Stationary Level Method for Measuring In-Situ kH and S

Méthode du Niveau Stationnaire pour l'Estimation In-Situ de kH et S

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SYNOPSIS In spite of its time consumption and cost, the pumping test is still the most reliable procedure to determine the transmissivity (kH) and storage coefficient (S) of aquifers. This paper outlines the principles of pumping tests of short duration. A chart is given for quick interpretation of the stationary condition and the first experimental evidence collected on a large scale is supplied.

INTRODUCTION

The transmissivity kH (product of the permeability k by the thickness H of the permeable stratum) and the storage coefficient S of a confined aquifer are usually deduced from pumping test data. When the interpretation is performed according to the steady-state flow condition, one must make sure that these conditions are fulfilled at the cost of a lengthy test, otherwise, results may not be reliable enough. When the interpretation is performed according to the transient flow conditions, the usual procedure is to solve graphically or mathematically two equations with two coefficients which yield the fundamental parameters of the aquifer. Even so, most of the procedures tend to use the later data, corresponding to a quasi steady-state. Only a few procedures (Chow, Theis 1940) use the true mathematical solution designed by Theis, and generally with some degree of imprecision due to visual adjustment of a standard curve, or some graphical construction.

The stationary level method, which is introduced herein, allows one to deduce quickly the values of kH and S from a combination of true Theis' solutions, which means that real field conditions are more closely taken into account. The complexity associated with the unsimplified solution is eliminated through the analysis of a particular point of their combination (the stationary point) and through the use of a simple chart.

THE STATIONARY LEVEL METHOD

Assumptions.

The assumptions are those admitted by Theis plus the principle of superposition. It is useful to remember here the hypotheses that led Theis to state his solution for the case of a constant discharge starting at time t = 0 :

1) over the area influenced by the pumping test, the aquifer is confined, homogeneous, isotropic, horizontal and of constant thickness
2) 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, and the storage of the well is negligible
3) Darcy's law of filtration and the principle of continuity are valid.

In itself, the principle of superposition with respect to time is a mere application of the principle of causality and it does not bring any mathematical restriction, due to the fact that Theis' solution for the drawdown is an integral of elementary fundamental solutions of its differential equation.

Solution.

It has been shown (Holeyman 1979) that the response curve of the piezometric level of a confined aquifer at a distance r from the well, resulting from pumping for a limited period of time, exhibits a minimum. As a matter of fact, after the pump has been turned off, the water level continues to decrease until it becomes stationary, and only then does it gradually recover its initial level.
In terms of speed of the water drawdown, the stationary level is characterized by a value of zero.

A fundamental solution to Theis equation
$\Delta\xi = \frac{1}{\alpha} \cdot \frac{\partial \xi}{\partial t}$ is:

$$Z(r,t) = \frac{Q}{4\pi kH} \cdot \frac{e^{-\frac{r^2}{4\alpha t}}}{t} \qquad (1)$$

in which :

r is the distance between the point of observation and the well
t is the starting time when the pump is turned on
Q is the constant well discharge
k is the permeability of the medium
H is the thickness of the confined aquifer
α is a coefficient which depends only on the characteristic of the aquifer:

$$\alpha = \frac{k}{(m_v + n\beta)\overline{\omega}} = \frac{kH}{S} \qquad (2)$$

where
m_v is the compressibility of the medium
n is the porosity of the medium
β is the coefficient of compressibility of water
$\overline{\omega}$ is the specific weight of water

It happens that Z(r,t) represents the velocity of the water draw down since its integration of time gives the well known Theis' curve.

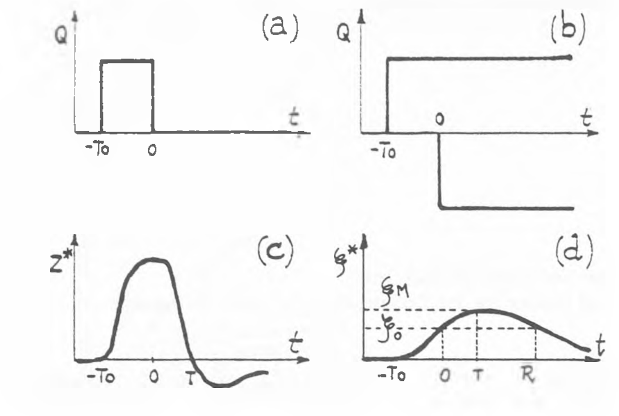

Fig. 1 (a),(b) pumping signals
(c) piezometric velocity
(d) piezometric response

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 and b).

Hence, the resulting velocity of the water drawdown is (Fig 1c) :

$$Z^* = \frac{Q}{4\pi kH}\left|\frac{e^{-\frac{A}{t+T_0}}}{t+T_0} - \frac{e^{-\frac{A}{t}}}{t}\right| \qquad \text{for } t > 0 \quad (3)$$

when summing opposite delayed solutions (1) with the substitution

$$A = r^2/4\alpha \;. \qquad (4)$$

When putting into mathematical terms the stationary condition ($Z^* = 0$) with equation (3), 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 :

$$\frac{A}{T} = \frac{\ell n\left(1 + \frac{T_0}{T}\right)}{1 - \frac{1}{1 + \frac{T_0}{T}}} \qquad (5)$$

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 (3) 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 1d) :

$$\xi_M = \frac{Q}{4\pi kH}\left|\int_0^{T+T_0}\frac{e^{-\frac{A}{\tau}}}{\tau}\,d\tau - \int_0^{T}\frac{e^{-\frac{A}{\tau}}}{\tau}\,d\tau\right| = \frac{Q}{4\pi kH}\cdot W_M \quad (6)$$

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.

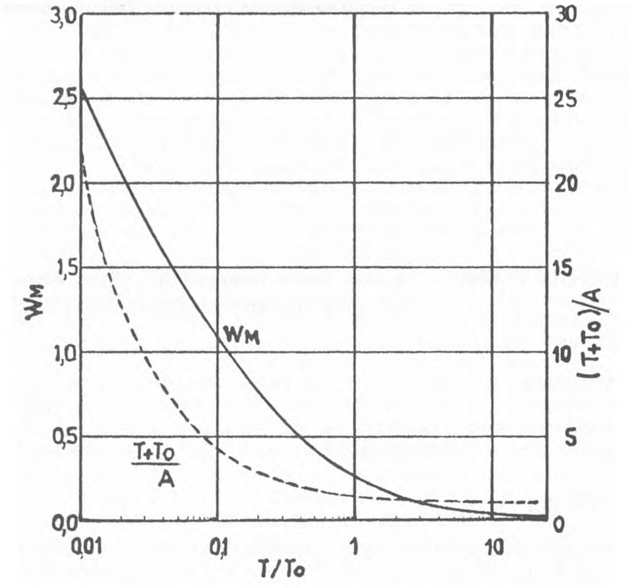

Fig. 2 Chart for the interpretation of the tests

Chart.

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

- the first curve, W_M, is the representation of equation (6) and allows one to deduce transmissivity with the expression :

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

- the second curve, $\frac{T + T_0}{A}$, is the equivalent representation of equation (5) and allows one to deduce the storage with the expression :

$$S = \frac{(T + T_0)_{\text{measured}}}{\left(\frac{T + T_0}{A}\right)_{\text{chart}}} \times \frac{4kH}{r^2}$$

In the field, one sets the pump to work for an arbitrary period T_0. After the pump is switched off, one measures the stationary water drawdown ξ_M and the time of its occurence T. Since one knows r and Q, kH and S can be obtained in a minute with the chart.

EXPERIMENTAL EVIDENCE

The project of a flood barrier in the area of Antwerp on the Scheldt river, has provided us with the opportunity to experiment with the stationary level method on a confined aquifer 12 to 14 m thick,consisting of medium sand. Tests to examine the validity of the method were run on a single well of 30 cm equivalent diameter equipped with a pump of an average flow rate of 52 m^3/h ($14 \cdot 10^{-3}$ m^3/s) and a set of open piezometric tubes.

Short pumping tests were run first, in order to provide values under true prediction conditions and compare the stationary level method with the return level method introduced two years ago (Holeyman 1979).

A classical pumping test was performed afterwards, in order to assure reference results.

Stationary level method.

After the regulation of the discharge to a maximun stable value, 7 pumping tests were performed with a duration varying from 1 to 15 minutes. During each pumping test, the water drawdown was measured every 15,30 or 60 seconds, simultaneously in four piezometers which were situated at a similar distance from the well, in different perpendicular directions.

A typical example of a response curve is drawn in fig. 3. It appeared that a correction due to the tidal variation of the water level was necessary for the longer periods of pumping. The interpretation of these curves can be readily made with the stationary level and the return . level charts. Significant results are presented in Table I.

It can be observed from these results that the values of kH and S are relatively spread out for each of the two methods. This fact can be noticed when an average value of the discharge is adopted, rather than the value given by the direct measurement for each test.

- The values given by the stationary level method show more consistency than the ones given by the return level method.
- The values of the transmissivity given by the stationary level method are inferior.
- There is a tendency towards higher transmissivity and lower storage coefficients for piezometers situated at the furthest distances.

From the results one can deduce a design value of the transmissivity between 1.8 and 3.6 10^{-3}m^2/s. For the storage, the value seems to depend on the direction and the location; two zones can be distinguished with two ranges of S : 0.3 to 0.6•10^{-3} and 1.3 to 2.4•10^{-3}.

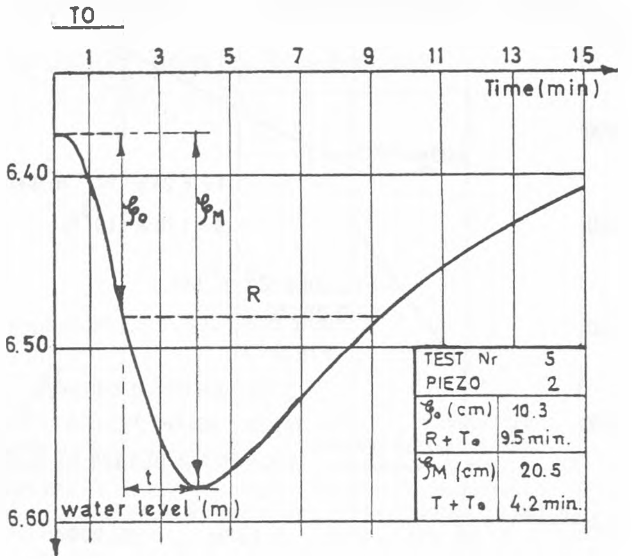

FIG.3 - Typical piezometric response curve to a short pumping signal.

Classical tests.

The classical tests have been run in four stages. First of all, an eight-hour test was performed with a discharge of 5 10^{-3}m^2/s (test A). The recovery behaviour was recorded during the evening. During the following two days similar tests were performed with discharges of 10 and 12•10^{-3} m^3/s (tests B and C). Thereafter a final test was conducted for 10 days with a nominal discharge of 10•10^{-3} m^3/s.Due to the vicinity of the Scheldt river which is under the influence of the tides, the data does not fit eas ly into the scheme adopted for the interpretation. For the drawdown period, Jacob's method was used. As can be seen on typical plots obtained from the

TABLE I : Results of the return level method (ξ_0, T_0+R) and of the stationary level method (ξ_M, T_0+T) Discharge assumed constant to 14•10^{-3} m^3/s.

INTERPRETATION			RETURN LEVEL METHOD				STATIONARY LEVEL METHOD			
Piezometer distance	Test No	T_0 (s)	ξ_0 (m)	T_0+ R (s)	kH (10^{-3} m^2/s)	S (10^{-3})	ξ_M (m)	T_0 + T (s)	kH (10^{-3} m^2/s)	S (10^{-3})
Piezo 2 r = 19.9 m west	4	60	0.056	468	2.2	1.9	0.107	180	1.5	2.2
	5	120	0.103	570	2.0	2.7	0.206	252	1.3	2.3
	6	90	0.060	540	2.7	3.0	0.148	222	1.4	2.4
	7	180	0.203	480	1.8	2.6	0.288	288	1.4	2.5
	9	600	0.712	708	1.7	2.4	0.734	648	1.9	2.4
Piezo 3 r = 119.65 m west	8	240	0.017	2040	6.5	0.64	0.099	630	1.9	0.27
	9	600	0.16	1590	2.3	0.30	0.242	915	1.9	0.28
	10	900	0.285	1575	2.1	0.28	0.345	1170	1.9	0.27
Piezo 7 r = 124.35 m east	9	600	0.029	2100	9.6	1.4	0.062	1140	4.9	1.0
	10	900	0.049	2520	7.0	1.3	0.090	1500	4.3	1.0
Piezo 9 r = 69.65 m north	8	240	0.036	2100	3.0	0.9	0.090	570	2.4	0.9
	9	600	0.147	1140	3.7	1.1	0.183	810	3.2	1.0
	10	900	0.226	1320	3.4	1.0	0.248	1095	3.2	1.1
Piezo 12 r = 119.30 m south	8	240	0.031	1440	5.2	0.44	0.074	525	3.3	0.36
	9	600	0.131	1170	4.0	0.41	0.165	810	3.6	0.38
	10	900	0.210	1320	3.7	0.38	0.235	1080	3.6	0.38

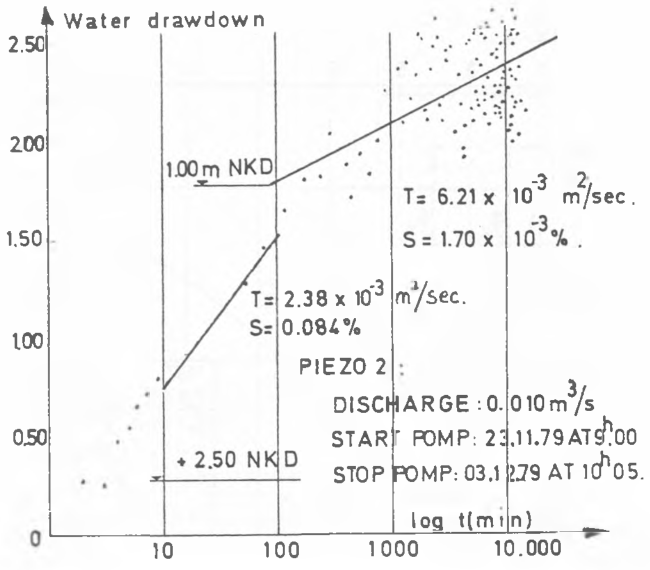

FIG.4 - Typical result of the classical tests

tests, (fig 4) it is rather difficult to draw a straight line through the scattering of the data points. Nevertheless, general figures can be adopted , which are summerized in table II.

When comparing the values of the transmissivity obtained by the different methods, one can notice the excellent agreement : kH from the short pumping tests can vary in a medium range of 1.8 to $3.6 \cdot 10^{-3} m^2/s$ (with a tendency towards higher values for the return level method for the shortest pumping periods) whereas kH from the classical tests vary in the medium range of 2.4 to $3.0 \cdot 10^{-3} m^2/s$.

The comparaison of the values of the storage coefficient is not as straightforward . Apart from piezometers 2 and 12 where comparable values are obtained with short and long pumping tests, one can see that the values of S obtained from the short pumping test are 2 to 3 times as high as the ones obtained from the classical test. This fact has already been noticed on other sites and a reason for it could be found in the decrease of S with time, due to the consolidation of secondary layers in contact with the main aquifer.

CONCLUSIONS.

By means of the analysis of the piezometric response to a pumping signal of a limited period, it has been possible to design a new method for estimating in-situ the transmissivity and storage coefficient of confined aquifers. A simple chart allows one to interpret the data related to the stationary point of this response curve and obtain the fundamental parameters kH and S in a matter of minutes.

Bearing in mind the precision with which hydrological parameters can be aserted, one can conclude from the tests conducted in the area of Antwerp that the stationary level method allows one to deduce consistent design values for the site. This latest method appears to be more reliable on this site than the return level method, because the water table was under tidal influence. Nevertheless, values obtained from both methods correlate satisfactorily with values obtained from classical tests run afterwards.

TEST			A	B	C
$Q(10^{-3} m^2/s)$			5	10	12
PIEZOMETERS	2	$kH(10^{-3} m^2/s)$	1.9/3.1	2.0/2.5	2.4
		$S(10^{-3})$	0.4/1.3	1.4/1.8	2.2/4.1
	3	$kH(10^{-3} m^2/s)$	2.6	2.2	2.3
		$S(10^{-3})$	0.1	0.2	0.1
	7	$kH(10^{-3} m^2/s)$	3.5	2.5	2.2/4.1
		$S(10^{-3})$	0.3	0.4	0.4
	9	$kH(10^{-3} m^2/s)$	3.4	1.2/4.3	1.6/2.5
		$S(10^{-3})$	0.3	0.5	0.4/0.5
	12	$kH(10^{-3} m^2/s)$	3.4	3.3	2.3/3.4
		$S(10^{-3})$	0.2	0.2	0.2/0.3

TABLE II - Ranges of values of kH and S deduced from the classical pumping tests.

Up to now, these new techniques of performing short pumping tests have proven to be reliable in general. In particular, one can foresee the utility of these methods where exploratory water drawdowns must be kept to a minimum or where time is a critical factor (i.e. economy, security or tidal influence). As the results are encouraging it is believed that more experimental evidence needs to be collected for the consulting and contracting engineer to take advantage of their two principal qualities : simplicity and rapidity.

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