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Hydrogeophysical Concepts in Aquifer Test Analysis

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Aquifer test data analysis is an art leading to reliable hydraulic parameter identifications rather than a mechanical curve fitting. Most often aquifer test data processing is achieved by matching the data with suitable type curve without detailed interpretations of deviations from this curve. In fact, relevant interpretations might yield valuable qualitative and quantitative features about the subsurface geological composition of the aquifer domain at least in the well vicinity. The view taken in this paper is to obtain additional information from various data segments by considering two or more successive measurements. Such a detailed investigation of aquifer test data is referred to herein as the "hydrogeophysical" approach since it yields important clues about the geological set up as well as the groundwater flow regime in the well vicinity. Main features of hydrogeophysical investigation are given based on author's experience. It is hoped that additional points will be supplemented in future applications by other groundwater hydrologists. The application of hydrogeophysical concepts are exemplified for some field data available in the groundwater literature.

Introduction

Available aquifer test data in terms of time- and/or distance-drawdown records help to identify the aquifer parameters such as the storage coefficient, transmissivity, hydraulic resistance, delayed yield factor, leakage factor, *etc*. However, any mechanical curve fitting without the qualitative interpretation of the data is an incomplete task. Type curve fittings devoid of physical reasoning lead to erroneous hydraulic parameter estimations and interpretation of the groundwater hydraulic mechanism. It is, therefore, advocated in this paper that prior to application of any ready-type curves to available data, one should do his or her best to extract physical interpretations from different types of paper (ordinary, semi- or double-logarithmic paper). The geology must not be forgotten in any hydrogeophysical reasoning.

With the advances in analytical and numerical modeling of groundwater flow toward wells, many scientific papers have discussed the response of an idealized aquifer geometry or flow regime under a set of simplifying assumptions with initial and boundary conditions. However, all the theories published so far and yet to be published should be viewed with their restrictive assumptions in any application. For instance, Theis (1935) solution and its various modifications are derived on the basis of ideal initial as well as boundary conditions in addition to some assumptions not generally found in nature except in the average sense. In some cases, the deviations of the field data from type curve are more significant than the use of the curve itself in calculating the aquifer parameter values. Hence, useful physical information should be obtained from the interpretation of these deviations by means of hydrogeophysical concepts.

The purpose of this paper is to present hydrogeophysical concepts based on field data plot and their comparison with the overall fitting type curve. It must be one of the major objectives of any hydrogeologist to obtain interpretations with the hydrogeophysical concepts in order to gain experience in his career and to deal with different situations in the future. It is not difficult to train an unskilled person for conventional type-curve matching and subsequent quantitative parameter estimations, but hydrogeophysical concepts reveal qualitative interpretations that require basic hydrologic, geologic and physical concepts at work.

Hydrogeophysics

This term is coined herein distinctively from the classical terminologies of "geohydrology", "hydrogeology" and "geophysics". It can be defined as a branch of earth sciences which deduces scientific information and interpretations about the physical behaviors of geological formations which are saturated with water. Hydrogeophysical concepts can be applied to aquifer test data only when there are deviations from the matched type curves. Furthermore, deduction of information is achieved through the plot of drawdown *versus* time or distance on various types of paper. It is, in fact, similar to what a physicist try to obtain of information by examining X-ray sheets, likewise hydrogeologist should learn simple ways of qualitative field data sheet interpretations. Such simple interpretation techniques are already provided by Şen and Al-Baradi (1991). Hydrogeophysics help to gather information about the following main points.

i) Geometrical type of streamlines that represent groundwater flow pattern within a certain flow domain. Among the most common streamline types are regular such as radial, elliptical, linear, spherical or irregular patterns.

ii) Hydraulic flow regimes which show the energy dissipation during the groundwater flow. In general, Darcian (linear) and non-Darcian (non-linear) flows are two complementary alternatives. However, groundwater flow laws have been applied in aquifer analysis overwhelmingly for Darcian cases (Theis 1935; Hantush 1958; Boulton 1960, *etc.*) whereas non-Darcian flows are relatively new in groundwater flow toward wells (Şen 1986, 1987, 1988, 1989a).

iii) Flow domain medium types are either porous or non-porous like fractured or karstic media. Again most of the attention has been directed to porous medium whereas others appear rather scarely in the literature. This is due to difficulties in the analytical solutions of groundwater movement equation.

iv) Hydrogeophysical concepts help to dertermine whether the aquifer material is homogeneous or not. In this connection it is also possible to know the spatial changes that might occur in the hydraulic parameters. For instance, the classical barrier effect, *etc.*

v) The checking of Jacob straight line validity is also among the most important hydrogeophysical concepts (Şen 1989b).

vi) Identification of major aquifer types (confined, unconfined or leaky) and related relevant interpretations are among the duties of hydrogeophysics.

vii) Identification of aquifer parameters from an unsteady groundwater flow record such as the aquifer test data. The best available average solution results from the suitable type curve matching to these data usually on double logarithmic paper. The local deviations from such a curve must be well documented. In some special cases similar graphical averaging may be accomplished by using semi-logarithmic paper. It is among the scopes of the hydrogeophysical concepts to identify the local significant persistent deviations with plausible physical explanations.

viii) The type curve methods assume that the aquifer is aerially unlimited, *i.e.,* extensive. On the other hand, Dupuit assumption in unconfined aquifers implies that in most groundwater flows the slope of the phreatic surface is very small. The fact that these conditions do not occur in nature leads to deviations, *i.e.,* errors hidden in the aquifer test data. Although such differences do not make great harm to the quantitative accuracy in many cases but need further reasoning with hydrogeophysical concepts for additional and practically useful interpretations.

ix) Due to elastic lag in confined aquifers and especially capillary fringe lag in unconfined aquifers, the storage coefficient calculation from short aquifer tests leads to comparatively smaller values than the asymptotic true value. Besides, due to aquifer material heterogeneity and/or thickness variations, the transmissivity might show fluctuations around an average value. Such systematic or erratic deviations in the parameter estimations may be dealt with the hydrogeophysical concepts. It is very difficult to determine the aquifer parameters in heterogeneous aquifers especially by means of conventional aquifer tests. In addition, there is also a need to address the uncertainties in the parameters being identified. Attempts have been made to study these by means of so-called stochastic continuum methods (Follin 1992) as well as a discrete approach (Black 1993). These studies show very clearly that the presently used aquifer test methods based on various types of idealized flow patterns are inappropiate (to various degrees) because of problems with definition of the support scales etc. It is in fact already known beforehand that it is irrelevant to perform the analysis on the basis of such simplified solutions.

As a consequence, today many investigators try to apply statistical techniques (deMarsily *et al.* 1983) combined with inverse modelling (LaVenue and Rama Rao 1992) in order to determine the hydrological parameters by matching observed and model curves of *e.g.* pumping tests, rather than to try to match standard type curves based on highly idealized flow patterns. This is particularly true in cases where it is obvious that observation data will deviate significantly from those of the type curves. Moreover, this approach provides measures on the uncertainties in the parameter data.

Nevertheless, the situation today is that many investigators (particularly in engineering problems) apply the 'classical' aquifer test methods. Hence, it is of value to see what possible information that could be extracted from these tests. The present paper contributes to this by demonstrating some ideas on how to explain various causes for the deviations from the 'standard curves'. The various explanations to the deviations will then guide the practicing engineer on how to proceed the aquifer analysis.

It is not possible to present a complete list of what a hydrogeologist can interpret through the hydrogeophysical concepts but the more he applies them the more he will be equipped with further insights into the meaningful physical aquifer test data interpretations.

Applications

The best way to gain appreciation in hydrogeophysical concepts is through the worked field examples. For this purpose the first example is taken from Kruseman and de Ridder (1990, page 64) as the aquifer test data from "Oude Korendijk". The geological well site description, type curve application and quantitative aquifer parameter estimations are presented by them in detail. For the sake of hydrogeophysical concepts discussion, their Fig. 3.6 is reproduced herein as Fig. 1. A close inspection of relative data points with respect to the Theis curve shows very clearly that there are significant deviations. Unfortunately, a mechanical type curve matching to overall data gives only suspective parameter estimates as average values equal to $S = 1.6\times10^{-4}$ and $T = 392$ m^2/day. However, the following hydrogeophysical interpretations can be made concerning the data.

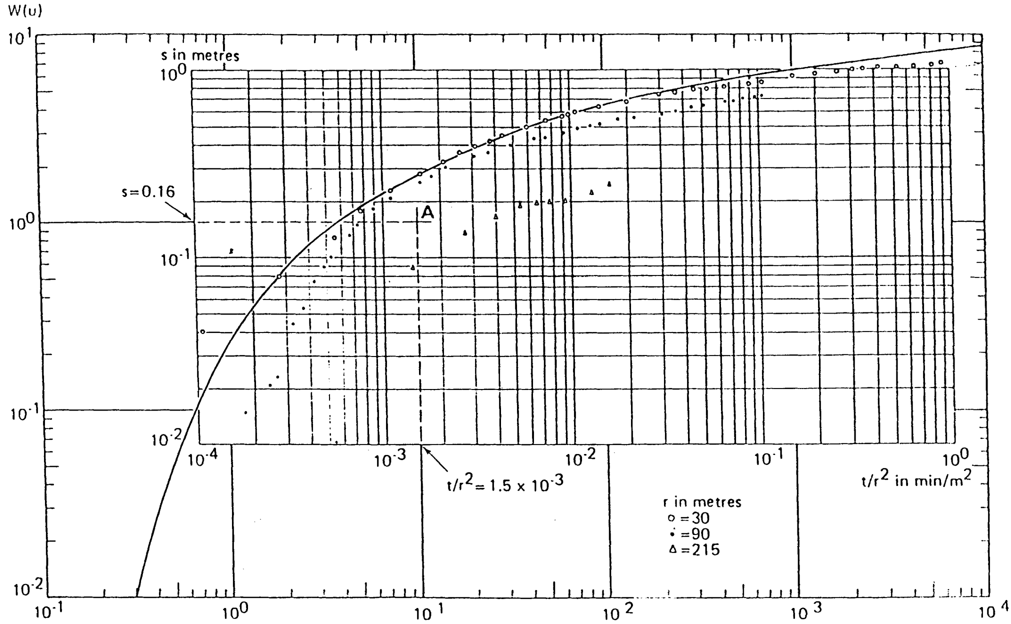

Fig. 1. Type Curve and Field Data from Oude Korendijk (Kruseman and de Ridder 1990).

i) The type-curve matching has been mechanical without any further concern since all of the field data fall below the Theis curve. However, in order to have average aquifer parameters the field data should lie in a rather balanced manner above and below this curve, if possible. Nevertheless, the first part of the type curves (r = 30 m) seems to fit the Theis curve but afterwards deviations occur perhaps due to leakage.

ii) It is not possible to match the field data in Fig. 1 with Theis type curve as shown but other suitable type curves must be tried in order to have representative aquifer parameter estimates.

iii) For small r/t^2 values, *i.e.*, either for small times or big distances the field data lie consistently below the Theis type curve. It means physically that the field data pattern has steeper slope than the type curve for early portions of data and smaller slope for late portion. However, for moderate data portions this patterns has almost the same slope as it is evident from Fig. 1. Increase in slope implies excessive energy dissipation than the laminar (Darcian) flow. Such an interpretation is indicative of non-Darcian flow which, in turn, reminds us that the flow domain might be non-porous.

iv) Among the classical non-porous media are the media of coarse or very fine porous medium, fractured medium or karstic medium. It has already been shown by Şen (1989a) that the flow regime is non-Darcian for these data since Reynolds number is 27 which is far greater than the upper limit (10) of Darcian flow.

v) It is interesting that the initial portion of field plot (about ten data points) confirms very clearly the existence of a straight line. It implies that

$$\log W(s) \, \alpha \log\left(\frac{t}{r^2}\right) \tag{1}$$

or

$$\log W(u) \, \alpha \log\left(\frac{1}{u}\right) \tag{2}$$

in which α is the proportionality sign. Such linear relationships on double logarithmic paper have been observed in groundwater flow toward wells in the case of large diameter well aquifer tests (Papadopulos and Cooper 1967). However, the slope in this case is equal to 1 whereas herein it is equal to almost 2. Physically, unit slope implies that initially the whole pump discharge comes from the available water in the well storage with no aquifer resistance. Herein, the large diameter is out of question but still there is a straight line appearance with greater slope than one. Increase in the slope might show that the aquifer material around the well is composed of coarse grains hence there is rather an easy (almost without resistance) entrance of water to the well.

vi) The aquifer test data from piezometer 215 m away fall altogether further below the other field data from other piezometers. This discrepancy indicates systematic heterogeneity in the aquifer material composition, *i.e.*, changes in hydraulic properties with distance from the well.

vii) Only moderate data from piezometer r = 90 m and early as well as moderate data from the other piezometer follow type curve rather closely. However, late data patterns from both piezometers show systematic downward deviations. This indicates recharge to the aquifer from adjacent layers. In fact, the geological cross-section presented by Kruseman and the Ridder (1990) for the aquifer test site shows that the main aquifer composed of coarse sand and gravel is overlain by rather thick fine-sand layer that gives rise to leakage.

viii) The field data points are not haphazardly different from each other and therefore, it can be concluded that the aquifer has regional homogeneity.

ix) The field data plot from piezometer at far distance have a sort of S-shape. As a result there appears delayed recharge.

The second example is also from Kruseman and de Ridder (1990, p. 66, Fig. 3.7) concerning Jacob straight line fit to field data from piezometer r = 30 m during aquifer test at "Oude Korendijk". Once again, the mechanical fitting, this time, a straight line is very obvious. In theory, the straight line is valid only for the late time-drawdown data. On the contrary, in their Fig. 3.7 (Fig. 2 herein) the straight line is fitted to early time data which is against the basic theoretical principle. It is interesting to notice that the late time-drawdown come along with another straight-line which is correct at least theoretically. On the basis of this line the aquifer parameters are estimated as T = 572 m^2/day and S = 3.0×10^{-5} which are significantly different from the ones given by Kruseman and de Ridder (1990) as T = 385

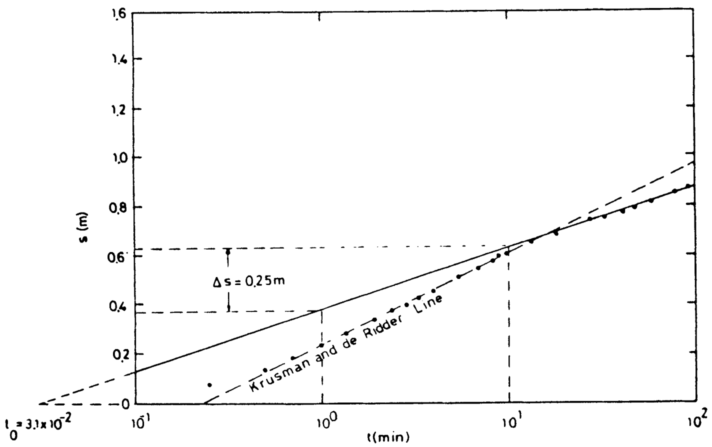

Fig. 2.
Straight-Line Method for Oude Korendijk Data.

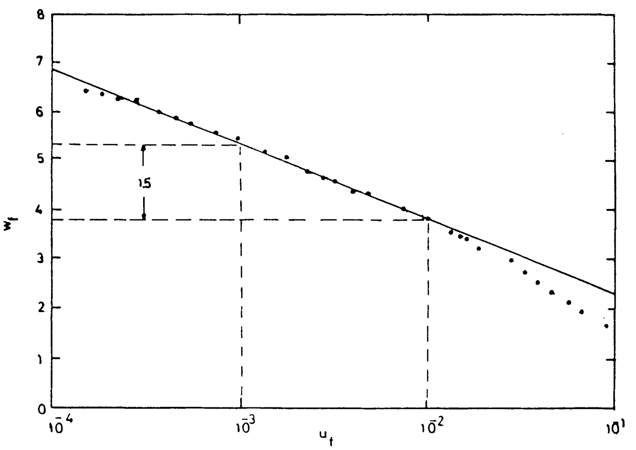

Fig. 3.
Dimensionless Time-Drawdown Data.

m²/day and $S = 1.7\times10^{-4}$. Hence, there are 32 per cent under-estimation in the transmissivity and 82 per cent over-estimation in the storage value. Besides, Kruseman and de Ridder (1990) did not give any reason for choosing their straight line. It is believed that mechanical concepts have led to these erroneous results.

Furthermore, two straight lines with different slopes for the same aquifer data imply physical existence of different layering in the aquifer configuration. In order to check whether the Jacob method application is valid even with the late time-drawndown data, dimensionless time-drawdown data are calculated according to the procedure presented by Şen (1989b). This dimensionless data plot is presented in Fig. 3 for late time. The important point is that the dimensionless straight line slope is equal to 1.5 which is significantly smaller than the standard Jacob slope of 2.3. It is known that the small slope implies recharge and this conclusion is consistent with type curve deductions in the previous paragraph.

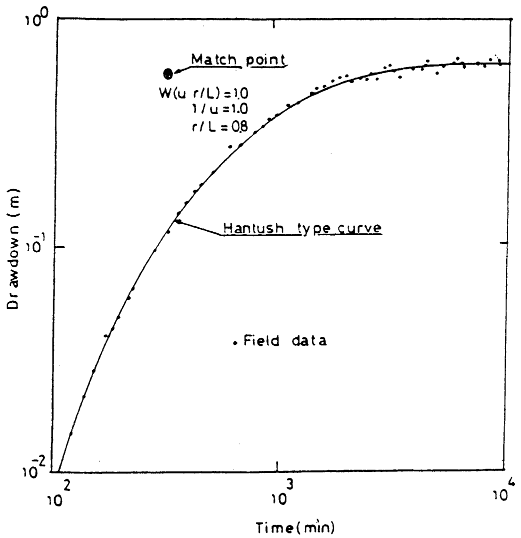

Fig. 4. Leaky Aquifer Type Curve and Field Data from Saq Sandstone.

As a general conclusion neither Theis' nor Jacob's method is applicable for the Oude Korendijk data. These data have been treated by the non-linear type curve fittings as already explained by Şen (1989a).

The third data set is from the Saq sandstone aquifer which lies in the northwestern part of Saudi Arabia. The aquifer is of leaky type and the conventional type curve has been matched to field data as shown in Fig. 4. There is no question that the type curve represents fairly well the field data leading to average aquifer parameters. The deviations from the type curves give domain for the application of hydrogeophysical concepts. The main point of this stage is that since there appears rather erratic variations in the drawndown especially for large times one may suspect that the aquifer material is not homogeneous. Consequently, these variations give rise to local variations in the aquifer parameters. The effect of these erratic variations on the parameter estimations can be obtained from the slope matching method developed by Şen (1986). The direct application of this method yields series of transmissivity and storage coefficient estimates. Their plots are shown in Figs. 5 and 6, respectively, with averages represented by horizontal straight lines. It is very obvious that the aquifer parameters change from one constant value to new constant value as the depression cone expands with time. There is not enough space in this paper for detailed discussion on Figs. 5 and 6. However, the reader himself may make many useful interpretations from these figures concerning the aquifer domain in the well vicinity.

Last but not the least, a final example is taken from a textbook where all of the field data lie on the type curve without any deviation (see Fig. 7). Non-existence of erratic or systematic deviations hinders the employment of hydrogeophysical concepts. Besides, such a situation never appears in nature and its existence implies that all of the under-lying assumptions in type curve derivation are valid exactly.

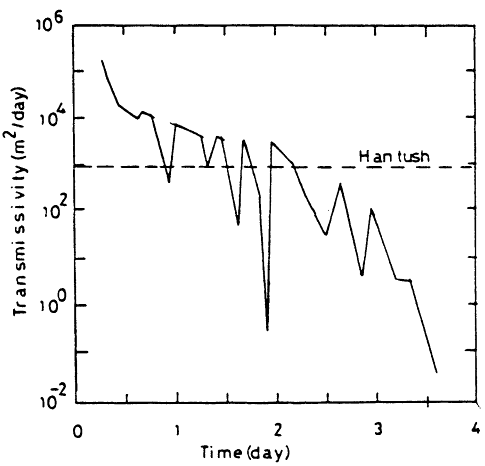

Fig. 5. Variations in Transmissivity.

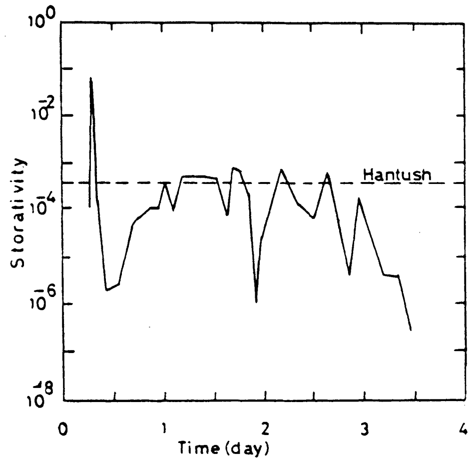

Fig. 6. Variations in Storage Coefficient.

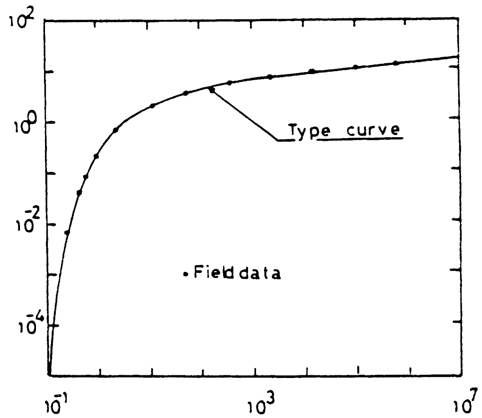

Fig. 7. Perfect Match of Type Curve to Field Data.

Conclusions

Some of the main hydrogeophysical concepts in interpreting aquifer test data are presented by employing real field records. It is emphasized that mechanical and forceful type curve fitting or straight line matching to the field data lead to erroneous aquifer parameter estimations. It is rather evident in this paper that prior to any calculation general and specific interpretations concerning the data must be done. Such an approach gives useful quantitative and at times qualitative results which are reliable. The hydrogeophysical methods as they are presented herein are never exhaustive and consideration of this concept in future applications is hoped to bring more interpretational concepts which will add to the physical understanding of a hydrogeologist.

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