d9. The return level method—a quick method for measuring in situ the transmissivity and storage coefficient of aquifers

La méthode du niveau de retour—une méthode rapide d'estimation in situ de la transmissivité et du coefficient d'emmagasinement des terrains aquifères

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Measuring the transmissivity and storage coefficient of an aquifer has so far proven to be difficult, time consuming and expensive. Owing to a pumping signal of a limited period of time and through the analysis of its piezometric response, the author presents herein a method which is free of the aforementioned disadvantages. Because of the short pumping time, this simple method is particularly suited to sites where settlements, due to the lowering of the water table, are to be expected. Formulation of transient seepage according to Theis and the principle of superposition have enabled the author to estimate the piezometric response of any point of the aquifer, following a constant discharge of water of limited time. The response curve reveals that water returns, after a certain delay to the level it reached when the pump was switched off (Return Level Method). Through the analysis of significant dimensionless parameters, end results can be presented in the form of a simple chart. This communication gives an overview of this new method and of the experimental evidence provided by tests performed on a confined aquifer. Initial hypothesis are verified whereas results agree very closely with values obtained from classical tests which lasted on an average 20 times longer.

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 give any information on the storage coefficient. Other methods approximate Theis's solution with a logarithmic expression in order to obtain graphically the two fundamental parameters (kH and S). These methods (Jacob's method and Theis's recovery method) require readings on piezometers in close proximity to the well and after a certain length of time.

These attempts of simplification of 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 through the consideration of true Theis's 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.

THE RETURN LEVEL METHOD

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 given by these hypothesis, one Darcy's law of filtration was accepted and the principle of continuity applied, and 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 admitted.

Solution and Chart

The response of the piezometric level ξ^* to pumping for a limited period T_o results from the combined effect of pumping, starting at time $t = -T_o$, and of an injection of water at the same rate, starting at time $t = 0$ (fig. 1a.).

Fig. 1b. represents this response and shows that the drop ξ^* in the piezometric level continues to increase after the pumping period has terminated and then reaches a maximum at time $t = T$: this particular point has been dealt with by the stationary level method which is outside the scope of this paper.

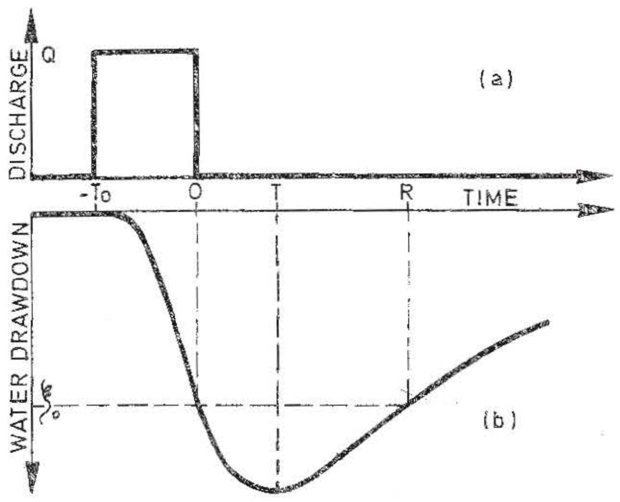

Fig. 1 (a) Pumping signal
(b) Piezometric response

Afterwards, as it decreases with time in an asymptotical manner to its initial value, the water level returns, after a delay R, to the value it reached at time t = 0, i.e. when the pump was switched off.

In 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, it can be shown that the relevant dimensionless parameters are R/A and T_o/A. A is a time parameter which depends on the values of the transmissivity kH and the storage coefficient S (i.e. the type of aquifer) and on the distance r between the piezometer and the well :

$$A = \frac{S \cdot r^2}{4 \quad kH}$$

Since the solution is unique, the final solution is graphically represented by more practical variables : $(R + T_o)/A$ as a function of R/T_o (fig. 2).

It is important to bare in mind that values of $(R + T_o)/A$ in the range of 3 to 10 are required to successfully apply this 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.

Technique and Interpretation

On the site, one sets the return value ξ_o by lowering a classical electric probe from the initial piezometric level to a depth of ξ_o. One starts to pump until chosen value ξ_o is reached and times T_o as one switches off the pump. Then, one waits for the water drawdown to return to value ξ_o and measures the value of $R + T_o$.

Once R and T_o are known, the chart (fig. 2) yields the theoretical values of $(R + T_o)/A$ and W_o. Dividing the measured value $R + T_o$ by the theoretical value $(R + T_o)/A$ gives A.

W_o is the value of the exponential integral proportional to the water drawdown at time t = 0 or t = R :

$$W_o = \int_0^{T_o} \frac{\exp\,(-\,A/\tau)}{\tau}\, d\tau$$

This function has been computed with value A given by the first step of the solution, so that it can be defined also through value R/T_o.

The transmissivity and storage coefficient are then given by

$$kH = \frac{Q \cdot W_o}{4\pi \cdot \xi_o} \quad \text{and} \quad S = \frac{A \cdot Q \cdot W_o}{\pi \cdot r^2 \cdot \xi_o}$$

EXPERIMENTAL EVIDENCE

The construction of an underground aquaduct in the area of Wavre (Belgium) along the Dyle valley provided us with the opportunity to test the return level method on a confined aquifer. Under about 7 m of alluvial deposits of poor geotechnical properties, the water table was kept under pressure in quaternary gravels and fissured primary rock, its natural piezometric level being 2,5 m deep. Tests to examine the validity of the method, its hypothesis and its consequences were run on a single well equiped with a pump of a 20 m^3/h capacity and on a set of open piezometric tubes.

Classical pumping tests

Classical methods of interpretation have been used to cross-check the results given by the return level method.

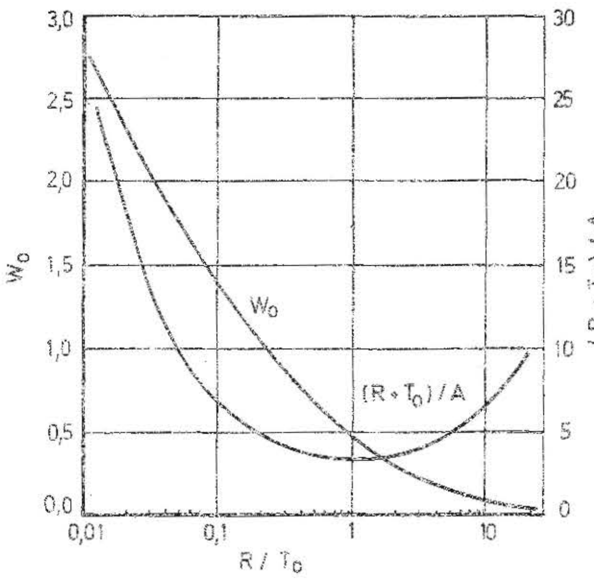

Fig. 2 Chart for the interpretation of tests.

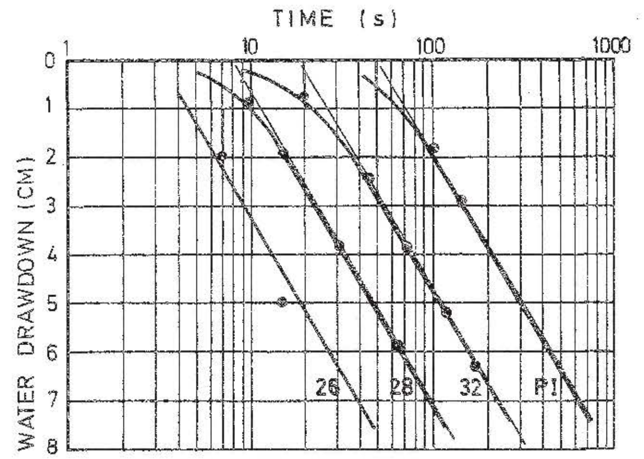

Fig. 3 Results of the Classical Tests (Points refer to experimental data and numbers or letters to piezometers).

Variations in the well due to continuous pumping for 15 min. allowed us to apply Theis's recovery method : for 3 different flow rates, obtained values of the transmissivity varied from kH = 6.7 10^{-3}/m^2/s to kH = 7.5 10^{-3} m^2/s. On the other hand, the specific water drawdown ξ/Q remained constant, confirming the confined aspect of the aquifer.

Observations of several piezometers in a classical pumping test enabled us to apply Jacob's method. Fig. 3 represents the water drawdown as a function of time for different piezometers. Its interpretation gave values of the transmissivity ranging from kH = 5.8 10^{-3} m^2/s to kH = 8.10^{-3} m^2/s whereas the interpretation of simultaneous observations gave kH = 5.10^{-3} m^2/s.

Depending on the method chosen to estimate kH, the storage coefficient ranged from S = 0.12 10^{-3} to S = 0.29 10^{-3}.

Return level method

Numerous tests were run in order to verify what the theoretical developments had brought to light.

The first step was to check the principle of superposition : with only a regular drawdown curve, observed in anyone of the piezometers, values of R can be obtained for different return levels by graphical superposition. These values compared well with those measured on the site (physical superposition) : the maximum relative difference on R/T_o was of about $\pm$ 5%, which corresponds to a practical relative error of $\pm$ 1,8% and $\mp$ 0,5% in estimating kH and S. From this can be concluded that in the precision range we are dealing with, the principle of superposition can be used.

The second step was to establish that the results kH and S were independent of the pumping time T_o (or the chosen return level ξ_o), of the flow rate Q and of the point of observation for a homogeneous aquifer. Table I presents an extract of the measures which summarize these three points.

As can be seen in the first part of table I (piezometer 32, 42 m from the well), the choice of ξ_o does not influence the values of kH and S, considering the usual confidence with which these results are guaranteed.

From the second and third part of table I (piezometer PI, 55 m from the well), it can be seen that the choice of Q does not influence the values of kH and S. As a matter of fact, Q varying with T_o, a better consistency in the results have been found if the flow rate (or the total flow) was measured each time.

From the comparison of the values of kH and S obtained with these two piezometers, it can be seen that the homogeneity of the aquifer appears with this method, as had been concluded from classical tests (fig. 3).

Another clue for the validity of the curves given in fig. 2 is the materialization of the symetry of the curve $(R + T_o)/A$ respectful to R/T_o = 1 by two experiments on piezometer 32. Indeed, for both conditions ξ_o = 1 cm and ξ_o = 3 cm, where R + T_o is equal to 89 sec., values of R and T_o are exchanged (i.e. R/T_o is inversed).

Table I Results of the Return Level Method using the measures of r, ξ_o, T_o, R + T_o and Q.

r (m)	ξ_o (m)	T_o (s)	R+T_o (s)	R (s)	R/T_o -	R+T_o/A -	W_o -	A (s)	Q (10^{-3}m^3/s)	kH (10^{-3}m^2/s)	S (10^{-3})
	0.01	27.5	89	61.5	2.24	3.6	0.27	27.4	2.77	6.0	0.34
	0.02	43	80.5	37.5	0.87	3.25	0.49	24.8	3.08	6.0	0.34
42	0.03	61	89	28	0.46	3.6	0.71	24.7	2.90	5.4	0.31
	0.04	83	106	23	0.28	4.2	0.9	25.2	2.88	5.2	0.30
	0.05	114	135	21	0.184	5.0	1.09	27	2.96	5.1	0.32
	0.01	68	201	133	1.96	3.5	0.29	57	2.85	6.7	0.51
55	0.02	104	184	80	0.77	3.3	0.53	56	2.99	6.3	0.46
	0.03	154	217	63	0.47	3.6	0.70	60	2.93	5.5	0.43
	0.05	297	330	33	0.113	6.2	1.33	53	2.91	6.2	0.43
55	0.01	38.5	229.5	191	4.96	4.8	0.15	48	5.6	6.7	0.42
	0.02	57.5	197.5	141	2.45	3.7	0.26	53	5.3	5.4	0.38

Comparison with classical methods

From tests run on piezometers analysed by both the classical and the return level method, an excellent agreement can be found for the transmissivity : classical methods give $kH = 5.10^{-3}$ to 7.10^{-3} m^2/s whereas the return level method gives $kH = 5.1\ 10^{-3}$ to $6.7\ 10^{-3}$ m^2/s.

Somewhat higher values for the storage coefficient are obtained with the return level method : $S = 0.24\ 10^{-3}$ to $0.59\ 10^{-3}$ versus $0.12\ 10^{-3}$ to $0.29\ 10^{-3}$ with Jacob's method.

The interpretation of S as a coefficient directly involved in the compressibility of the aquifer makes the assumption of the constancy of S throughout the test rather precarious. Indeed, S is a damping factor in Theis's parabolic differential equation and, at the early stages of the pumping period, consolidation of the compressible layers bounding the aquifer is responsible for the apparent increase of S. Since the return level method works with short pumping signals, it takes into account the compressibility of the whole soil influenced by the reduction of the water pressure; hence, the value of S obtained with this method is a better indication of the danger of settlements.

CONCLUSIONS

The analysis of the piezometric response to a pumping signal of a limited period has enabled the author to design a new method for estimating in situ the transmissivity and storage coefficient of aquifers. Through the analysis of the parameters involved in the phenomenon, it has been possible to draw a chart taking into account the complexity of Theis's solution and enabling one to interpret the tests in a matter of minutes.

Experimental evidence has been provided by tests run on a confined aquifer. It has been possible to verify the principle of superposition, and that the values of the transmissivity and storage coefficient were independent of the chosen value of the return level, of the flow rate and of the point of observation for homogeneous conditions. The performance of a few quick tests provides confirmation of the obtained values. The use of the curve $(T_o + R)/A$ in fig. 2 in order to minimize the time it takes to perform the whole test, has been confirmed. The values of the transmissivity compare perfectly with the values obtained with classical methods, whereas the values of the storage coefficient are somewhat higher. An explanation for this apparent discrepancy has been found in the decrease of S with time, due to the consolidation of the compressible layers in contact with the aquifer.

When considering a water drawdown problem, this method provides the engineer with the following qualities :

- range of application suited to most aquifers
- simplicity of measure
- rapidity of measure and interpretation
- one of the direct results (A) is connected with the influence area
- storage coefficient obtained with a quick pumping test gives a better estimation of the danger of settlements
- possibility of rapid intervention when the pumping system is already at work (analysis with the stopping of one pump for a short period).

It is hoped that this new technique will help the engineer find an efficient and rapid solution for designing water drawdown installations.

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