is not already installed in the system (the Setup program sends a warning message when not found).

The application is supplied in CD together with the aforementioned programs, including the files needed for installing, the example files and the documentation.

To install, execute the file Setup_SlugIn.exe from Windows, and select the installation language. Afterwards it will display the install wizard window (**Figure 3.1**).

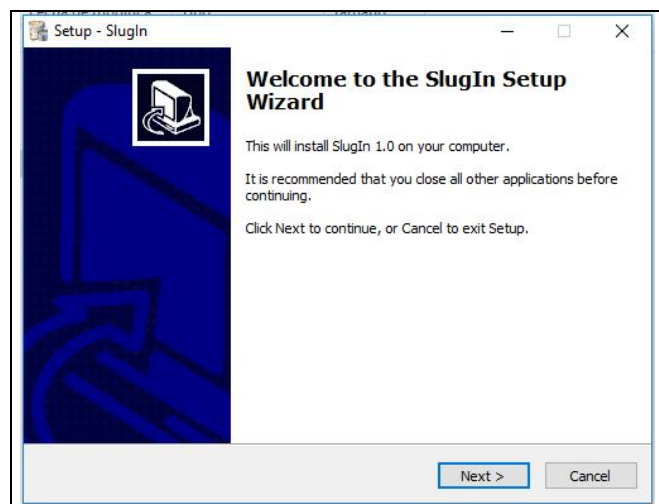


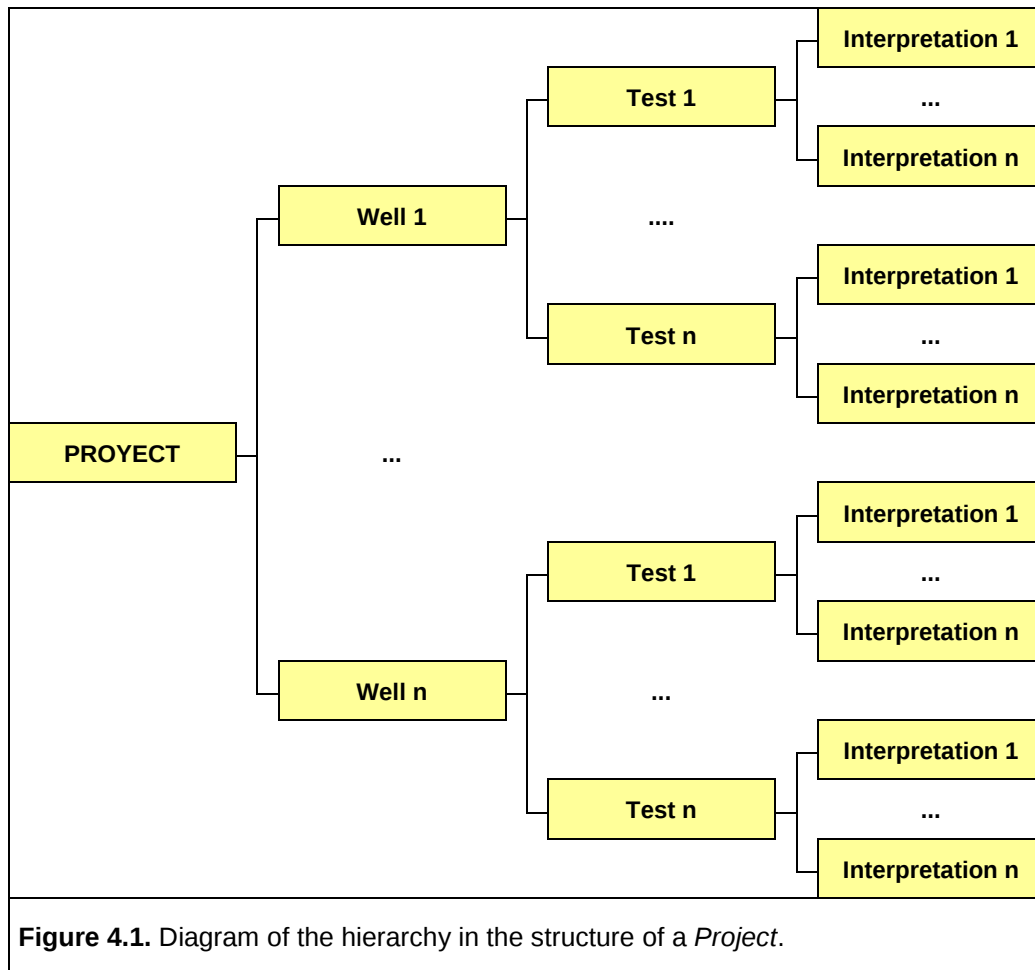
Figure 3.1.- Installation wizard.

Select *Next* button and accept or change the options provided by the successive forms, such as the installation folder, or the shortcut icon either at the *Windows desktop* or the *Quick Start Bar*. Following, the confirmation is requested to start the installation. Finally, when the installation is successfully completed the user is reported and prompted to execute **SlugIn1.0**. If confirmed, the application starts as described in the next chapter.

4.- DESCRIPTION OF THE APLICATION

The design of **SlugIn 1.0** is intended to be user friendly, leading the user through intuitive menus, buttons and forms, so that the introduction of the permeability tests data, as well as the interpretation and visualization are done swiftly and clearly.

The information is organized in projects saved as structured files (xml) that can be displayed, if wanted, with any text editor. A **Project**, besides its own descriptive data, admits the data of one or several wells, each one having one or more tests, which, in turn, may be subject to one or more interpretations. The diagram in **Figure 4.1.** clarifies better the hierarchy described.



4.1.- MAIN WINDOW

SlugIn1.0 starts with the main window of the application and the blank form of a **New Project** (Figure 4.2). This form is structured around a central section where the different sub forms appear for the respective hierarchy elements, namely: **Project**, **Well**, **Test** and **Interpretation**, as well as one form for test measurements and five tool bars with different utilities.

At the window top, the following bars appear: **title bar** containing the application logo, the name of the current **Project** and the usual buttons for window management. Below the title, the **Menu bar** appears, enabling access to all the application functions, together with the **Toolbar**, with some of the functions to be used more frequently. At the main window bottom, the **Status bar** shows the information regarding the current **Project**, and, finally, at the left margin, the **Legend bar** (or navigation bar) displays the different elements of the **Project**.

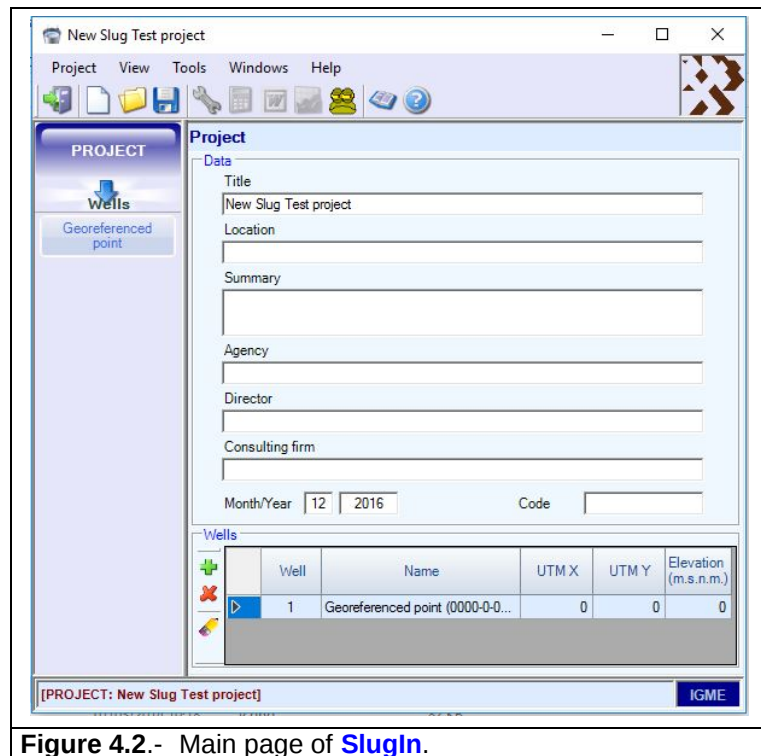


Figure 4.2.- Main page of **SlugIn**.

It is not worth to go into details about the title and status bar, but this manual will focus on explaining those toolbars that allow carrying out the functions of the application to navigate within the different elements. Subsequently, other available forms and sub forms will be described.

Menu bar and tool bar

A joint description is made because in fact the tool bar is a selection of the most commonly used functions accessible from the menu bar.

The menu bar contains five submenus:

- ✓ *Project*, provides functions for project management, configuration, reporting and quitting the application, as well as a list of the most recent projects.
- ✓ *View*, to display or not the legend bar and select its appearance.
- ✓ *Tools*, for selecting the application language (Spanish or English) and for test interpretation.
- ✓ *Windows*, to display the other forms available in the application (map and graph).
- ✓ *Help*, with the user manual and the description of the application.

Figure 4.3 shows some screen captures with these submenus.

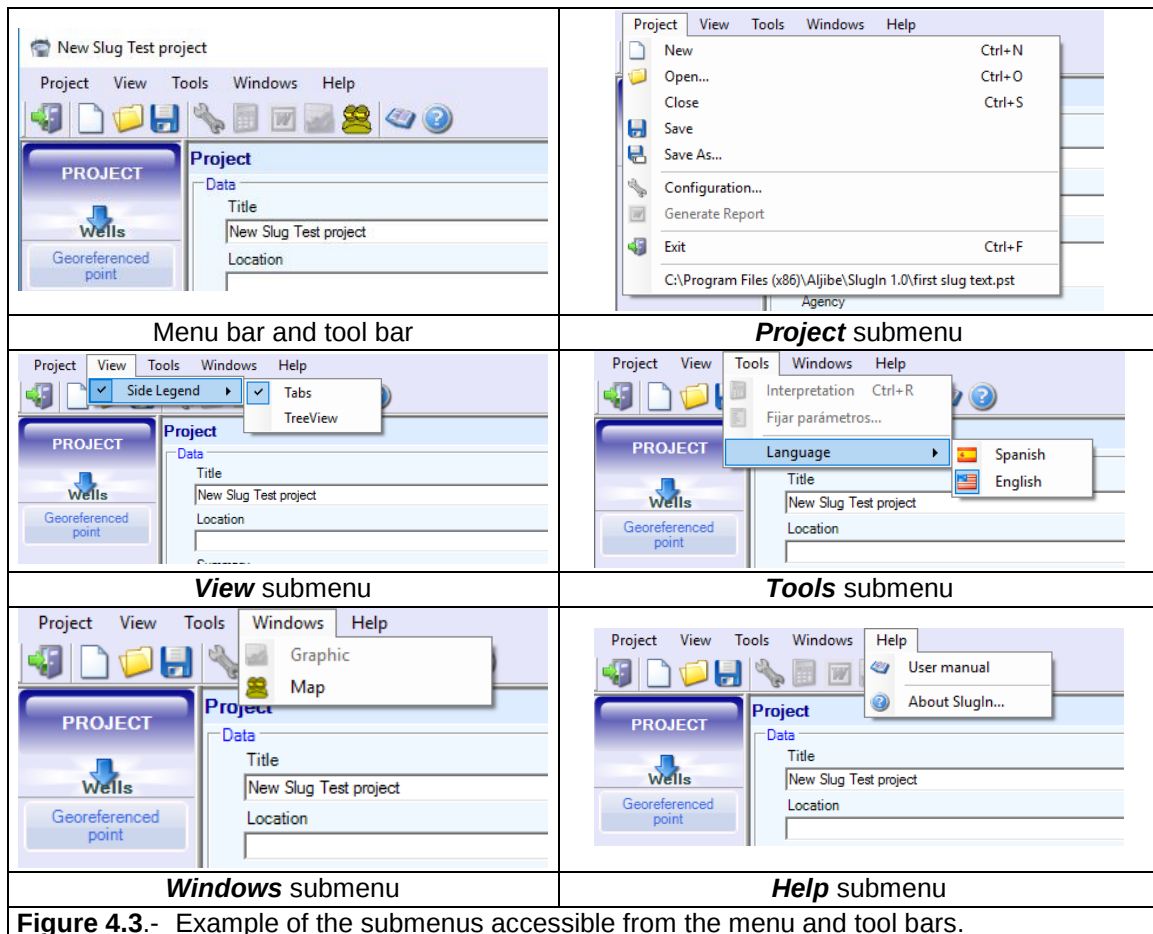


Figure 4.3.- Example of the submenus accessible from the menu and tool bars.

Legend or navigation bar

It is the sidebar at the middle-right side of the window. It enables navigating through the different elements of the application that appear as subforms with data at the window center.

They can appear in any of two formats, as tabs (by default), that enable a sequence access through the hierarchy of elements, or as a tree-view, that allows direct access to the element intended to activate.

Figure 4.4. shows both formats. The legend width can be resized by moving the split bar at the right edge. When moving it, the form width resets so that all the data continues displayed.

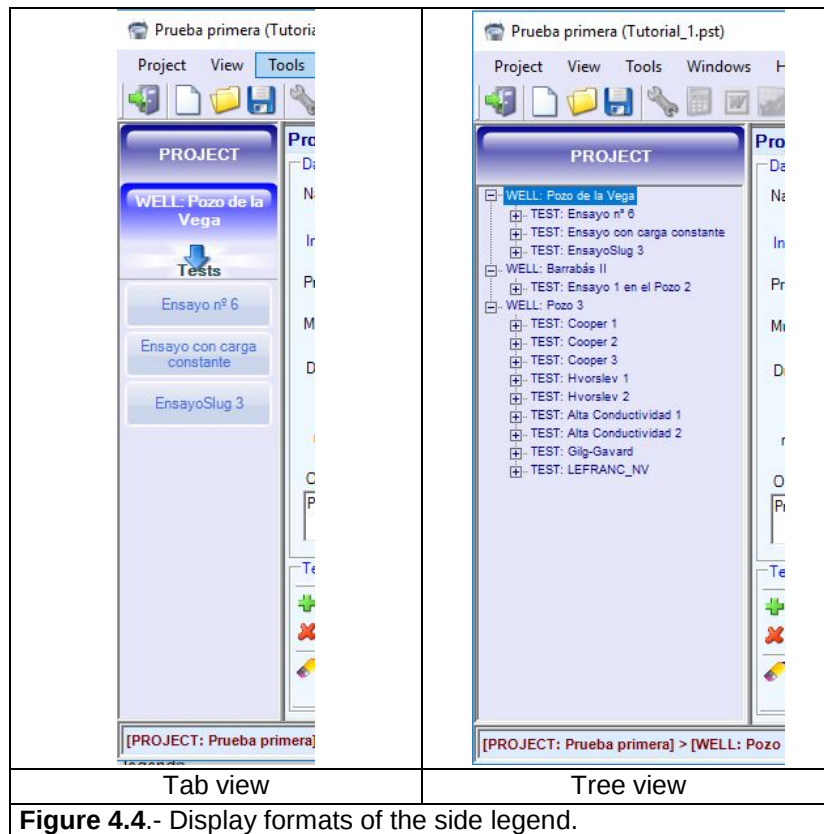


Figure 4.4.- Display formats of the side legend.

4.2.- SUBFORMS

There are five subforms available in the central window of **SlugIn1.0**, those corresponding to the four different elements and, also, the test measures:

- ✓ *Project*
- ✓ *Well*
- ✓ *Test*
- ✓ *Test measurements*
- ✓ *Interpretation*

The screenshot shows the 'Project' subform with the following data:

Well	Name	UTM X	UTM Y	Elevation (m.s.n.m.)
1	Pozo de la Vega (1009-7-1111)	439000	4117000	100
2	Barrabás II (1009-6-0038)	435000	4121000	250
3	Pozo 3 (9999-9-9003)	433000	4118000	0

Figure 4.5.- Project data.

As the buttons of the side legend are pressed, the subform of the selected element is displayed along with its data.

In the case of selecting **Project**, the descriptive data is displayed together with the list of the wells, as a table at the bottom (**Figure 4.5.**). At the side legend, a button appears for each well. When clicking on any of them (or double clicking at the table row) the well form appears.

The buttons at the left side are intended to add or delete new wells, and to display the form of the selected well.

All the subforms look similar. In the case of the **Well** form, some descriptive data of the well are displayed, together with a list (formatted as a table) of the tests performed in the well (**Figure 4.6**).

It must be noted that, both for this window and the **Project** window, the button **Map**, highlighted in the next figure, is enabled. This button allows displaying the location of the **Project** wells in a georeferenced context (**Figure 4.7**).

Project > Well

Name: Pozo de la Vega Place: Vega de Granada

Inventory number: 1009 | 7 | 1111

Coordinates and Elevation: X: 439000 Y: 4117000 Z: 30

Province: Geogr.: 34°11'14" W 37°11'49" N

Elevation: 100 m.s.n.m.

Municipality: Drilling method: Rotary Depth: 25 m.

Diameter (mm): min. 343 max. 343 Tubing (mm): min. 167 max. 167 Engravillado: ☐

Observations: ☒ Pozo terminado

Prueba del programa

Test	Name	Date	From (m)	To (m)
1	Ensayo nº 6	13/02/2014	0	25
2	Ensayo con carga constante	25/02/2014	0	0
3	Ensayo Slug 3	25/02/2014	0	0

[PROJECT: Prueba primera] > [WELL: Pozo de la Vega] IGME

Figure 4.6.- Well data.

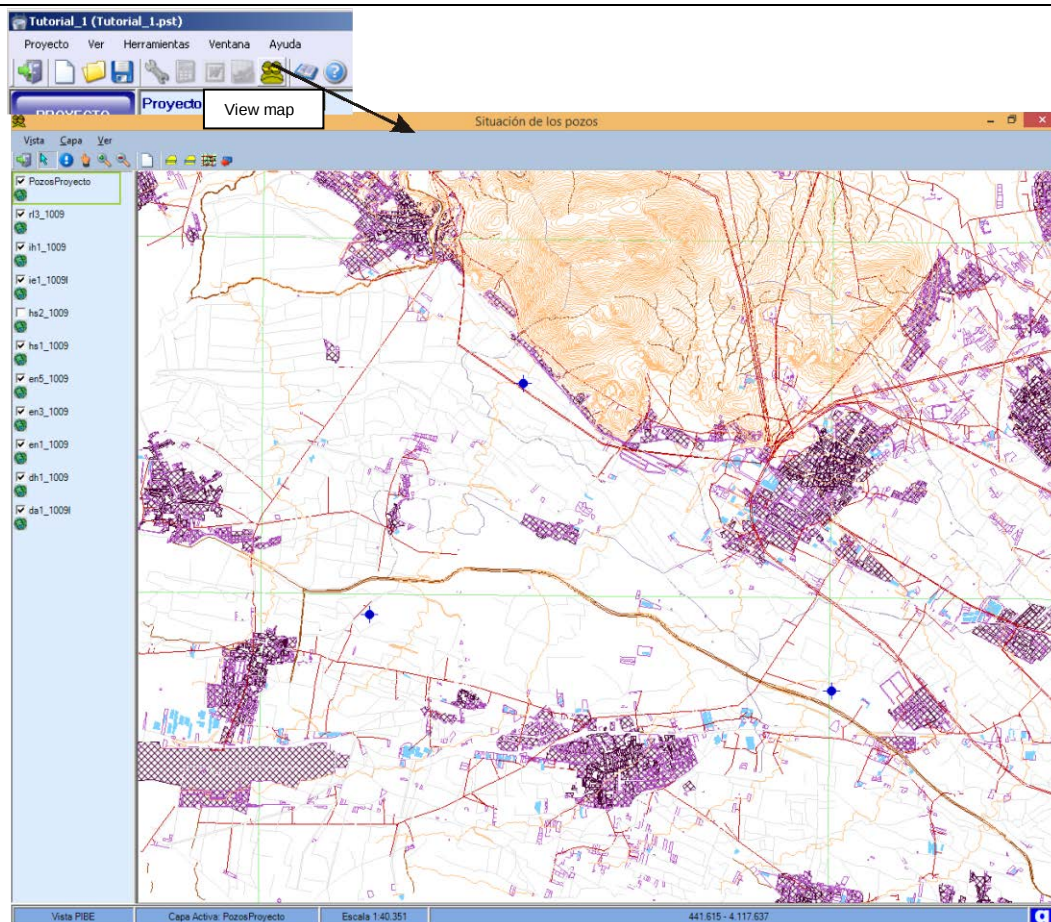


Figure 4.7.- Georeferenced view of the wells in the Project.

When double-clicking over one of the table rows, or when pushing one of the sidebar buttons, the subforms of the selected test will appear (**Figure 4.8.**). This window displays the data of a permeability test with the parameters needed in the available interpretation methods. The tests can be selected as either variable head or constant head; being advisable to follow the protocol indicated in the chapter on methodology to make the choice. The variable head test involves measurements during the test until the stabilization of the water level at the well being tested. This stabilization happens sooner or later, depending on the terrain permeability. On the contrary, the constant head tests are solved independently of time, only considering the flow rate that allows for the stabilization of the water head level.

Figure 4.8.- Test data.

In the case of variable head tests, the measurements are entered through a form that opens when clicking the tab at the upper right corner: **Test data** (**Figure 4.9.**). This subform has a menu to edit, cut, copy and paste data rows. With the **Tools**, these data can be brought to MS Excel in order to edit them and bring them back to the application. The data are displayed as a table with five columns:

Yes/No, to choose whether this datum is used or not in the computing.

Time, the second in which the data was taken, measured from the test outset.

Water depth, water level in the well.

Yes/No	Time (sec)	Water depth (m)	Drawdown (m)	Comments
✓	0	4.64	1.44	
✓	2	4.825	1.255	
✓	4	4.864	1.216	
✓	6	4.91	1.17	
✓	8	4.952	1.128	
✓	10	4.995	1.085	
✓	12	5.035	1.045	
✓	14	5.068	1.012	
✓	16	5.1	0.98	
✓	18	5.131	0.949	
✓	20	5.161	0.919	
✓	22	5.189	0.891	
✓	24	5.217	0.863	
✓	26	5.242	0.838	
✓	28	5.269	0.811	
✓	30	5.293	0.787	
✓	32	5.317	0.763	
✓	34	5.34	0.74	

Figure 4.9.- Table with the data of water level evolution during the Test

Drawdown, difference between the average depth and the depth before the test
Observations, possible comments about the measured data.

The window with the data of an interpretation (several can be made in the same test) looks differently according to the method selected (**Figure 4.10**). Some methods, such as that of Cooper-Bredehoeft-Papadopoulos, use transmissivity (T) and the storage coefficient (S). The button with a lock image serves to fix the parameter during the interpretation process. This process computes the values of the parameters that best fit to the measured data. Other methods, such as that of Hvorslev or Bouwer-Rice use the hydraulic conductivity (k).

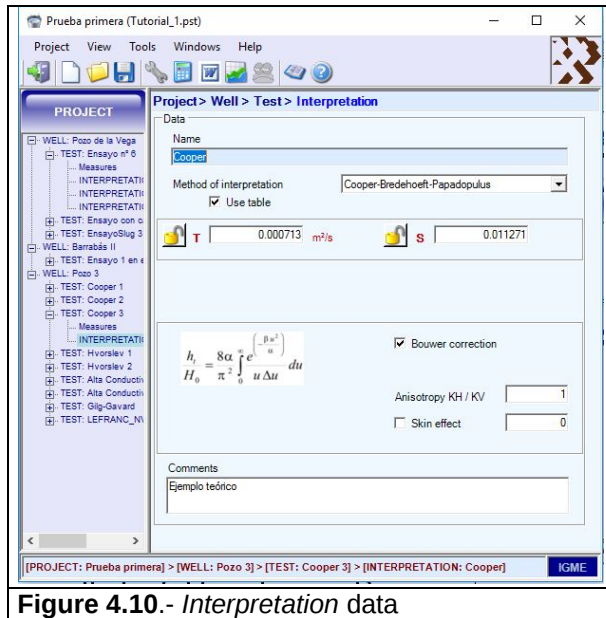


Figure 4.10.- Interpretation data

4.3.- GRAPH

The button highlighted at the left is the one that launches the interpretation, and, when finished, displays a note showing the iterations made and the optimum results for the variables computed (**Figure 4.11**).

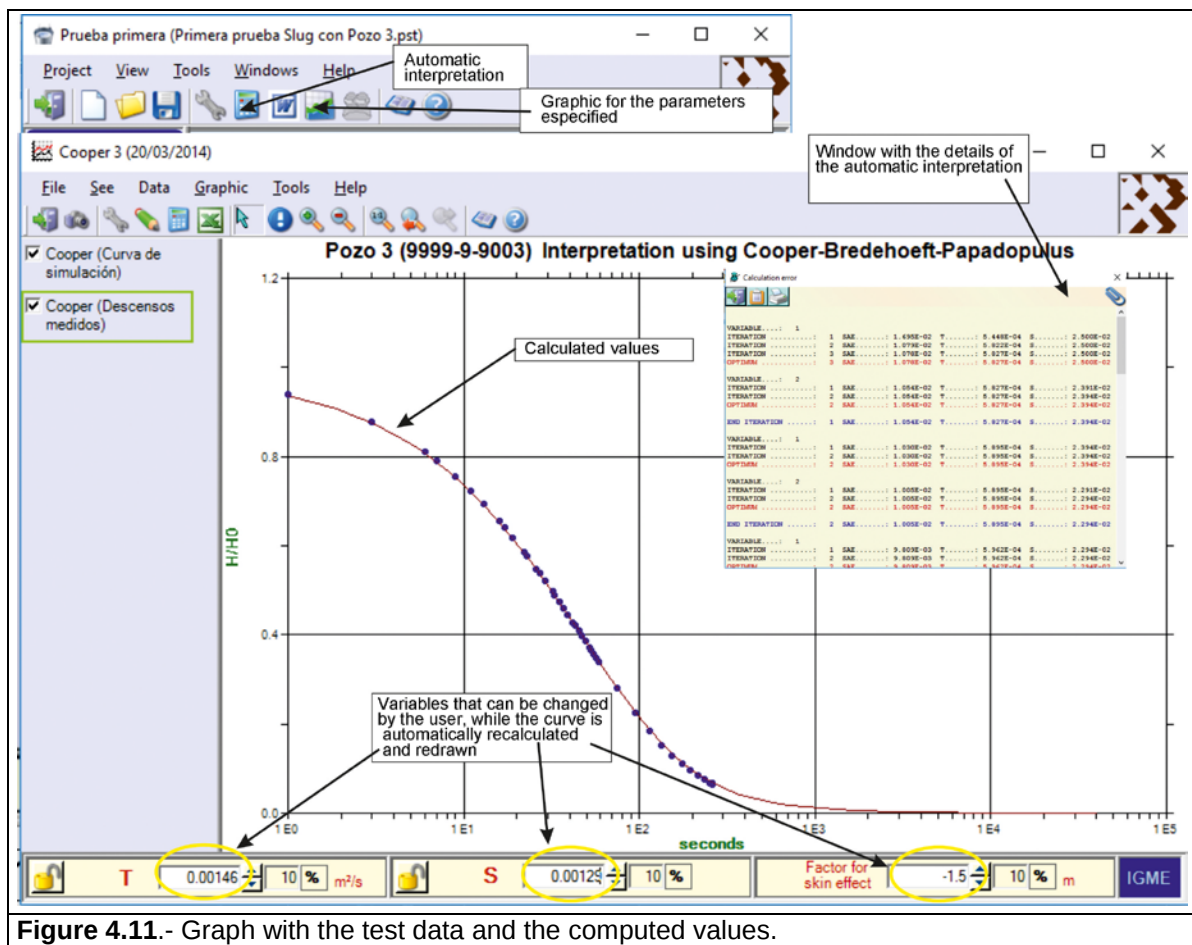
Besides the informative note, the graph with the temporal data series and the computed results are also shown.

This graph can also be displayed even if the interpretation process is not performed, showing a simulation with the current parameters.

The graph is customizable, and allows the user to interact with the variables computed. As they are being changed in the bottom bar, the curve is automatically recalculated and redrawn.

The graph form has a similar disposition to that of the main form: Menu and tool bars, side bar with the series legend used in the graph, status bar with the controls to modify the variables and the central window displaying the graph.

The graph is displayed with the default plotting options depending on the test type; for instance, the time abscissa axis is logarithmic in the case of Cooper-Bredehoeft-Papadopoulos interpretation, while in the Hvorslev and Bouwer-Rice methods the axis displayed as logarithmic is the ordinate one.



The submenus **Data** and **Tools** outstand from the menu bar, the former intended to display the data of the test curves or the average corrected data (H/H_0), while the latter is for fixing the parameters involved in the simulation, launching the interpretation or exporting the data to MS Excel (**Figure 4.12**). Over the graph (as well as in the data form with the column **Yes/No**) the data to be used in the computing can be selected (unused data appear in red color). Also, the axis properties can be changed.

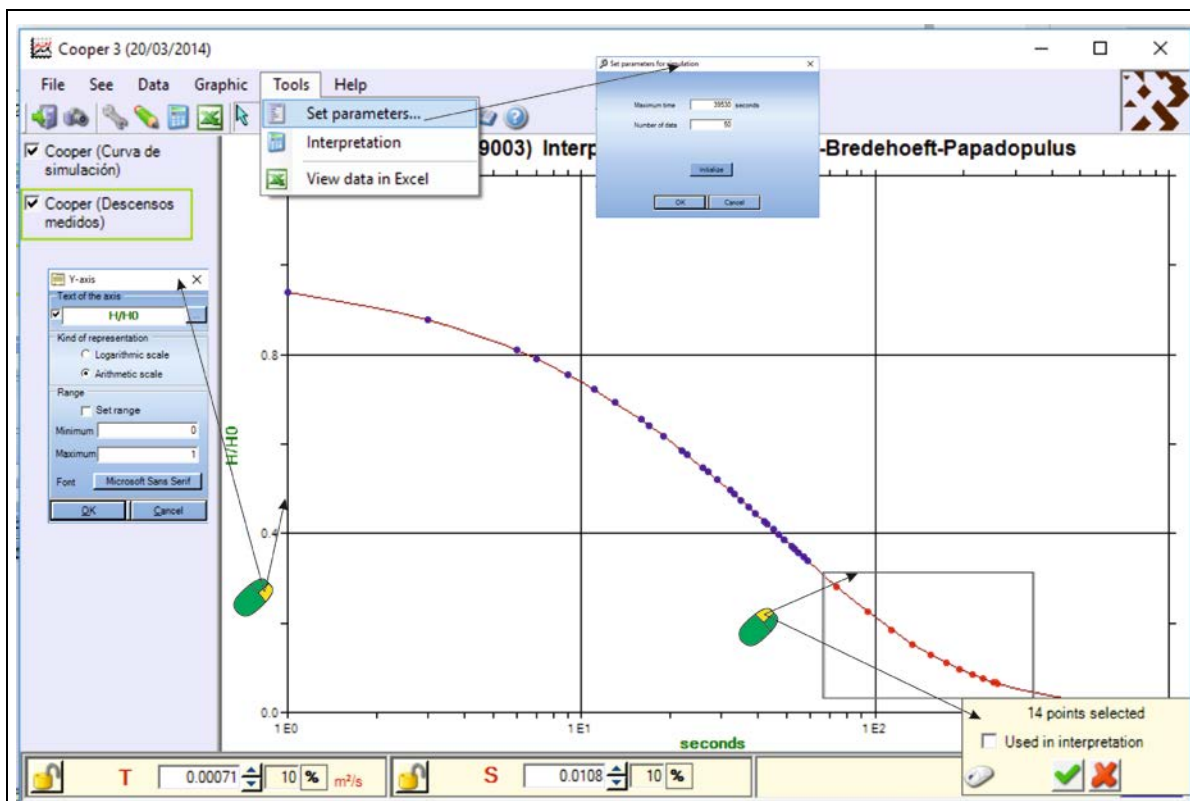


Figure 4.12.- Graph with the test data and the computed values.

In the button bar, additionally to some functions selected from the menu bar, there are some buttons to interact with the graph itself: zoom, selection and query functions.

	Close and back to the main window		Zoom in
	Export to image file		Zoom out
	Change view options for the graph		Full graph view
	Redraw graph		Previous view
	Interpret test and redraw graph		Next view
	Open data in Excel		Open user manual
	Select element in the graph		Show <i>About</i> form
	Show info of a selected point		

Figure 4.13.- Button tool bar to interact with the graph.

4.4.- REPORTING

Using the information of the interpretation selected and the test and well data, as well as the graph with the simulation curve, a report can be generated in MS Word. For this purpose, the user must click either on the button highlighted at the tool bar or in the submenu at the menu bar: **Project** → **Generate report**. Then, a MS Word report is created as shown in **Figure 4.14**. The document can be saved in Word or can be printed.

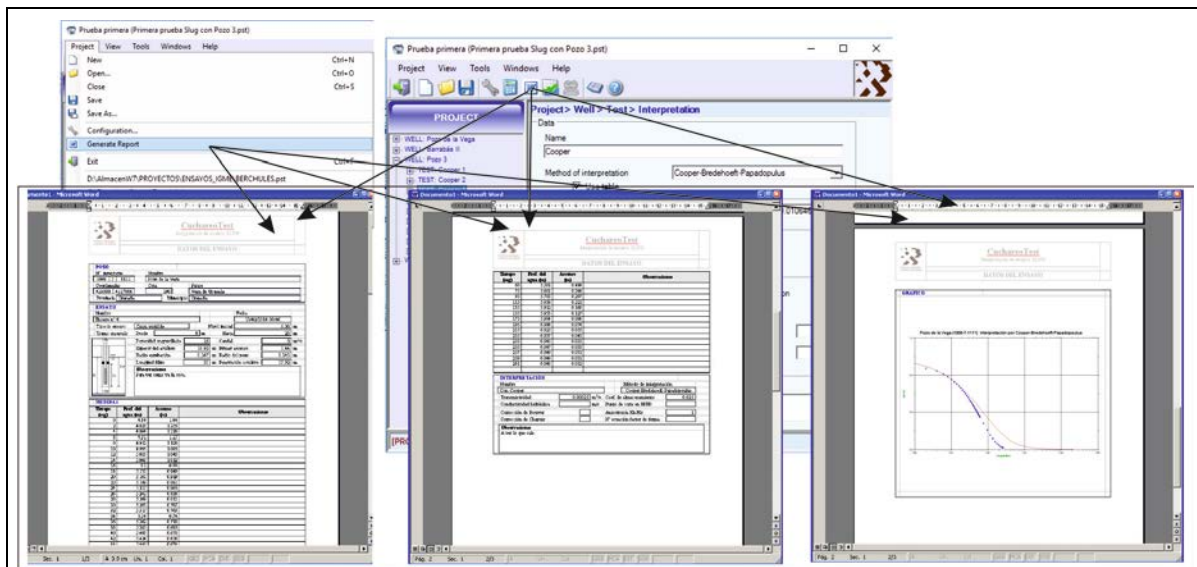


Figure 4.14.- MS Word report with the data of the interpretation.

5.- TUTORIAL

This section describes step by step an example of use of the application to interpret a slug test by several methods.

After launching the program, using **Project → New**, a new project opens, that has been named as *Tutorial_1*. Project data are included in the form, as shown in **Figure 5.1**.

This project can use the data of several research boreholes. As the user creates them, they are added to a list below the project data *form*.

Well	Name	UTM X	UTM Y	Elevation (m.s.n.m.)
1	Well 1 (9999-9-9001)	0	0	0

Figure 5.1.- Work project data form, to be filled in.

This tutorial includes the data of a borehole where a slug test has been performed, with the conditions shown in the scheme of **Figure 5.2**. By double clicking either in the tab of the side menu called “not inventoried well”, or in the list below the project form, the well form opens to be filled in (**Figure 5.3**).

Test	Name	Date	From (m)	To (m)
1	Ensayo nº 6	13/02/2014	0	
2	Ensayo con carga constante	25/02/2014	0	

Figure 5.3.- Access to the form to fill in the well data .

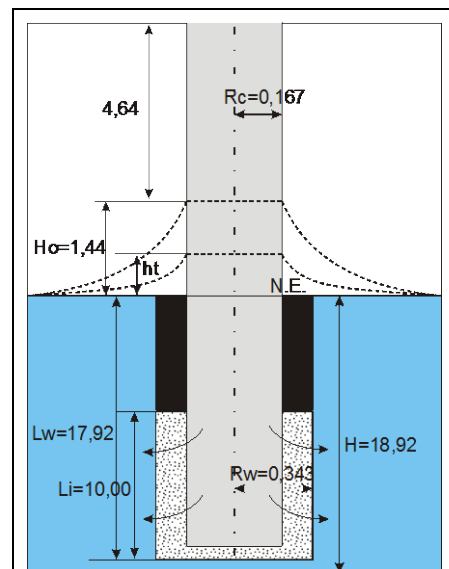


Figure 5.2.- Characteristics of the slug test used in this tutorial.

Using the option **See → Side legend → Tree**, the side legend has been changed to a tree structure (**Figure 5.4**).

The bottom of the well form displays the list of wells drilled. By double clicking on any of them or in the side legend, the well form appears (**Figure 5.5**).

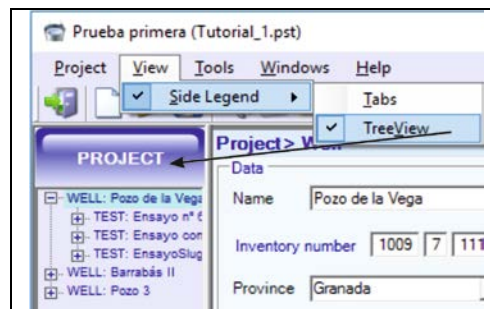


Figure 5.4.- Changing the side legend to tree structure.

In this form, the values and conditions of the slug test are entered. This example is a test in which the level has been sharply risen from 6,08 m of starting depth to 4,64 m, with an initial rise of 1,44. Residual drawdowns will be measured until the static initial level is again reached, i.e. it is a variable head test. The test conditions, shown in the scheme of **Figure 5.2** are also indicated in this form.

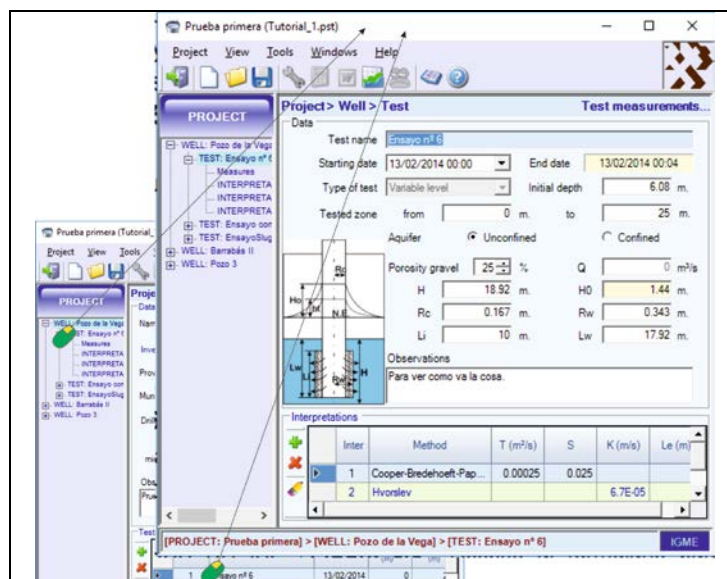


Figure 5.5.- Access to the form to fill in the slug test data.

The change of depths vs time are indicated in the form of *measurements*, which is opened from the test form, either from the lateral legend or from the button of the right upper corner (**Figure 5.6**). The measurements of the test can be fulfilled directly in this form or from an Excel spreadsheet that can be accessed directly from the option of the measurements form:

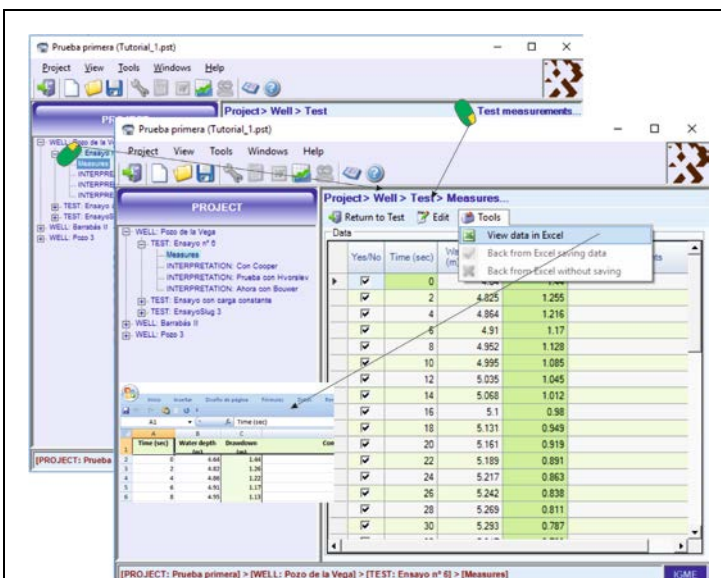


Figure 5.6.- Access to the form to fill in the field data of depth vs time.

Tool → Open in Excel.

For any test, several interpretations can be made, either by one or several methods. To interpret the test, the form must be opened from the Test form option, either from the side legend or from the list of data interpretations displayed below. In this example, a first interpretation will be made using the Cooper-Bredehoeft-Papadopoulos (Figure 5.7.). This interpretation is made with starting values of transmissivity (T) of 0.01 m²/s and storage coefficient (S) of 0.001. The Bouwer correction is not used since the water level ranges outside the intake screen. Neither the “skin effect” that could distort the results, will be considered in the surroundings of the well.

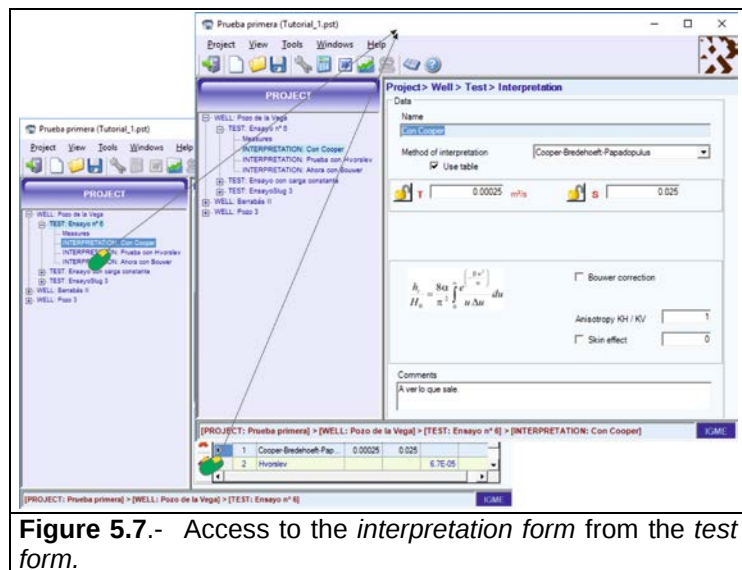


Figure 5.7.- Access to the *interpretation* form from the *test* form.

This initial interpretation can be displayed together with the field data using the option **see graph** from the toolbar (Figure 5.8.). In this case, the first interpretation of T and S is quite poor; the computed data are quite different from those measured. In addition, there are two measured points (fourth and fifth) which seem anomalous, so they will not be considered in the interpretation. To get them out of the interpretation just select them with the mouse and disable with the drop-down option.

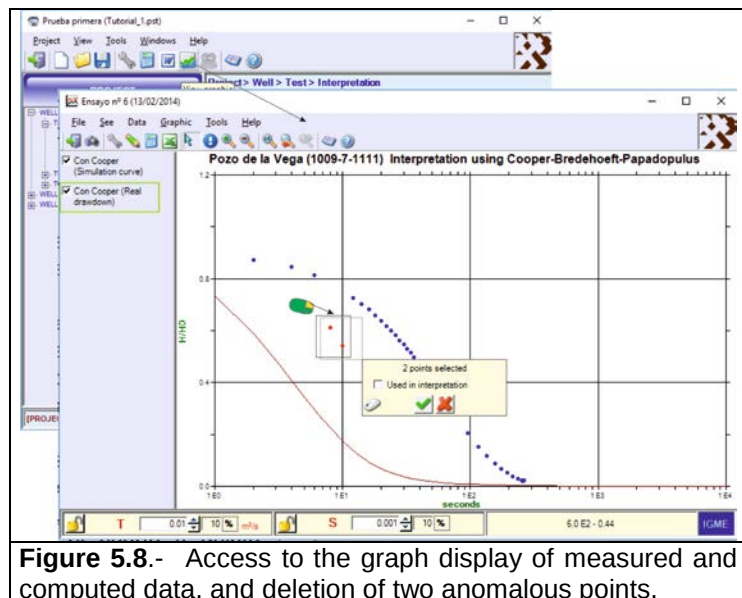
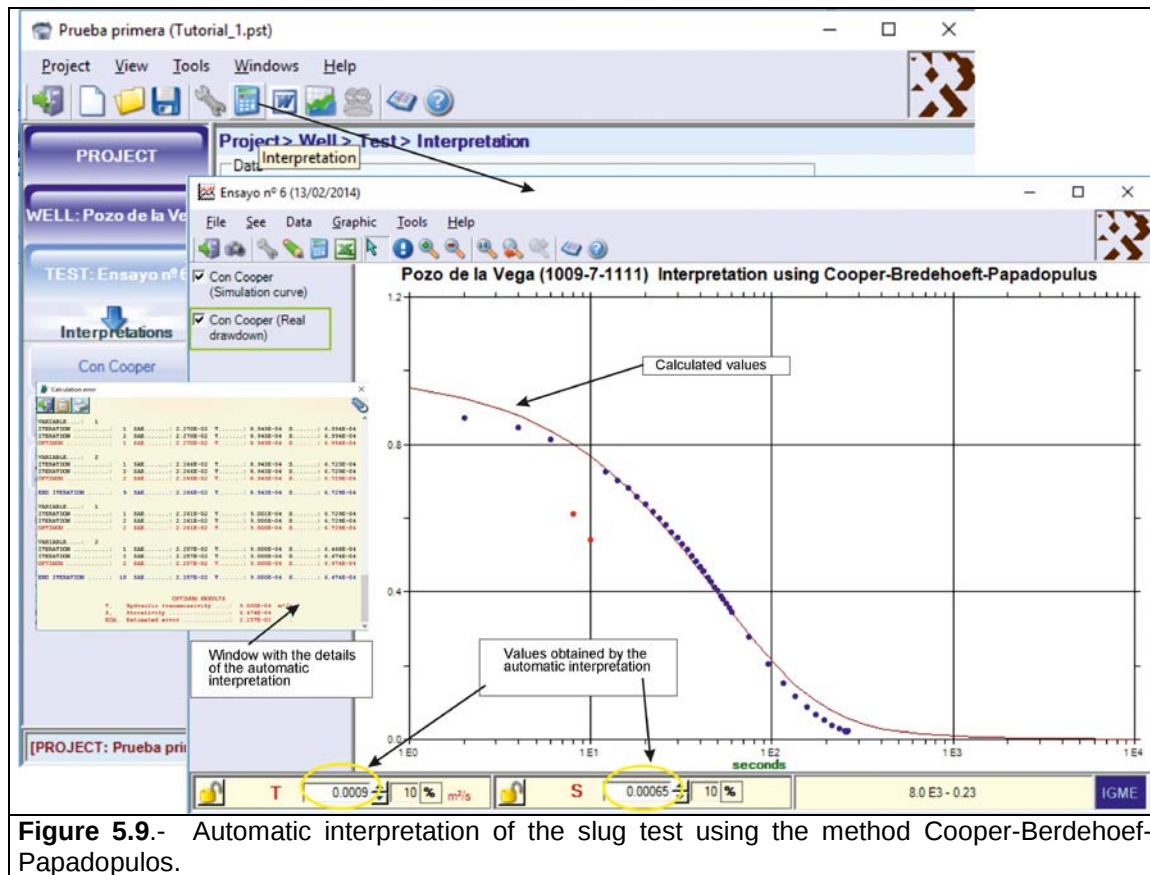
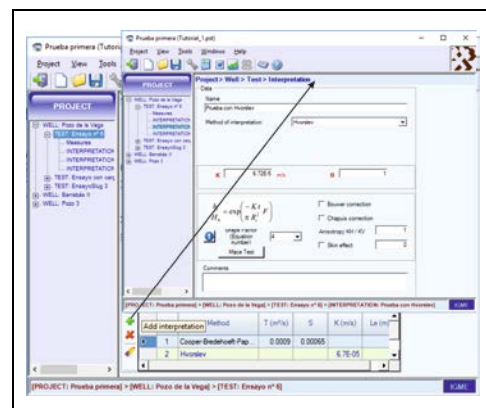


Figure 5.8.- Access to the graph display of measured and computed data, and deletion of two anomalous points.

The automatic interpretation of the hydraulic parameters is selected from the option **Interpretation**, located at the toolbars either of the graph window or the interpretation form. After the interpretation, an informative window appears showing the errors obtained in each iteration. Finally, the interpretation is moved into the corresponding boxes in the graph and the interpretation form (Figure 5.9.)

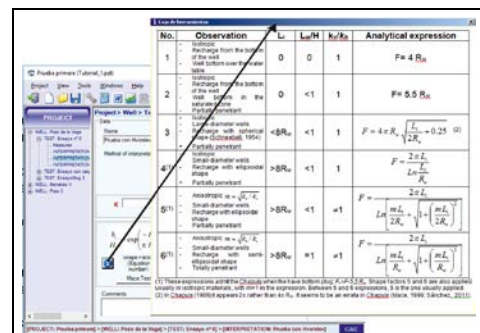


In order to contrast the adjustment achieved, another interpretation method will be used. For this purpose, select at the bottom of the opened test form (*Variable head_1*) *Add interpretation* (**Figure 5.10**).



A form appears, as shown in **Figure 5.7.**, to be filled in. In this case, the Hvorslev method has been selected. The initial conductivity and the intersection point with the ordinate axis must be indicated ($k=0.01$ m/s and $B=1$). According to the test conditions, the shape factor selected by default is the 4th, which corresponds to an

ellipsoid-shaped water intrusion. Nevertheless, the user can choose any other shape factor from those included in the application (**Figure 5.11**). In this case, the automatic interpretation will be directly made from the form by clicking the button Interpretation in the toolbar (**Figure 5.12**). As in the case in which the Cooper-Berdehoeft-Papadopoulos was used, the application displays an information window with the computing performed and the graph of measured and computed data. The assessed parameters correspond to a hydraulic conductivity ($k=6.73 \text{ E-5 m/s}$) and the intersection point in the ordinate axis is $B=0.848$. The user can, interactively, modify these values in the graph and choose those that better fit the test.



No.	Observation	L	L_w/H	k_u/k_a	Analytical expression
1	Observation from the top of the well	0	0	1	$F = 4 R_w$
2	Observation from the bottom of the well	0	<1	1	$F = 5.5 R_w$
3	Observation from the side of the well	<0	<1	1	$F = 4 R_w \sqrt{\frac{L}{2R_w} - 0.25}$
4	Observation from the side of the well	>0	<1	1	$F = \frac{2L}{R_w}$
5	Observation from the side of the well	<0	<1	1	$F = \frac{2L}{R_w} \sqrt{1 + \frac{mL}{2R_w}}$
6	Observation from the side of the well	>0	<1	1	$F = \frac{2L}{R_w} \sqrt{1 + \frac{mL}{2R_w}}$

Figure 5.11.- Procedure to change the shape factor assigned by default in the Hvorslev method.

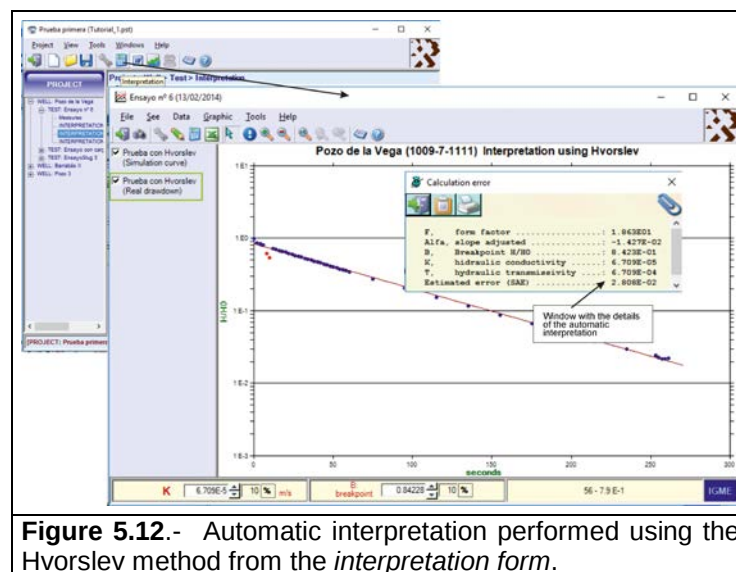


Figure 5.12.- Automatic interpretation performed using the Hvorslev method from the *interpretation form*.

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