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A mini slug test method for determination of a local hydraulic conductivity of an unconfined sandy aquifer

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ABSTRACT

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A new and efficient mini slug test method for the determination of local hydraulic conductivities in unconfined sandy aquifers is developed. The slug test is performed in a small-diameter (1 inch) driven well with a 0.25 m screen just above the drive point. The screened drive point can be driven from level to level and thereby establish vertical profiles of the hydraulic conductivity. The head data from the test well are recorded with a 10 mm pressure transducer, and the initial head difference required is established by a small vacuum pump. The method described has provided 274 spatially distributed measurements of a local hydraulic conductivity at a tracer test site at Vejen, Denmark. The mini slug test results calculated by a modified Dax slug test analysing method, applying the elastic storativity in the Dax equations instead of the specific yield, are in good accordance with the results from two natural gradient tracer experiments performed at the test site. The original Dax, the Bouwer and Rice, and the Chirlin analysing methods all led to an underestimation of the effective hydraulic conductivity by a factor of more than 2, when compared with the tracer tests. In contrast the spherical flow model of Karasaki et al. overestimated the results of the tracer tests by approximately a factor 1.4. The Dax and the Cooper et al. methods, assuming only radial flow to the partially screened well, yielded a better approximation of the horizontal hydraulic conductivity, than the Chirlin method, which also considers axial flow. This fact is suggested to be a result of aquifer anisotropy, as a significant higher horizontal than vertical hydraulic conductivity may suppress the significance of the axial flow component.

INTRODUCTION

Concern about the pollution threat to aquifers has led to a considerable effort in the last decade to describe the migration of pollutants in aquifers. It

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is recognized that the spatial variability of hydraulic conductivity, is one of the most important aquifer properties that controls the advection and macro-dispersion of conservative pollutants (e.g. Gutjahr et al., 1978; Anderson, 1979; Gelhar and Axness, 1983; Davis, 1986; Sudicky, 1986; Zhang and Neuman, 1990). The ability of groundwater flow models to predict the spread of pollutants in aquifers, is, therefore, strongly dependent on input of a detailed and reliable description of the spatial distribution of a local hydraulic conductivity (Andersen, 1988; Peck et al., 1988). For this reason there is a need for efficient and reliable methods to determine representative local hydraulic conductivities (Dagan, 1986; Gelhar, 1986; Peck et al., 1988; Molz et al., 1989).

Today the most convenient and economical methods for this purpose are in situ methods, such as the borehole flowmeter measurement techniques (Hufschmied, 1986; Hess et al., 1989; Molz et al., 1989, 1990) and multilevel slug test techniques (Molz et al., 1990). Molz et al. (1989), when comparing the two methods, advocate the use of the flowmeter techniques, because they are more convenient to use, and because in their study they were more accurate for delineating zones having higher values of hydraulic conductivity. Furthermore, the flowmeter methods are less sensitive to skin effects, i.e. relatively high or low hydraulic conductivity zones around the well caused by drilling procedures, than the slug test.

However, the slug test method may have some advantages in pollution investigations, e.g. the advantage of not requiring large amounts of water to be recharged into, or discharged from, the borehole, and it can be performed in connection with the sampling of ground water at the same levels (Andersen, 1988; Hinsby, 1990). Therefore, an effort was made to develop a combined drilling and slug test method which was suitable and reliable for determination of the vertical distribution of hydraulic conductivity in unconsolidated sandy aquifers.

The difficulty of ensuring undisturbed hydraulic contacts between the aquifer and the screened well interfaces, is a crucial aspect of in situ measurements of the hydraulic conductivity, because every drilling procedure disturbs the aquifer materials around the well (Keely and Boateng, 1987; Morin et al., 1988). In the method outlined here significant disturbances seem to be avoided by using small-diameter (1 inch) driven wells. The described mini slug test method in connection with the applied drilling technique is very convenient to use, and by avoiding gravel packs the method minimizes the risk of 'short-circuiting' aquifers.

The objective of this paper is to present a newly developed mini slug test method for in situ determination of a local hydraulic conductivity, which provides the possibility of determination of the spatial variability of the hydraulic conductivity (Bjerg et al., 1992). The applied slug test set-up is critically tested, e.g. for skin effects and reproducibility of the test results. The selection of an appropriate slug test analysing method is carefully considered by: (1) evaluation of the physical and hydrogeological set-up; (2) comparison of the results from a number of slug test models including steady-state and non-steady-state models, as well as radial, and combined radial and axial flow models (Cooper et al., 1967; Bouwer and Rice, 1976; Dax, 1987; Karasaki, 1988; Chirlin, 1991); and (3) comparison with the results from two large-scale natural gradient tracer experiments at the test site. The comparison of the methods includes a discussion of the importance of the storativity, which is determined by a small pumping test in the actual case. Furthermore, the influence of anisotropy is addressed in order to explain the relationship between the results obtained by the radial slug test models, the combined radial and axial slug tests models, and the tracer tests.

THE SLUG TEST AND ITS ANALYSIS

Hvorslev (1951) developed models to calculate the hydraulic conductivity for the surrounding formation by measuring the water flux to or from a well after removal or injection of a known volume of water. Later the method was further developed and modified by a number of authors (e.g. Ferris et al., 1962; Cooper et al., 1967; Bouwer and Rice, 1976; Dagan, 1978; Bredehoeft and Papadopulos, 1980; Dax, 1987; Hayashi et al., 1987; Karasaki et al., 1988; Marschall and Barczewski, 1989; Chirlin, 1991) to cover different settings and/or assumptions (boundary conditions).

How drilling procedures and well losses (e.g. skin effects and clogging) can affect the slug test results has also been addressed (Faust and Mercer, 1984; Moench and Hsieh, 1985; Sageev, 1986; Dax, 1987; Bouwer, 1989).

Steady-state conditions vs. non-steady-state conditions

The slug test analysing methods either rely on the assumption that steady-state conditions prevail, and neglect aquifer storativity (Hvorslev, 1951; Bouwer & Rice, 1976; Dagan, 1978), or they assume non-steady-state conditions, and take aquifer storativity into consideration (Ferris et al., 1962; Cooper et al., 1967; Bredehoeft and Papadopulos, 1980; Dax, 1987; Hayashi et al., 1987; Karasaki et al., 1988; Marschall and Barczewski, 1989; Chirlin, 1991). The steady-state approach assumes that magnitude and direction of the flow to the well is constant with time during the test. In contrast, the non-steady-state approach assumes that magnitude or direction of the flow changes with time. The differences between these two approaches have recently been discussed by Chirlin (1989). The analysis by Chirlin shows that the two approaches can lead to substantially different results. For approximately the last two decades the Cooper et al. (1967) method, assuming non-steady-state conditions, has been used for analysing slug test data from fully screened wells in confined aquifers, while the Bouwer and Rice (1976) method, assuming steady-state conditions, has been used for slug test analysis in partially screened wells in unconfined aquifers. Recently Dax (1987) simplified and approximated the Cooper et al. model and applied his model to partially penetrating wells in unconfined aquifers, assuming radial flow to the well.

For confined aquifers the radial flow steady-state and non-steady-state situation can be described mathematically in polar coordinates by the basic eqns. (1.1) and (2.1) (Bear, 1979; Freeze and Cherry, 1979) in Table 1.

Equation (2.2.b) is the solution to eqn. (2.1) for the head $H(t)$ inside the well (Cooper et al., 1967). By introducing the function $D(\alpha)$ (eqn. (2.2.a)) Dax simplifies and approximates the exact solution to eqn. (2.2.b), given by Cooper et al. Equations (1.1) and (2.1) are furthermore the fundamental equations governing the development of the Bouwer and Rice (1976) and the Dax (1987) equations (eqns. (1.2) and (2.2)), by analogy with the well-known Thiem's and Theis' equations for pumping test analysis of steady-state and non-steady-state conditions, respectively.

Radial flow models vs. combined radial and axial flow models

In partially penetrating wells combined radial and axial flow to the well is expected during the slug test (Hayashi et al., 1987; Karasaki et al., 1988; Chirlin, 1990, 1991). The models proposed by these authors consider combined non-steady radial and axial flow to partially screened wells in different settings, assuming an isotropic media. Hayashi et al. developed a model for pressurized slug tests of partially screened wells in tight formations. Chirlin modifies the Hayashi et al. method, to apply to medium and highly permeable aquifers. The model of Karasaki et al. is a spherical flow model, for the case where the screened interval of the well is small compared with the thickness of the aquifer, and can be approximated by a point, i.e. when the ratio between length and diameter of the screen is close to 1. If the ratio between length and radius of the well screens increases the significance of the axial flow component diminishes and for very large ratios the significance disappears. Hence the radial and 'axial' models will yield equal results. Similarly, the axial component may be of less importance if the vertical hydraulic conductivity is less than the horizontal hydraulic conductivity (anisotropic case). In this case, however, combined radial and axial flow models, considering the length of the

TABLE 1

Equations for slug test analysis

Steady state conditions	**Nonsteady state conditions**
The basic equation:	**The basic equation:**
1.1) $\frac{\delta^2 h}{2\delta r^2} + \frac{1}{r}\frac{\delta h}{\delta r} = 0$	2.1) $\frac{\delta^2 h}{\delta r^2} + \frac{1}{r}\frac{\delta h}{\delta r} = \frac{S}{T}\frac{\delta h}{\delta r}$
Initial conditions:	Initial conditions:
$h(r,0) = 0 \quad r > r_w$	$h(r,0) = 0 \quad r > r_w$
and	and
$H(0) = H_0 = V/\pi r_c^2$	$H(0) = H_0 = V/\pi r_c^2$
Boundary conditions:	*Boundary conditions:*
$h(r,t) = 0 \quad r = R_e, \quad t > 0$	$lim\ (r,t) = 0 \quad t > 0$
	$r \to \infty$
$lim\ h(r,t) = H(t) \quad t > 0$	$lim\ h(r,t) = H(t) \quad t > 0$
$r \to r_w$	$r \to r_w$
$lim\ 2\pi\ r_w K L \delta h(r,t)/\delta r$	$lim\ 2\pi\ r_w K L \delta h(r,t)/\delta r$
$r \to r_w$	$r \to r_w$
$= \pi r_c^2\ d\ H/\delta t$	$= \pi r_c^2\ d\ H/\delta t$
Bouwer and Rice analysis:	**Dax analysis:**
1.2) $K = \frac{r_c^2 \ln(R_e/r_w) \ln(H_0/H(t))}{2Lt}$	2.2) $K = \frac{r_c^2 \ln(H_0/H(t))}{L\ t\ D(\alpha)}$
Where:	*Where:*
1.2.a) $ln\ (R_e/r_w) = [\frac{1.1}{ln(P/r_w)} + \frac{A+B\ ln\ [(B_a-P)/r_w]}{L/r_w}]^{-1}$	2.2.a) $D(\alpha) = -\delta\ ln\ F(\alpha,\beta)/\delta\beta$ (*Dax*, 1987)
or if $P = B_a$	$\alpha = S\frac{r_w^2}{r_c^2}\frac{L}{B_a}$, $\beta = Tt/r_c^2$, $T = K \cdot L$
1.2.b) $ln\ (R_e/r_w) = (\frac{1.1}{ln(P/r_w)} + \frac{C}{L/r_w})^{-1}$	2.2.b) $F(\alpha,\beta) = (8\alpha/\pi^2)\int_0^\infty \frac{exp\ (-\beta u^2/\alpha)\ du}{u\ g(u,\alpha)}$
	$g(u,\alpha) = [uJ_o(u) - 2\alpha J_1(u)]^2 + [uY_o(u) - 2\alpha Y_1(u)]^2$.
1.2.a and 1.2.b are empirical equations determined by an electrical resistance network analog where A, B and C are constants for a given well screen geometry (L/r_w), Bouwer and Rice (1976).	*Where the functions $J_0(u)$, $J_1(u)$ and $Y_0(u)$, $Y_1(u)$ are the zero and first – order Bessel functions of the first and second kind, respectively* (*Cooper et al*, 1967; *Dax*, 1987; *Abramowitz and Stegun*; 1972). *$D(\alpha)$ is tabulated by Dax* (1987).

Notation: H_0, head in well at time $t = 0$; $H(t)$, head in well at time t; $h(r, t)$, head in aquifer at the distance r and at time t; T, transmissivity; S, storativity; K, hydraulic conductivity; R_e, effective radial distance over which h is dissipated (Bouwer and Rice, 1976); r_w, effective radius of the well (=0.0130 m, present study); r_c, nominal radius of the well (=0.0127 m, present study); r, distance from the well; L length of well screen (=0.24 m, present study); P, depth of penetration below the groundwater table; B_a, thickness of aquifer (=5.5 m, present study); $A = 2.12$, $B = 0.33$, $C = 1.67$ (determined for the present setting from Bouwer and Rice, 1976).

well screen and assuming isotropic conditions, would underestimate the true horizontal hydraulic conductivity, and the radial flow models could be more appropriate.

MATERIALS AND METHODS

The mini slug test set-up

The symbols of the slug test and the applied slug test set-up are shown in Figs. 1 and 2. The initial head difference (H_0), i.e. the difference between the water level inside and outside the well at time t_0, is established by a small electrical vacuum pump raising the water level in the well. The initial head difference can be accurately controlled by a vacuum-meter, a valve, and the read-out from the pressure transducer. A fixed vacuum can be supplied to the borehole, causing the water level in the well to rise to a new predefined equilibrium level, equivalent to the supplied vacuum. At this point the read-out from the pressure transducer will show the same value as before the fixed vacuum was supplied. After allowance for equilibration to the supplied vacuum, the vacuum is released and the falling water level in the well is

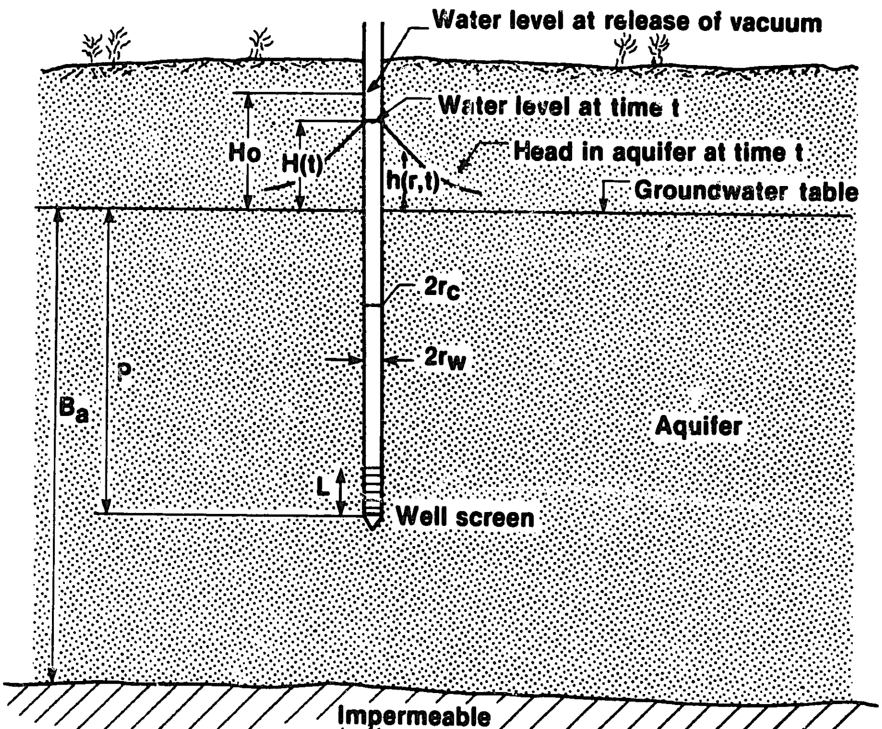

Fig. 1. Schematic illustration of a slug test in a partially penetrating and partially screened driven well in an unconfined aquifer.

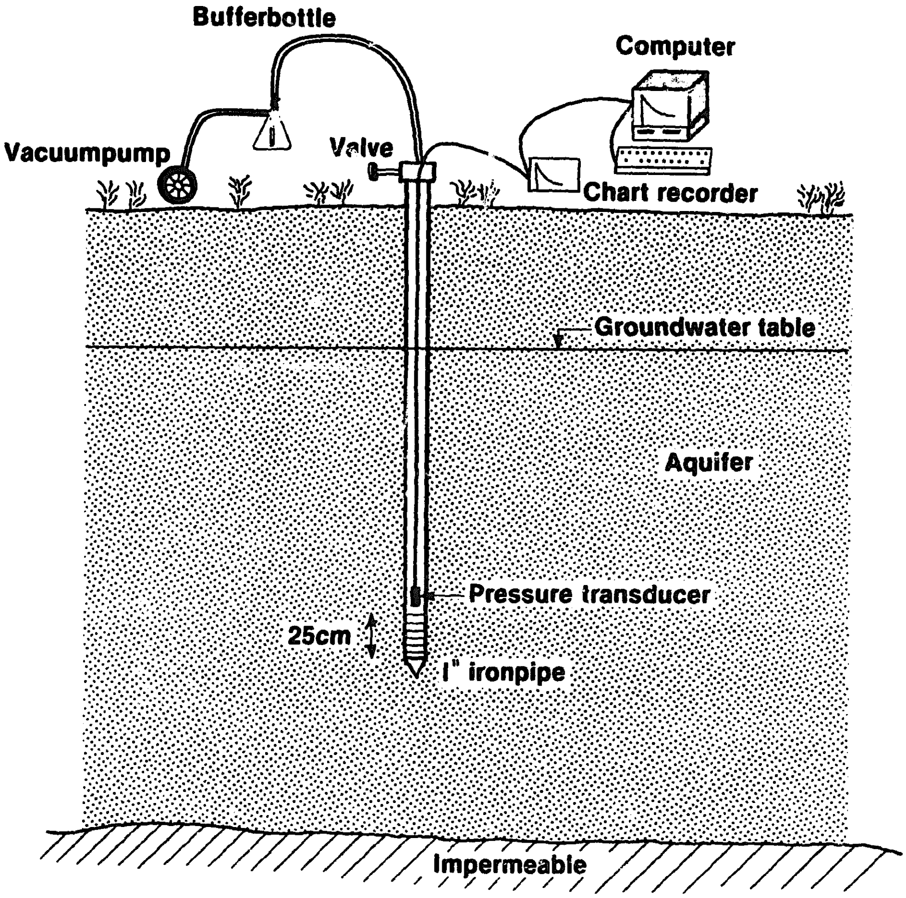

Fig. 2. Schematic representation of the applied mini slug test set-up.

recorded as a function of time (Fig. 3). In the study described in this paper the initial head difference (H_0) was generally 1–2 m.

When a slug test has been performed at one level the drive point can be driven further downwards if desired and a new slug test can be performed. In this way the vertical distribution of the hydraulic conductivity (see Bjerg et al., 1992) can be determined by the help of slug tests in successive intervals in only one driven well.

Field site description

The slug test described has been performed at 274 different locations in a 40 m × 200 m tracer test site, at levels approximately 6–10 metres below surface (m.b.s.) (30.5–34.5 m.a.s.l.). The wells were established in an unconfined sandy glaciofluvial aquifer, with the groundwater table at approximately 35.5 m.a.s.l., and the lower boundary of Weichselian glaciolacustrine clay at approximately 30.0 m.a.s.l. For further geological site description see Bjerg et al. (1992).

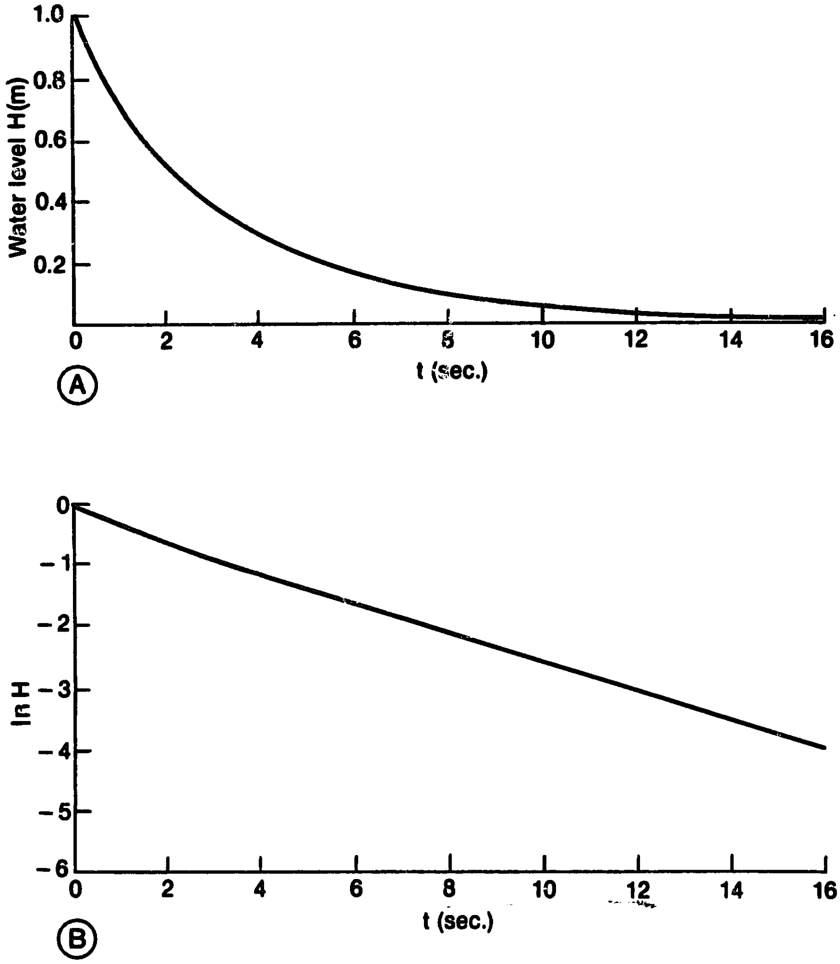

Fig. 3. (A) A typical record of slug test data, from the Vejen test site, Denmark. Sampling rate 30 Hz. (B) Semilog plot of the data from (A).

RESULTS AND DISCUSSION

Test of the mini slug test method

To get a representative local hydraulic conductivity for the aquifer at the well, one must be sure that there has been no significant disturbances of the aquifer materials around the well and that there has been no clogging or any other kind of well loss in the well screen. Although it is possible to overcome these problems, it can be a difficult task to ensure that there has been no disturbance of the aquifer materials around the well (Keely and Boateng, 1987; Morin et al., 1988). By using driven wells and small-diameter well pipes this problem should be minimized. In the present study several tests of the applied method have been performed to see how possible well losses and skin effects (Faust and Mercer, 1984; Moench and Hsieh, 1985; Sageev, 1986;

Bouwer, 1989) influence the results. These tests are: of exponential decay, of reproducibility, of well screen flow resistance, on effect of purging, on the sensibility to varying H_0 values, and finally on the effect of no equilibration of the imposed head difference.

Test of exponential decay

In Fig. 3 data plots of a typical slug test record are presented in a normal and a semi log plot. The plot in Fig. 3(B) shows a perfectly straight line illustrating the expected exponential decay and indicating a reliable test. If a disturbed and/or developed zone exists around the well, deviations from the straight line can be expected (Bouwer, 1989). Exponential decay was observed in almost all the tests.

Test of reproducibility

To test the reproducibility of the results from the slug test developed, several tests were performed in selected wells at short intervals (min) and after longer periods (months). The results from these tests are shown in Table 2. They show that the slug test results can be reproduced very well.

Test of well screen flow resistance

To test the construction of the applied well screen for well loss caused by flow resistance through the screen, the well screen was tested in an open 4 in well and in a laboratory basin. The results from these tests showed that the initial well screen construction actually can cause significant flow resistance if

TABLE 2

Reproducibility of the mini slug test results (*K* values)

Test well	*N*	Date	$K(\times 10^{-4} m s^{-1})$	SD
1	3	February 1990	3.0	0.06
	1	April 1990	2.9	–
	5	May 1990	3.3	0.07
2	3	February 1990	3.7	0.05
	2	April 1990	3.7	0.06
	12	May 1990	3.7	0.18
3	9	February 1990	7.3	0.19
	3	April 1990	7.7	0.06

N is number of tests, *K* is hydraulic conductivity, and SD is standard deviation.

the hydraulic conductivity of the aquifer is higher than approximately $3 \times 10^{-3}\,m\,s^{-1}$. A slight modification of the screen has removed this problem, but further investigation on how the test reacts at high hydraulic conductivities is continuing.

Test on effect of purging

Purging can have an effect on the estimation of the hydraulic conductivity of the aquifer (Barcelona et al., 1985). This phenomenon was studied by slug testing a well after purging with different water volumes. In Fig. 4 it can be seen that purging as expected increases the hydraulic conductivity. Generally purging is wanted or required in order to optimize the performance of the well, and to get 'clear' water samples. To get similar test conditions 25 l have been purged from the wells in the present study, before slug testing. Theoretically too much purging could increase the 'natural and undisturbed' hydraulic conductivity around the well, due to the removal of the fines from the aquifer materials around the well, while too little purging could lead to an underestimation of the true hydraulic conductivity due to clogging of the well screen.

Test on sensibility to varying H_0 *values*

The sensitivity of the hydraulic conductivity to different H_0s was tested by varying the initial head between 0.2 and 5 m in a specific well. The tests showed that varying the initial head between these limits had no significant effect on the computed values of the hydraulic conductivity.

Test on the effect of lacking equilibration

Finally a test was performed to determine whether a possible lack of equilibration to the imposed vacuum (head difference), could influence the test

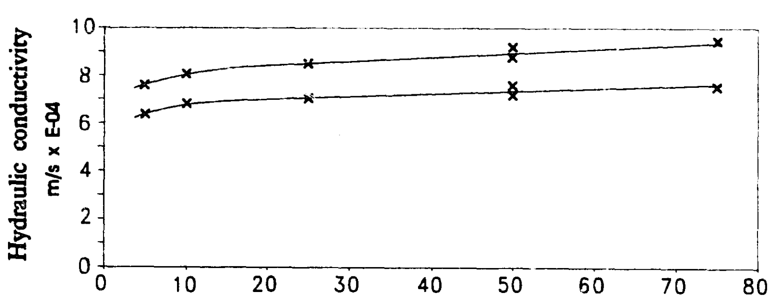

Fig. 4. The slug test measured hydraulic conductivity as a function of purged water volumes, in two tested wells.

results. This test could not demonstrate a significant difference on the results obtained, whether the vacuum was released exactly at the point of vacuum-equilibration or several minutes later. But a minor effect was observed if the vacuum was released before vacuum-equilibration.

The tests performed document that the applied drilling techniques and the applied well screen in combination, do not disturb either the formation or the hydraulic contact between the aquifer and the borehole, in a manner of practical interest. Furthermore, they show that the applied mini slug test set-up, seems to be a realiable basis for estimating a representative local hydraulic conductivity.

Computation of the hydraulic conductivity

We have performed an evaluation of different slug test models to ensure that the calculation of the hydraulic conductivity was based on a sound model, which takes the actual aquifer conditions and physical set-up into account. Special emphasis is placed upon the steady-state vs. the non-steady-state assumption and on the flow field (radial vs. combined radial and axial).

The Bouwer and Rice (1976) vs. the Dax (1987) method

As demonstrated in a previous section the Bouwer and Rice method relies on a steady-state assumption, while the Dax method is based on a non-steady state assumption. To calculate the hydraulic conductivity and to evaluate these assumptions and the importance of the storativity in the actual case the two methods are compared.

By comparing eqns. (1.2) and (2.2) in Table 1 it is clear that $\ln(R_e/r_w)/2$ in eqn. (1.2) must be equal to $1/D(\alpha)$ in eqn. (2.2), to get the same estimations of K, from the Bouwer and Rice and the Dax methods.

In Fig. 5 the reciprocal of the Dax function $D(\alpha)$ is shown as a function of the storativity. Furthermore, the lower and upper limits for the present setting for the 'equivalent' Bouwer and Rice function $\ln(R_e/r_w)/2$ have been indicated. As it appears the function $\ln(R_e/r_w)$ is not a function of the storativity (see also eqns. (1.2.a) and (1.2.b) in Table 1): though, $\ln(R_e/r_w)$ is a function of the depth to the bottom of the well screen (P), the location of the lower impermeable boundary (B_a) and of the well screen geometry (L/r_w). The upper limit of $\ln(R_e/r_w)/2$ in the present setting is where $P = B_a = 5.5$ m and the lower limit is where $P = 0.5$ and $B_a = 5.5$ m. The ratio between $1/D(\alpha)$ and $\ln(R_e/r_w)/2$ in Fig. 5 illustrates the relation between the Dax-, and the Bouwer and Rice-determined hydraulic conductivities, as a function of the storativity, for the present setting. It appears that if the storativity is 'high',

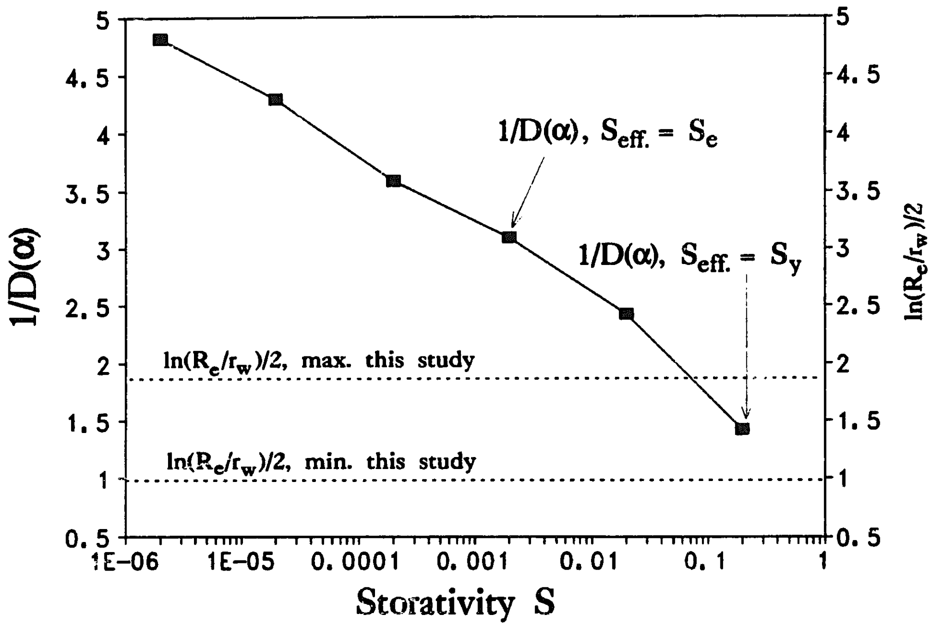

Fig. 5. The reciprocal of the Dax function $D(\alpha)$ as a function of the storativity. The limits for the Bouwer and Rice function ln $(R_e/r_w)/2$ for the present setting are indicated for comparison. The upper limit for ln $(R_e/r_w)/2$ is where $P = B_a = 5.5$ m and the lower limit is where $P = 0.5$ and $B_a = 5.5$ m.

i.e. in the order of the specific yield (S_y) for an unconfined sandy aquifer ($> 10^{-1}$, as assumed by Dax, 1987), the two methods give comparable results (as concluded by Dax). Conversely if the storativity is 'low', i.e. $< 10^{-1}$ the Dax method computes significantly higher values of a local hydraulic conductivity, for the present setting.

This study demonstrates that an effective storativity (S_{eff}) expressed only by the elastic storativity ($S_e \approx 2 \times 10^{-3}$), and not the specific yield ($S_y \approx 2 \times 10^{-1}$), should be used in the computation of the hydraulic conductivity by the Dax method. This is a consequence of the analogous phenomenon of delayed water table response (delayed gravity response) known from pumping tests in unconfined aquifers (e.g. Boulton, 1973; Neuman, 1975, 1987; Gambolati, 1976; Walton, 1978). In pumping tests three segments on the drawdown vs. time curve are normally observed. In the first segment the water table in the observation wells reponds exactly like the head in a non-leaky artesian aquifer and the drawdown follows a Theis curve (see Fig. 6 and Neuman, 1975). In this short period it is only the elastic storativity (S_e) that responds to the applied head difference (Gambolati, 1976).

In the second segment at intermediate times the delayed water table response affects the drawdown, resulting in a flat curve segment. At later times

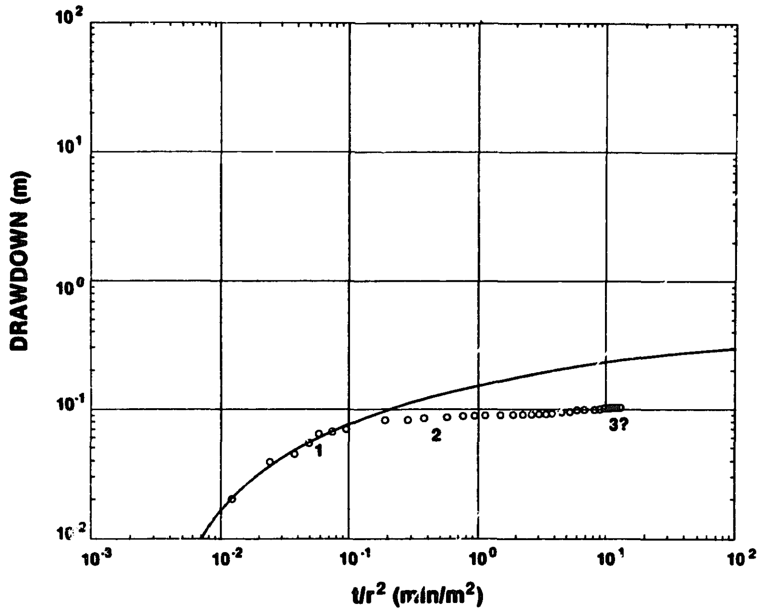

Fig. 6. Pumping test data from the tracer test field with a fitted Theis curve. The pumping well and the observation well were fully penetrating. $Q = 2.5\,m^3h^{-1}$, $r = 1.63\,m$. The numbers indicate the three segments discussed in the text.

a somewhat steeper segment is observed, indicating that the effective storativity now is equal to $S_y + S_e$. At this time the drawdown curve once again follows the Theis curve.

Similarly, in this study it has been assumed that the water table either does not, or only at later times, affect the progress of the slug test. When no skin effects are present, a semi log plot of the water-level data vs. the elapsed time yields a perfectly straight line in the beginning of the test. Later on a deviation from the straight line is sometimes observed, at this point the change in the water level in the well is slower than expected (Bouwer, 1989). By analogy with the observations from pumping tests it is assumed, that this phenomenon is the result of the delayed water table response, and that the course of the slug test curve in the beginning (the straight line segment of the curve) is influenced only by the elastic storativity of the aquifer. The slug tests in this study generally last only 10–30 s, and generally only the straight line segment is observed and recorded. Therefore, it was assumed that an elastic storativity representative for the aquifer should be used in the calculation of the hydraulic conductivity.

In the light of this a small pumping test has been performed in the tracer test field (Fig. 6), to determine the elastic storativity. The drawdown curve in Fig. 6 comes in three parts as previously described but the last segment of the curve is only just beginning due to the short pumping time of the test. The performed pumping test thus progresses as expected and it appears that the

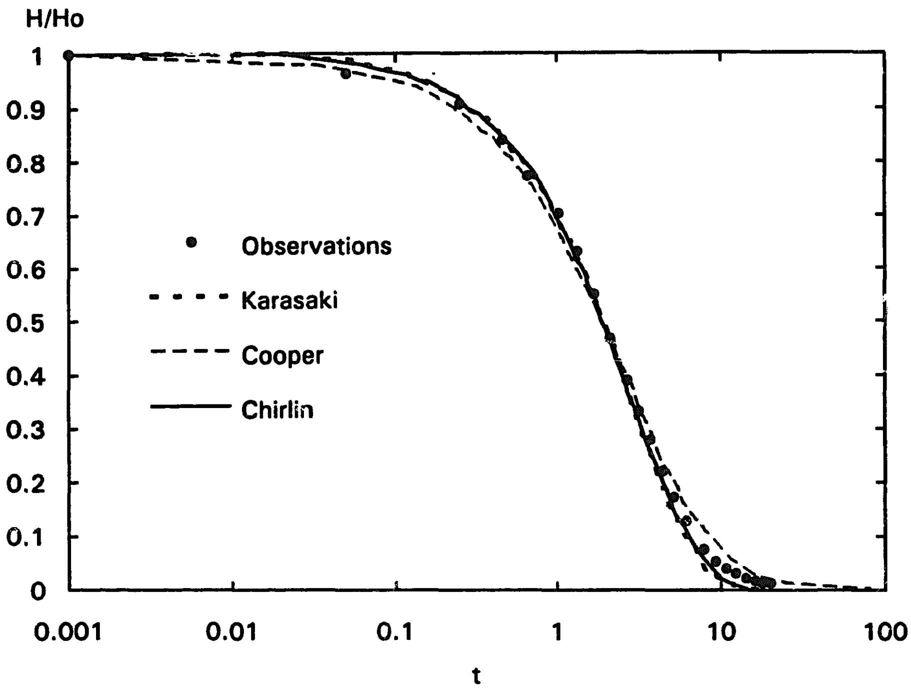

Fig. 7. Slug test data from a well in the tracer test field, matched with type curves from Chirlin (1991), Karasaki et al. (1988) and Cooper et al. (1967). The type curves are for $\alpha = 1 \times 10^{-4}$, and for the Chirlin type curve $L/r = 19$.

first curve segment lasting for approximately the initial 15 s ($t/r^2 \approx 10^{-1}$, in Fig. 6) of the test can be fitted very nicely by the Theis curve. The fitted Theis curve in Fig. 6 estimates an elastic storativity for the unconfined aquifer of 2.1×10^{-3}. This value used as S_e is similar to values obtained in a comparable aquifer described in Neuman (1975). The value is further supported by the match of the slug test data with the type curves of Chirlin (1991), Karasaki et al. (1988) and Cooper et al. (1967). This match (Fig. 7) clearly shows that the storativity in the test aquifer is of an order of 10^{-3} or less.

In Fig. 8 the 274 determinations of the hydraulic conductivity computed by the modified Dax method ($S_{eff} = S_e = 2.1 \times 10^{-3}$) are illustrated as a relative frequency polygon and compared with the relative frequency polygons from the equivalent determinations by the Bouwer and Rice, and Dax methods ($S_{eff} = S_y = 2 \times 10^{-1}$). It appears that the modified Dax method computes significantly higher values of the hydraulic conductivity than the two other methods, while the Bouwer and Rice and Dax methods produce similar results. Thus $K_{Dax}(S_e)/K_{Dax}(S_y) = 2.2$ in the present study using $S_y = 2 \times 10^{-1}$ (estimated value) and $S_e = 2 \times 10^{-3}$ (from the aforementioned pumping test), while the ratio between the geometric mean [$K_g = \exp(1/N \, \Sigma \ln K)$] of $K_{Dax}(S_e)$ and $K_{B\&R}$ is 2.3. The geometric mean of the 274 K_{Dax} (S_e) estimations is $5.0 \times 10^{-4}\,\mathrm{m\,s^{-1}}$. This value is in good

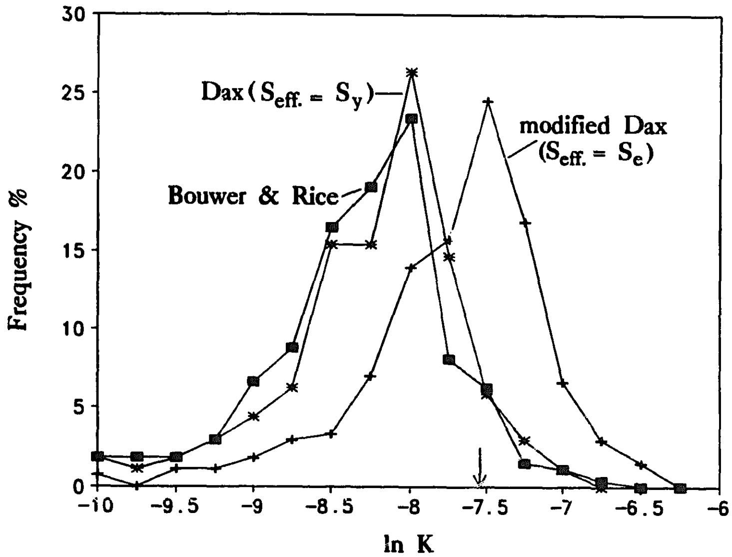

Fig. 8. Relative frequency polygons for the log-transformed 'Bouwer and Rice' —, and the 'Dax' computed hydraulic conductivities at 274 slug test locations at the Vejen test site. The Dax method has been applied with an 'unconfined' effective storativity ($S_{eff} = S_y$) as originally suggested, and in a modified version with a 'confined' effective storativity representing only the elastic storativity (S_e) of the aquifer. The arrow indicates the effective log-transformed tracer-test-estimated hydraulic conductivity.

agreement with the results from two large-scale natural gradient tracer tests performed at the test site (Bjerg et al., 1992). The arrow in Fig. 8 indicates the tracer-test-estimated effective hydraulic conductivity at the test site.

Cooper et al. (1967) vs. Dax (1987)

The Dax model is an approximation of the Cooper et al. model and it is important to know the relation between these two methods in our case. To make this comparison a total of 28 mini slug tests have been selected and computed by the Dax model and the Cooper et al. type curve matching procedure (Fig. 7). The geometric means of the 28 results are 4.2E–04 m s^{-1} and 3.0E–04 m s^{-1} for the Dax and the Cooper et al. methods, respectively. The ratio between the results from the two methods is relatively constant as shown by a standard deviation of 0.09 of the 28 ratios. That is, the Dax method overestimates the Cooper et al. results by about 40% at the storativity determined in this study. However, taking the uncertain type curve fitting procedure (±33%, Anderson and Zoback, 1982), the uncertain knowledge about the variability of the storativity, and the fairly constant ratio between the results from the two methods into consideration, the use of the Dax model seems reasonable, as an approximation to the radial flow situation.

Furthermore, as stated by Chirlin (1989):

"In practice there is also a premium on mathematical tractability and ease of use, as well as incomplete knowledge of the field setting. Therefore, approximate models can be attractive if their limitations are known and respected."

Radial vs. combined radial and axial flow

In order to discuss the assumption of radial flow, the Dax and the Cooper et al. results are compared with the results from the combined radial and axial flow models of Chirlin (1991) and Karasaki et al. (1988). The aforementioned 28 slug tests have been computed by the type curve matching procedures in these models.

The slightly better fit between the slug test data from the present study and the 'axial flow' type curves, than between the slug test data and the Cooper et al. type curves (Fig. 7), indicates that axial flow is present. However, as can be seen from the type curves of Chirlin (1991), this is no certain proof that axial flow has a significant influence on the results of the slug test analysis. Radial flow could predominate, e.g. as a consequence of aquifer anisotropy, and thereby suppress the influence of the axial flow component, without a significant change in the shape of the plotted data curves. That radial flow predominates in the present setting is de facto what the comparisons between the results from the Dax, the Cooper et al., and the Chirlin slug test analysing methods, and the two large-scale natural gradient tracer tests, indicates.

The geometric mean of the Dax results from the 28 slug tests, is $4.2 \times 10^{-4}\,\mathrm{m\,s^{-1}}$, while the geometric mean for the Chirlin and the Karasaki et al. results is $1.7\,\mathrm{m\,s^{-1}}$ and $5.9 \times 10^{-4}\,\mathrm{m\,s^{-1}}$, respectively. The ratio between the geometric mean of the results from the Dax method and the results from the Chirlin method is 2.5, i.e. the results from the Chirlin method, and the Bouwer and Rice method compare well, and are significantly underestimating the tracer test results. The results from the Karasaki et al. method overestimate, by a factor of 3.5, the results from the Chirlin method, which in the case of isotropic conditions should yield the correct estimates. This overestimation, compared with the Chirlin results, and in fact all the other test results, is a consequence of 'neglecting' the length of the well screen in the calculation of the hydraulic conductivity. That is, by using the Karasaki et al. model in the actual case, it is assumed that the ratio between the well screen length and radius (L/r) is 2. This ratio is de facto 19 for the actual case.

The ratios between the Cooper et al., the Chirlin, and the Karasaki et al. methods are all constant. This is a consequence of the fixed positions of their type curves, at a fixed storativity.

The comparison between the results from the radial flow models, the results from the 'axial' flow models, and the results from the tracer tests, indicates that anisotropy of the aquifer plays a significant role in the slug test analysis in the present study. Anisotropy is expected in the geological deposits at the test site, as significantly higher horizontal than vertical hydraulic conductivity is normally expected for fluvial deposits (Freeze and Cherry, 1979; Chirlin, 1990). This is further supported by the Cape Cod investigations (e.g. LeBlanc et al., 1991), which estimated a ratio of horizontal to vertical hydraulic conductivity of 2 : 5 in glaciofluvial deposits similar to the deposits at our test site (the Twin Lake investigation which estimated a mean ratio of 4 (e.g. Killey and Moltyaner, 1988)), and maybe by the Borden Site investigations (Zhang and Neuman, 1990)? Chirlin (1990) states that anisotropy is not easily addressed in slug test interpretation at the present time. This study suggests that radial flow models may be one way to overcome this problem in aquifers where the horizontal hydraulic conductivity is significantly higher than the vertical hydraulic conductivity. Finally, the small difference, and the fairly constant ratio, between the Dax results and the Cooper et al. results makes it reasonable to use the Dax results to estimate the variability of the hydraulic conductivity of the test aquifer (Bjerg et al., 1992).

CONCLUSIONS

A new and efficient mini slug test method for the determination of local hydraulic conductivities in sandy unconfined aquifers has been developed and introduced. Several tests of the method have been performed to verify the applied slug test set-up, e.g. the tests for skin effects. These tests show that the slug test results can be consistently reproduced, that no significant skin effects have been present, and that the applied mini slug test set-up seems to be a reliable basis for estimating a representative local hydraulic conductivity. Furthermore, a modified Dax (1987) slug test analysing method has been introduced. In this method the elastic storativity, determined from a short pumping test in the aquifer, has been used in the Dax equations, instead of the specific yield. This approach has shown favourable results. By comparison with two large-scale tracer tests the Bouwer and Rice (1976) method, the Chirlin (1991) method, considering axial flow, and the Dax method using specific yield as the effective storativity, all led to an underestimation of the expected average local hydraulic conductivity by a factor of more than 2. In contrast the spherical flow model of Karasaki et al. (1988) overestimated the expected hydraulic conductivity, as a consequence of neglecting the length of the well screen. The fact that the slug test models of Dax (1987) and Cooper et al. (1967), assuming radial flow, yield better estimations of the expected hydraulic conductivity than the Chirlin (1991) model, also considering axial flow, indicates that aquifer anisotropy plays a significant role in the slug test results, in the present setting. That is, the axial flow component is probably suppressed by a significant higher hydraulic conductivity in the horizontal direction than in the vertical direction.

The hydraulic conductivity values, determined from the modified Dax method, and the spatial variability of these, have been successfully compared with the results from two large-scale natural gradient tracer experiments, at Vejen, Denmark (Bjerg et al., 1992).

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