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Hydrodynamic pumping test

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ABSTRACT: Thanks to a pumping signal of a limited duration and through the analysis of its piezometric response, the author presents herein an original method to evaluate the transmissivity and storage coefficient of an aquifer. The method is simple and particularly suited to contaminated sites : it limits the volume of pumped water that has to be disposed of and helps mitigate the alteration of the contaminants migration pattern.

Formulation of transient seepage according to Theis and the principle of superposition have enabled the author to estimate the piezometric response at any point of the aquifer, following a constant discharge of water of limited duration. The response curve posesses a hydrodynamic character in that the water level at a given distance from the well continues to drop after the pump is switched off. This delayed character of the piezometric response has allowed the author to identity two singular points where the transmissivity and storage coefficient combine into a single unknown.

The transmissivity and storage coefficient are obtained from test data observed at any of the two singular points and from non-dimensional charts. This communication gives an overview if this original method and of the experimental evidence provided by tests performed on a confined aquifer. Initial hypotheses are verified whereas results agree closely with values obtained from classical tests which lasted on an average 100 times longer.

1 INTRODUCTION

Most of the commonly used methods of determining in situ the transmissivity kH (product of permeability k by thickness H of the permeable stratum) and the storage coefficient S of an aquifer rely on conditions which are seldom realized, or which necessitate a long period of pumping.

Thiem's method, valid for a confined aquifer, assumes that the flow to the well is in a steady-state and does not provide information on the storage coefficient. Other methods approximate Theis' solution with a logarithmic expression in order to obtain graphically the two fundamental parameters (kH and S). These methods (Jacob's method and Thei's recovery method) require readings from piezometers in close proximity to the well and after a certain length of time.

These attempts to simplify the exact solution were justified by the complexity of the true mathematical solution and the imprecision in the graphical method designed by Theis himself and Chow.

The method presented herein allows one to estimate the values of kH and S througth the consideration of the Theis equation, without the mathematical and graphical complexity which has hindered the practical use of its exact solution and with the advantage that real field conditions are more closely taken into account.

2 ASSUMPTIONS

It is assumed that over the area influenced by the pumping test,
- the aquifer is confined
- the aquifer is homogeneous, isotropic, horizontal and of constant thickness
- the initial piezometric surface is horizontal
- the velocity of water is purely horizontal
- the water removed from storage is discharged instantaneously with decline of head.

Theis wrote the fundamental equation resulting from those hypotheses, once Darcy's law of filtration was accepted and the principe of continuity applied. He also found its solution for the case of a constant discharge, starting at time t = 0 from a well whose storage can be neglected.

For the purpose of working out the solution in the case of a constant flow rate of a limited duration, the principle of superposition will be accepted.

A fundamental solution to Theis equation

$\Delta\xi = \frac{1}{\alpha}\cdot\frac{\partial \xi}{\partial t}$ (1) is the drawdown velocity Z (r,t) :

$$Z(r,t)=\frac{Q}{4\pi kH}\cdot\frac{e^{-\frac{r^2}{4\alpha t}}}{t}\quad (2)$$

r is the distance between the point of observation and the well

t is the starting time when the pump is turned on

k is the permeability of the medium

H is the thickness of the confined aquifer

α is a coefficient which depends only on the aquifer parameters :

$$\alpha=\frac{kH}{S}\quad (3)$$

where S is the storage coefficient.

3 SOLUTION

The response of the piezometric level ξ^* to pumping for a limited period T_0 presents remarkable hydrodynamic properties, as shown in Fig. 1.

Fig. 1b represents that response and shows that the drop ξ^* in the piezometric drawdown continues to increase after the pumping period has terminated, reaching a maximum ξ_M at time t = T : this singular point can be used to apply the stationary level method as described below.

Afterwards, as the piezometric drawdown decreases with time in an asymptotical manner back to zero, the water level returns, after a delay R, to the value it reached at time t =0, i.e. ξ_0 when the pump was switched off. That singular point can be used to apply the return level method as described also below.

Using the principle of superposition, one can view pumping for a limited period of time T_0, as the sum of pumping, starting at time t = $-T_0$ and injecting at the same rate, starting at time t = 0 (Fig. 1a).

Hence, the resulting velocity of the water drawdown is

$$Z^*=\frac{Q}{4\pi kH}\left[\frac{e^{-\frac{A}{t+T_0}}}{t+T_0}-\frac{e^{-\frac{A}{t}}}{t}\right]\quad \text{for } t>0 \quad (4)$$

when summing opposite delayed solutions (2) with the substitution $A=r^2/4\alpha=S\cdot r^2/4kH$ (5)

Stationary level method

When putting into mathematical terms the stationary condition (Z^* = 0) with equation (4), one can see that the only unknown is A which can be expressed in an adimensional relationship in which T is the value of t for the stationary condition :

$$\frac{A}{T}=\left[\ell n(1+\frac{T_0}{T})\right]/\left[1-1/(1+\frac{T_0}{T})\right]\quad (6)$$

which means that by measuring T in the field and knowing or choosing T_0, a value of A can be obtained. This value is used to integrate the expression (4) and compare the actual value of the water drawdown with its mathematical expression. The value chosen here is the stationary water drawdown ξ_M (Fig. 1b) :

$$\xi_M=\frac{Q}{4\pi kH}\left[\int_0^{T+T_0}\frac{e^{-\frac{A}{\tau}}}{\tau}-\int_0^{T}\frac{e^{-\frac{A}{\tau}}}{\tau}d\tau\right]=\frac{Q}{4\pi kH}\cdot W_M\quad (7)$$

It can be shown that W_M is a unique function of the adimensional parameter T/T_0.

This means that by measuring ξ_M in the field and knowing T/T_0 and Q, a value of kH can be immediately obtained, provided the value of W_M has been tabulated as a function of T/T_0.

To ease the interpretation of the data of such pumping tests, two curves are presented in fig. 2 as functions of the relevant parameter T/T_0 :

- the first curve, W_M, is the representation of equation (7) and allows one to deduce the transmissivity with the expression :

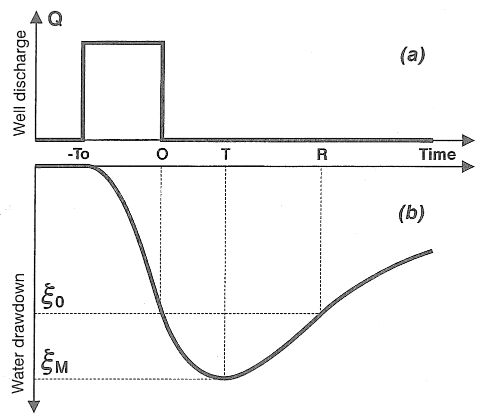

Fig. 1 : *(a) Pumping signal*
(b) Piezometric response

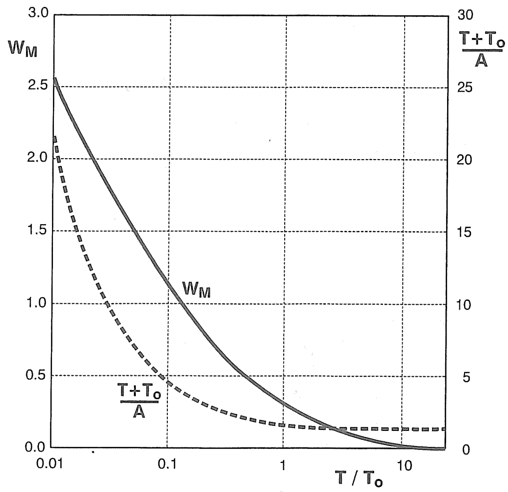

Fig. 2 : Chart for the interpretation of the Stationary Level Method Test Results

$$kH = \frac{Q \cdot W_M}{4\pi \cdot \xi_M}$$

- the second curve, $\frac{T+T_0}{A}$, is the equivalent representation of equation (6) and allows one to deduce the storage with the expression :

$$S = \frac{(T+T_0)measured}{(\frac{T+T_0}{A})chart} \cdot \frac{4kH}{r^2}$$

Return level method

The return level condition can be expressed by :

$$\xi_0 = \frac{Q}{4\pi kH}\int_0^{T_0} \frac{e^{-\frac{A}{\tau}}}{\tau} d\tau = \frac{Q}{4\pi kH} W_0$$

$$= \frac{Q}{4\pi kH}\left[\int_0^{T+R} \frac{e^{-\frac{A}{\tau}}}{\tau} d\tau - \int_0^{R} \frac{e^{-\frac{A}{\tau}}}{\tau} d\tau\right] \qquad (8)$$

i.e. by computing the members of the integral equation expressing the condition that the water drawdown at the end of the pumping period is equal to the one at time R. Further mathematical development of eq. (8) shows that the relevant dimensionless parameters are R/A and T_0/A.

Since the solution is unique, the final solution is graphically represented in Fig. 3 by more practical variables : $(R + T_0)/A$ as a function of R/T_0.

It is important to bare in mind that values of $(R + T_0)/A$ in the range of 3 to 10 are required to successfully aply the proposed method. Considering that the time required for classical approximation methods is of about 100 A, one can see that the return level method is on an average 10 to 30 times faster.

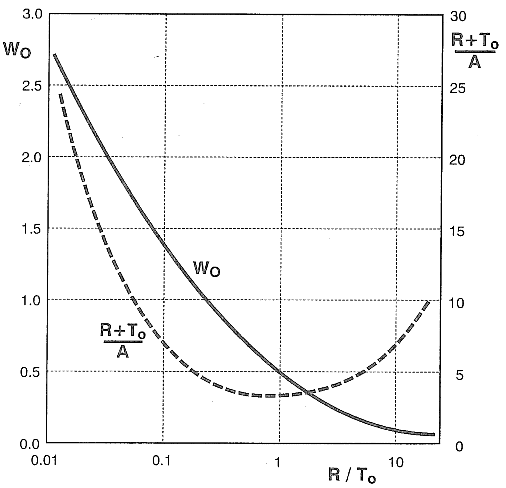

Fig. 3 : Chart for the interpretation of the Return Level Method Test Results

A specific testing procedure involves setting the return value ξ_0 by lowering a classical electric probe from the initial piezometric level by an additional depth ξ_0. One starts to pump until the chosen value ξ_0 is reached. Times T_0 is recorded as one switches off the pump. Then, one waits for the water drawdown to return to value ξ_0 and measures the value of $R + T_0$.

Once R and T_0 are known, the chart (fig. 3) yields the theoretical values of $(R + T_0)/A$ and W_0. Dividing the measured value $R + T_0$ by the theoretical value $(R + T_0)/A$ gives A. W_0 is the value of the exponential integral proportional to the water drawdown at time t = 0 or t = R , therefore :

$$kH = \frac{Q \cdot W_0}{4\pi \cdot \xi_0} \quad and \quad S = \frac{A \cdot Q \cdot W_0}{\pi \cdot r^2 \cdot \xi_0}$$

4 CASE HISTORY

Construction of a water treatment plant located within the Lasne valley in Rosières, Belgium provided the opportunity to verify the methods described above.

The subsurface conditions at the site consisted of alluvial deposits filling the -10 to -12 m deep valley carved into low permeability older formations. The soft alluvium consisted of layers of sand and silt overlying peat layers. The lower dense alluvium consisted of silt overlying high permeability gravels. Fig. 4 provides a schematic section drawn across part of the valley, based on the information collected from the geotechnical investigation (borings, CPT tests and DPT tests).

The semi-confined aquifer contained in the gravel layers lad to be lowered in order to insure the stability of several excavations necessary to construct the structures of the plant.

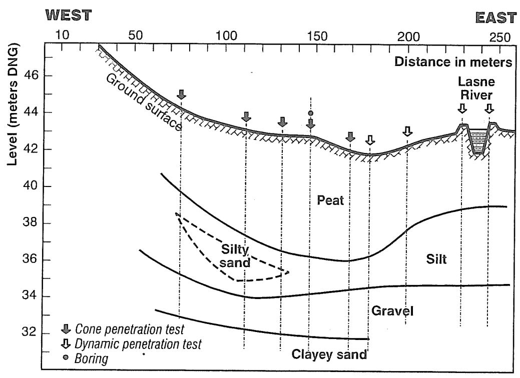

Fig. 4 : Subsurface conditions across part of the Lasne Valley

A pumping test program was therefore conducted by the contractor in order to design the dewatering system. A 380 mm diameter hole was drilled to a depth of 14 m to install a 200 mm diameter well casing with a 10 m long filter lower section. The immersed pump lad a nominal flowrate of 8 m^3/hr. under a water head of 18 m. The outlet conduit lad a diameter of 50.8 mm (2 inches).

Twelve 32 mm diameter open stand-pipes were installed into the sand-gravel layer, using jetting. Only the lower 2 m were filter elements and a 1 m thick annular plug made of bentonite pellets was placed above it. The piezometers were installed along four mains directions (West, South, East and North) at distances from the well varying between 4 and 75 m.

All piezometers are refered to according to the layer they are installation and position , e.g "G24N" refers to the piezometer installed in Gravel, 24 m North of the well.

The classical (long-term) pumping test lasted for 7 days during which piezometric levels and flow rate were recorded. Fig. 5 provides the flow rate based on meter readings at regular intervals. Fig. 6 provides the piezometric levels as recorded in piezometers aligned along the Northern direction : G4N, G24N, G75N, P5N and P25N.

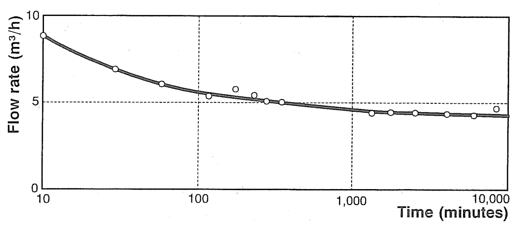

Fig. 5 : Flow rate measured during 7-day pumping test

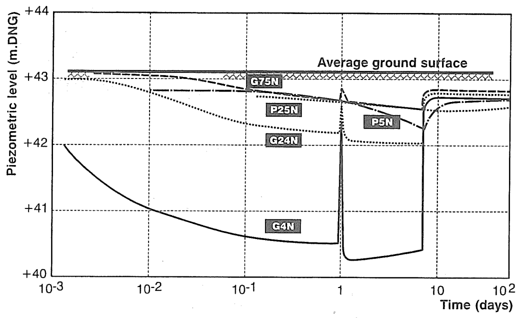

Fig. 6 : Piezometric levels recorded along Northern direction during 7-day pumping test and recovery

The return level method was applied using the specific pumping procedure described above at five different piezometers. The pre-determined drawdown varied between 0.05 and 0.5 m, which resulted in pumping episodes lasting between 57 and 355 seconds. The time delay necessary for the return level condition to be fulfilled varied between 60 and 850 sec. The results of the fifteen tests conducted within a five hour period are sumarized in Table I.

5 COMPARISON OF INTERPRETATION METHODS

7 day pumping test data were interpreted using the methods of Jacob, Theis, Chow, Thieu-Dupuit and Hantush. The return level pumping events were interpreted using Fig. 3. Aquifer parameters are summarized in Table II and discussed below.

Dupuit's method, assuming the flow to be confined and permanent, produces a transmissivity value of the order of 0.5 to 2 10^{-4} m^2/s.

Jacob's method based on a time dependent logarithmic approximation of the water drawdown for a confined transient flow provides an average transmissivity value of 17 10^{-4} m^2/s and a storage coefficient S = 4 10^{-5}. That low storage confirm the mainly confined character of the aquifer.

Theis method based on the graphical matching of the data with a log-log standard curve produces transmissivity values ranging between 1.3 and 7.4 10^{-4} m^2/s and a storage ranging between 5 and 2 10^{-3} that is significantly higher than that obtained from Jacob's method.

Chow's method based drawing a tangent to the drawdown-log time curve and using a chart produced different values of kH and S, depending on the point selected to draw the tangent line. T was noted to increase with the time selected and with the distance of the piezometer to the well. For the shorter time range, kH was noted to range between 2 and 9 10^{-4} m^2/s, and S between 7 and 0.4 10^{-6}, which compared well with values obtained using Theis's method.

The recovery method, also based on a time dependent logorithmic approximation, produced transmissivity values ranging between 1.5 and 4.5 10^{-4} m^2/s.

The observation that the interpreted aquifer parameters depended on the time range chosen to conduct the interpretation led to the suspicion that the aquifer could be semi-confined, i.e. that communication with the upper water-filled peat layers was possible. This communication was evidenced by the drawdown also observed in the peat layers : see piezometric levels of P5N and P25N in Fig. 6.

TABLE I - Test data and interpretation using the return level method

Test nr	Piezometer	Initial water depth (m)	ξ_0 (m)	T_0 (sec)	$T_0 + R$ (sec)	Q (m^3/sec) x 10^{-3}	A (sec)	T (m^2/sec) x 10^{-4}	S - x 10^{-3}
1	PN4	1.33	0.5	72	132	3.64	41	3	3
2	PS4	1.21	0.3	80	198	3.16	60	3	5
3	PW6	1.15	0.4	90	225	3.14	68	2	2
4	PE6	1.20	0.2	128	320	3.05	97	4	5
5	PE6	1.25	0.1	78	292	3.08	127	9	13
6	PW6	1.21	0.2	57	202	3.18	81	5	4
7	PS4	1.29	0.5	120	218	3.07	67	2	4
8	PN4	1.50	0.5	71	135	3.10	42	2	2
9	PS24	0.70	0.05	62	345	3.22	75	8	0.4
10	PS24	0.72	0.1	132	450	3.07	123	6	0.5
11	PE26	1.19	0.1	230	990	2.98	247	5	0.7
12	PW26	1.40	0.1	330	735	2.78	226	9	1
13	PN24	1.61	0.05	355	1204	2.62	330	11	2
14	PS24	1.78	0.15	190	520	2.91	153	5	0.5
15	PN4	1.68	0.5	69	147	3.14	46	2	2

Hantush's method was therefore used to study the aquifer curve semi-confined conditions. That method produced a transmissivity of the order of 2 to 7 10^{-4} m^2/s and a storage of the order of 0.5 to 1.5 10^{-3}. In addition, the vertical permeability of the peat layers was inferred to vary between 2 and 7 10^{-7} m/s.

The short pumping events interpreted usingthe return level method produced values of the transmissivity ranging between 2 and 10 10^{-4} m^2/s and of the storage between 0.5 and 4 10^{-3}.

6 CONCLUSIONS

Based on all of the above interpretation methods the aquifer was assigned a transmissivity of 5 10^{-4} m^2/s and storage of 10^{-3}. For that site, it was observed that Jacob's method provided kH and S values in excess of the range defined by the other methods used. Aquifer parameters obtained from short pumping events interpreted using the author's suggested procedure for the « Return level method » were comparable to those obtained using heavier procedures based on a much longer pumping test.

It is suggested that the short duration of the pumping events allows one to find more realistic, intrinsic values of the transmissivity and storage of the aquifer at a local scale, that are less influenced by long-term governing boundary conditions such as semi-confined conditions and/or long-distance recharge conditions.

7 ACKNOWLEDGMENTS

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TABLE II - Comparison of hydrogeological parameters (T in m^2/s)

Method Piezometer		N4	N24	N75	S4	S24	S75	E6	E26	W6	W76
THIEM-DUPUIT	T	1.3 10^{-4}			1.1 10^{-4}			0.5 10^{-4}		2.1 10^{-4}	
JACOBS	T	17 10^{-4}			-			-		-	
	S	4 10^{-5}			-			-		-	
Recovery	T	1.8 10^{-4}	-	-	1.8 10^{-4}	-	-	3.1 10^{-4}	4.3 10^{-4}	-	-
THEIS	T	-	5.3 10^{-4}	7.3 10^{-4}	1.3 10^{-4}	6.6 10^{-4}	4 10^{-4}	5.3 10^{-4}	5.3 10^{-4}	-	6.6 10^{-4}
	S	-	10^{-3}	10^{-3}	2 10^{-3}	0.2 10^{-3}	1.5 10^{-3}	0.6 10^{-3}	0.5 10^{-3}	-	0.7 10^{-3}
CHOW	T	6.10^{-4}	6.1 10^{-4}	9 10^{-4}	6.4 10^{-4}	11 10^{-4}	7.1 10^{-4}	6.4 10^{-3}	6.4 10^{-3}	5.9 10^{-4}	10 10^{-4}
	S	0.04 10^{-3}	0.9 10^{-3}	0.9 10^{-3}	0.1 10^{-3}	0.02 10^{-3}	1.8 10^{-3}	10^{-3}	0.4 10^{-3}	0.02 10^{-3}	0.6 10^{-3}
HANTUSH	T	2 10^{-4}	4.7 10^{-4}	4.9 10^{-4}	2.2 10^{-4}	3.7 10^{-4}	6.6 10^{-4}	5.3 10^{-4}	5.5 10^{-4}	1.6 10^{-4}	14 10^{-4}
	S	10^{-3}	10^{-3}	0.8 10^{-3}	1.8 10^{-3}	0.5 10^{-3}	1.7 10^{-3}	1.3 10^{-3}	0.4 10^{-3}	1.3 10^{-3}	1.5 10^{-3}
	k_v	7 10^{-6}	5 10^{-7}	5 10^{-7}	1.3 10^{-6}	5 10^{-7}	4 10^{-7}	7 10^{-7}	2 10^{-7}	1.6 10^{-5}	3 10^{-7}
RETURN	T	2.5 10^{-4}	1 10^{-4}	-	2.5 10^{-4}	6 10^{-4}	-	4 10^{-4}	5 10^{-4}	4 10^{-4}	9 10^{-4}
LEVEL	S	2.5 10^{-3}	2 10^{-3}	-	4.5 10^{-3}	0.5 10^{-3}	-	5 10^{-3}	0.7 10^{-3}	3 10^{-3}	10^{-3}

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