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COMPARISON OF TWO PROCEDURES FOR THE DETERMINATION OF SOIL HYDRAULIC PROPERTIES: AN INSTANTANEOUS PROFILE METHOD AND A NONLINEAR PARAMETER ESTIMATION METHOD

Part IV: Experimental data

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CONTENTS

ABSTRACT

* For many years, experiments were performed on evaporating soil samples at the soil physical laboratory of the ICW, to determine the water retention characteristic and the unsaturated hydraulic conductivity. Boels and co-workers developped an automatic system for this type of experiment.

* For these samples, soil hydraulic properties can be determined with two procedures of calculation:

1. an instantaneous profile method, described by Wind
2. a nonlinear parameter estimation method, adapted by Kool and co-workers

* This note is the fourth part of a work in which is investigated the reliability and the precision of the two procedures. In this note some experimental data are used. Soil samples have a zavel to a sandy texture.

The determination of the soil hydraulic properties with the instantaneous profile method has been done according to the procedure used now at the soil physical laboratory.

With the nonlinear parameter estimation method all the sixth parameters of the analytical model for the description of the soil hydraulic properties have been estimated. In order to study the uniqueness of the solution, 26 initial parameter estimations have been chosen.

* According to the results, the main conclusions are the following:

1. With the instantaneous profile method, it is possible to identify a priori some biased results: a unique unsaturated conductivity curve is not obtained. In order to know better the origin of this bias and its importance, some "numerical experiments" should be done.

2. When the results of the instantaneous profile method do not seem to be biased a priori, the situations encountered are in agreement with the "numerical experiments" done in the third part of this work. In particular:

   a. The nonlinear parameter estimation method is difficult to use.

   b. At the high water contents, the incertitudes on the conductivity data determined with the instantaneous profile method are more important.

MAIN SYMBOLS AND CONVENTIONS

ABOUT THE SOIL HYDRAULIC PROPERTIES

θ	: volumetric water content	[L3.L-3]
h	: matric potential	[L]
K	: unsaturated hydraulic conductivity	[L.T-1]
pF	: log(|h|) ; h-value expressed in cm	[log(L)]

ABOUT THE NONLINEAR PARAMETER ESTIMATION METHOD

SSQ	: sum of squares	[-]
RSQ	: square of the linear correlation coefficient between the observations and their prediction	[-]
wi	: "user-specified weight", as defined in Kool et al. (1987) (see Tamari,1988a)	[-]

* For sake of clarity, the following system of units is used in the text: cm, day.

In the appendix, the used system of units is: cm, min.

* INTRODUCTION

* For many years, experiments were performed on evapo- -rating soil samples at the soil physical laboratory of the ICW, to determine the water retention characteristic and the unsaturated hydraulic conductivity. Boels and co-workers (1978) developed and automatic system for this type of experiment.

For these samples, soil hydraulic properties can be determined with two procedures of calculation:

1. An instantaneous profile method adapted for the laboratory, described by Wind (1966).

2. A nonlinear parameter estimation method, adapted by Kool and co-workers (1987).

* The purpose of this work is to investigate the relia- -bility and the precision of the two procedures for the determination of soil hydraulic properties. Two different approaches are possible (Tamari, 1988a):

1. The use of "numerical experiments".

2. The use experimental data.

* Some "numerical experiments" have been done before (Tamari, 1988c); in particular, it has been concluded that the nonlinear parameter estimation problem as it had been posed in this study would lead to a non reliable technique.

Of course, with a real experiment, the real soil hydraulic properties are unknown. But for each procedure of calculation, it is still possible to see if the conclusions of the "numerical experiments" and of the real experiments are in agreement or not. It is also possible to compare the soil hydraulic properties determined with these two procedures. In this note, some results based on real experiments will be presented.

1 - MATERIAL AND METHOD

11. THE EXPERIMENTAL SET-UP

* This experimental set-up developed by Boels and co-workers (1978) has been described more in detail before (Tamari,1988a). Fig.1 shows the dimensions of the samples used now at the soil physical laboratory of ICW (FYSLAB).

1. A vertical column of soil, initially saturated (or wet) is allowed to evaporate at the top; all other sides are completely closed. Total height of the sample is 8 cm.

2. Several times a day, the total weight of the column is determined.

   From these measurements and because the final mean water content at the end of experiment is determined, it is possible to calculate the changes of mean water content of the sample with time.

   Evaporation rate can also be calculated by multiplying these changes of mean water content with time by the total height of the sample.

3. At the same time the weight is determined, the matric potential is measured at different depths of the column with microtensiometers. Microtensiometers are installed at four depths below the soil surface: -1 , -3 , -5 and -7 cm.

* Some classical assumptions about the behaviour of the soil are made (Tamari,1988a): the transfers are vertical, the sorption potential is equal to its matric component, the sample is homogeneous for its hydraulic properties.

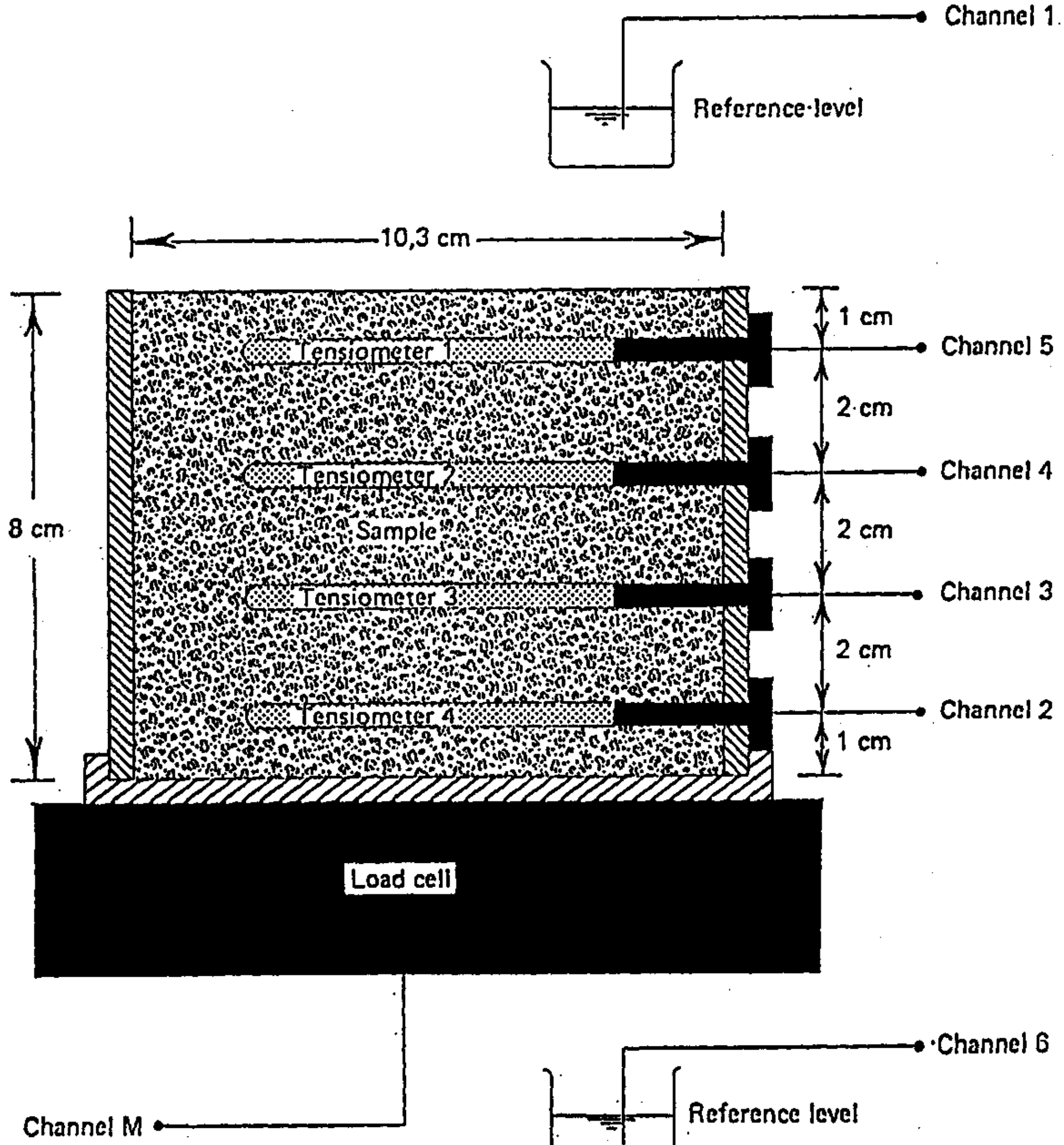

Fig. 1 - Set-up used at FYSLAB for the determination of soil hydraulic properties (schema)

12. SAMPLE DESCRIPTION AND EXPERIMENTAL DATA

* At the FYSLAB, up to now, some experimental data recorded with the automatic system described by Boels et al. (1978) are available for more than 300 samples of soil.

* Here, nine soil samples have been chosen. They have a sandy to a zavel texture. Eight of them are coming from the same soil profile at Lelystad. They are described at Tab.1 (and in Appendix I).

* The choice of these samples is based on the following points:

  1. The soil hydraulic properties determined with the instantaneous profile method do not have a very strange appearance, compared to the results obtained with some other samples (eg. a very flat water retention curve, a very important dispersion of the calculated conductivity points).

  2. For soil samples of the same kind, some points of the water retention characteristic have been determined with the tension plate technique and the sand box apparatus (Veerman, 1983 ; Veerman,1986); and the agreement is rather good, with the water retention curve determined with the instantaneous profile method (in comparison to other experimental data; eg. see the discussion in Tamari, 1988a). As a matter of fact, the differences between the potential values are always less than half an order of magnitude, for a given water content (of course, in the range of tensiometric data). some examples are shown at Fig.4 to 7 .

* The experiments and the treatment of the raw data have been done by Halbertsma and Veerman (1983,1986).

  For both the instantaneous profile method and the nonlinear parameter estimation method, the same tensiometric data have been used. The range for the recorded matric potential is between -4 cm and -850 cm (see Appendix II).

Tab.1 - Textural properties and description of soil samples

Code	Texture and description	Horizon
01.040	heavy "zavel" (Ijsselmeer-sediment)	Ap
05.040 15.040	extremely fine sand with "zavel" aggregates (Zuiderzee-sediment)	C21gp
07.040 17.040	moderately light and heavy "zavel" (Almere-sediment)	C22g
01.041	very light "zavel" (Almere-sediment)	C23g ?
03.041	clayey (?) extremely fine sand (idem)	C24g ?
05.041	clay-poor extremely fine sand (idem)	C25g ?
01.038	sandy-loamy sand ? (Mariahout)	B ?

13. INSTANTANEOUS PROFILE METHOD

* This method described by Wind (1966) has been presented before (Tamari,1988a). The main points are the following:

1. Soil hydraulic properties have been calculated with the KH/KH directory of FORTRAN programs (FYSLAB,1988).

2. The determination of the water retention curves has been done by Halbertsma and Veerman (1983,1986). During the iterations, the data were fitted with a sixth order polynomial (always), using the "normal" mode ($|h|$ versus Θ), except the sample 01.038 for which the "half-log" mode ($\log|h|$ versus Θ) has been used.

3. The original program for the calculation of the unsaturated conductivities has been changed a little, so that all the conductivity points are calculated.

14. NONLINEAR PARAMETER ESTIMATION METHOD

* Parameter estimations have been done with the FORTRAN program SFIT (Kool et al.,1987b), that has been presented before (Tamari,1988a). Some preliminary studies have been done by Lafolie (1987) and Tamari (1987). Characteristics of the calculations are nearly the same as for the "numerical experiments" (Tamari, 1988c). The main points are the following:

1. The analytical model for the soil hydraulic properties is the model of "Mualem-van Genuchten" (van Genuchten, 1978). The six parameters of this model (Ks, θs, θr, α, N, l) are estimated.

2. The initial condition corresponds to the first profile of matric potential recorded just after the start of the experiment (see Appendix II).

3. For the top condition, the evolution of the evaporation rate with time is described by a straight line (see the Appendix IV). It comes from a second order polynomial regression on the load cell data; when the results are plotted, the agreement seems to be good.

4. The observation vector contains the tensiometric data, and in addition two points of the water retention curve; these two points, that have been determined with other samples of the same kind (see paragraph [12]), correspond to h = -3.2 cm and h = -15800 cm .

5. The method of ponderation, for the resolution of the generalized least square problem, has been defined empirically. The relative weights of the tensiometric data are equal to a constant value (wi=1). The "user specified weight" of the two points of the water retention curve is: wi = 2. This last value has been chosen rather arbitrarily, after a few trials with wi = 0, 1, 2, and 10.

6. In order to study the uniqueness of the solution, the calculations have been done here using as initial parameter values the 26 parameter sets published by Wosten (1987).

7. Only the final parameter sets for which RSQ > 0.500 and with one convergence test passed are assumed to be reliable. Then different groups of parameter sets are distinguished empirically (see Tamari, 1988c). For any initial set of parameters, the final estimated set of parameters obtained after the calculations is put together with some other sets of estimated parameters for which the estimated parameter values and the RSQ are nearly the same. For sake of clarity, not more than 4 groups of estimated parameter sets are distinguished. The parameter sets of "group 1" correspond to the highest RSQ values, while the parameter sets of the "last group" correspond to the lowest RSQ values. On the following figures (Fig. 4 to 7) I have represented with the same kind of line all the hydraulic properties which correspond to all the estimated parameter sets of the same group (eg. "full lines" correspond to the parameter sets of "group 1").

8. Other characteristics of the calculations are the same as in Tamari (1988c).

2. RESULTS

21. INSTANTANEOUS PROFILE METHOD

* According to the Fig. 4 to 7, a more important dispersion of the calculated conductivities is found at the higher water contents; it can be of 2 orders of magnitude.

This is in agreement with the results of the "numerical experiments", when the incertitudes on the tensiometric data are simulated (Tamari, 1988c).

* But sometimes, it seems also that different conductivity curves can be distinguished. This is the case of the samples 07.040, 05.040, 15.040, 03.041, 05.041, at least.

Fig.2 represents the unsaturated hydraulic conductivitiy as a function of the matric potential, for the sample 07.040 . According to this figure, the different conductivity curves correspond to the different layers (resulting from a discretization of the "soil" system; see Tamari,1988a). Here, the maximum difference between these curves can be of 1 order of magnitude for the conductivity.

This situation can be due to different biases (see the discussion in Tamari, 1988a):

A1. The sample is not homogeneous for its hydraulic properties.

A2. The microtensiometers are not in equilibrium.

A3. The depths at which the microtensiometers have been installed is not correct.

B1. When the soil is more dry, the linear interpolations done on the gradients of potential should be less reliable.

B2. Far from the bottom of the sample (used as a boundary condition) the calculation of the fluxes should be less reliable.

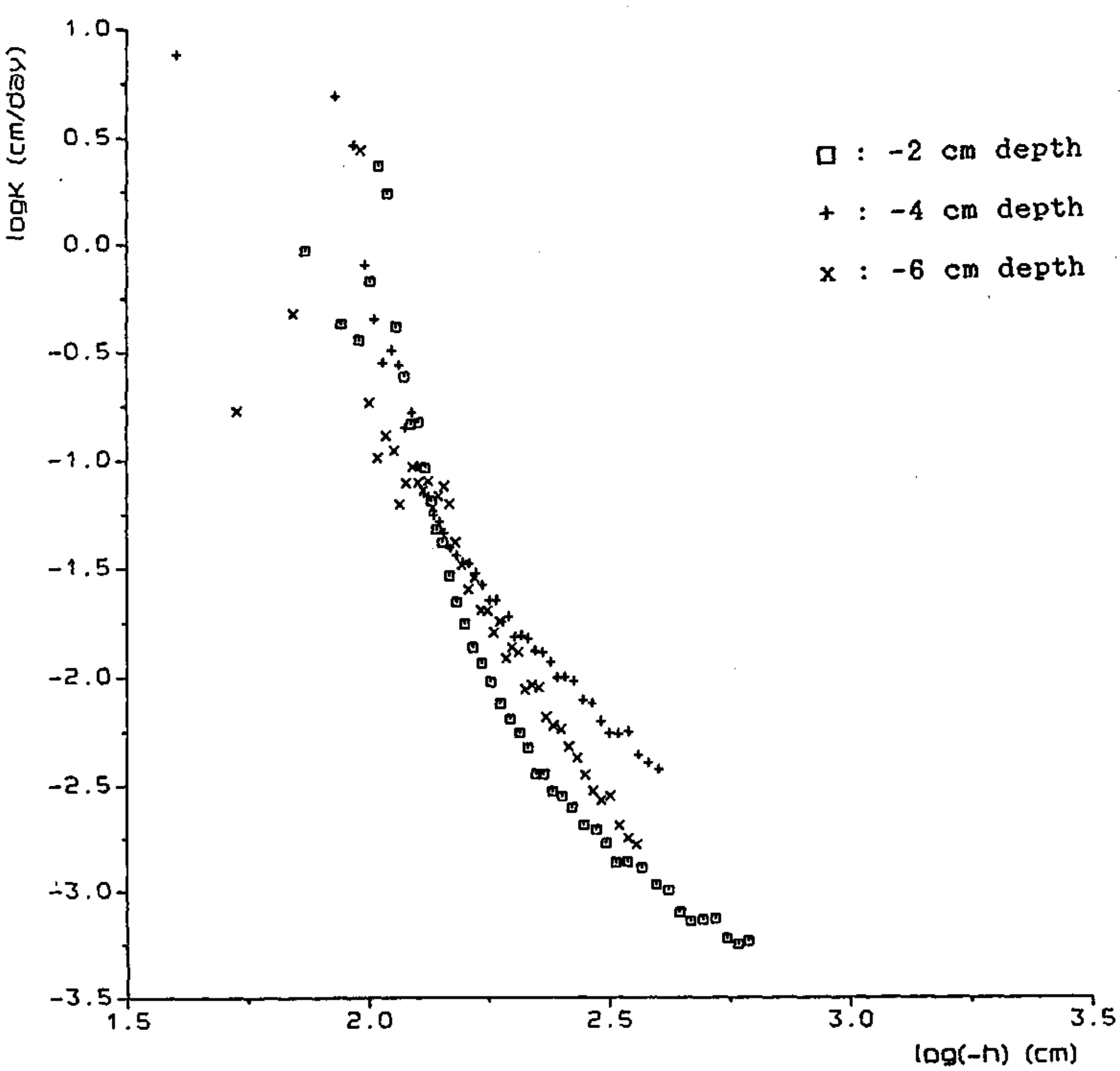

Fig. **2** - Exp **07.040** : instantaneous profile method. Distinction between the conductivity points calculated at different depths.

When doing the "numerical experiments" (Tamari, 1988c), it has been concluded that the numerical biases B1 and B2 has no influence, compared to the other sources of incertitudes and of bias that have been considered. But also it has been pointed out that in reality, these two problems should be more important (because a low input evaporation rate has been used for the simulations).

So, it would be interesting to do some other "numerical experiments", in order to see if this situation can be simulated.

But it must be pointed out that the samples 05.040 and 15.040 are likely not to be homogeneous: they are coming from an horizon wich contains some bands of gravels and of peat (see Appendix I).

22. NONLINEAR PARAMETER ESTIMATION METHOD

* When doing the "numerical experiments" (Tamari, 1988c), it has been concluded that the parameter Θs (at least) of the model of "Mualem-van Genuchten" was not very sensitive to the problem, if only the tensiometric data are used as observations.

A confirmation is given at Fig.3, where the sum of squares is represented as a function of the parameter Θs , for the sample 01.040 . The lines correspond to the same initial parameter estimation. If the observation vector contains the tensiometric data only, it seems that a wide range is possible for the estimator of the parameter Θs (Fig.3a). On the opposite, this possible range is more narrow when the two points of the water retention curve for h = -3.2 cm and h = -15800 cm are added to this vector (Fig.3b).

Looking at Fig. 3a, it seems that different minima of the surface response for parameter Θs can be distinguished (see Tamari, 1988a). One minimum corresponds to a Θs value inbetween 0.4 and 0.5, and the other minimum would correspond to a Θs value comprised between 0.50 and 0.75. On the opposite, looking at Fig. 3b, it seems that there is only one minimum of the surface response for the parameter Θs (Θs value inbetween 0.4 and 0.5).

Otherwise, for both Fig. 3a and 3b, the convergence of the iterative process is often slower for the parameter Θs at the end of the calculations. Following one line (which corresponds to one iterative process), we can see that the crosses (which correspond to one iteration during this process) are often closer when the SSQ values are lower.

* Also, the main conclusion of the "numerical experiments" was that the method of calculation proposed should be very difficult to apply, since the analytical model of "Mualem - van Genuchten" cannot describe exactely the "real" soil hydraulic properties.

At least, for the experimental data, it appears that the distinction of different groups of estimated parameter sets is often difficult to do (see Appendix IV):

1. For samples 01.040, 05.040 and 15.040, this distinction is rather easy, and the group of estimated parameter sets for which RSQ is the highest contains more than 2 sets.

2. But for samples 07.040, 17.040, 01.041 and 01.038, less than 2 estimated parameter sets have been obtained with the proposed method.

3. Even more, for samples 03.041 and 05.041, no estimated parameter set is obtained.

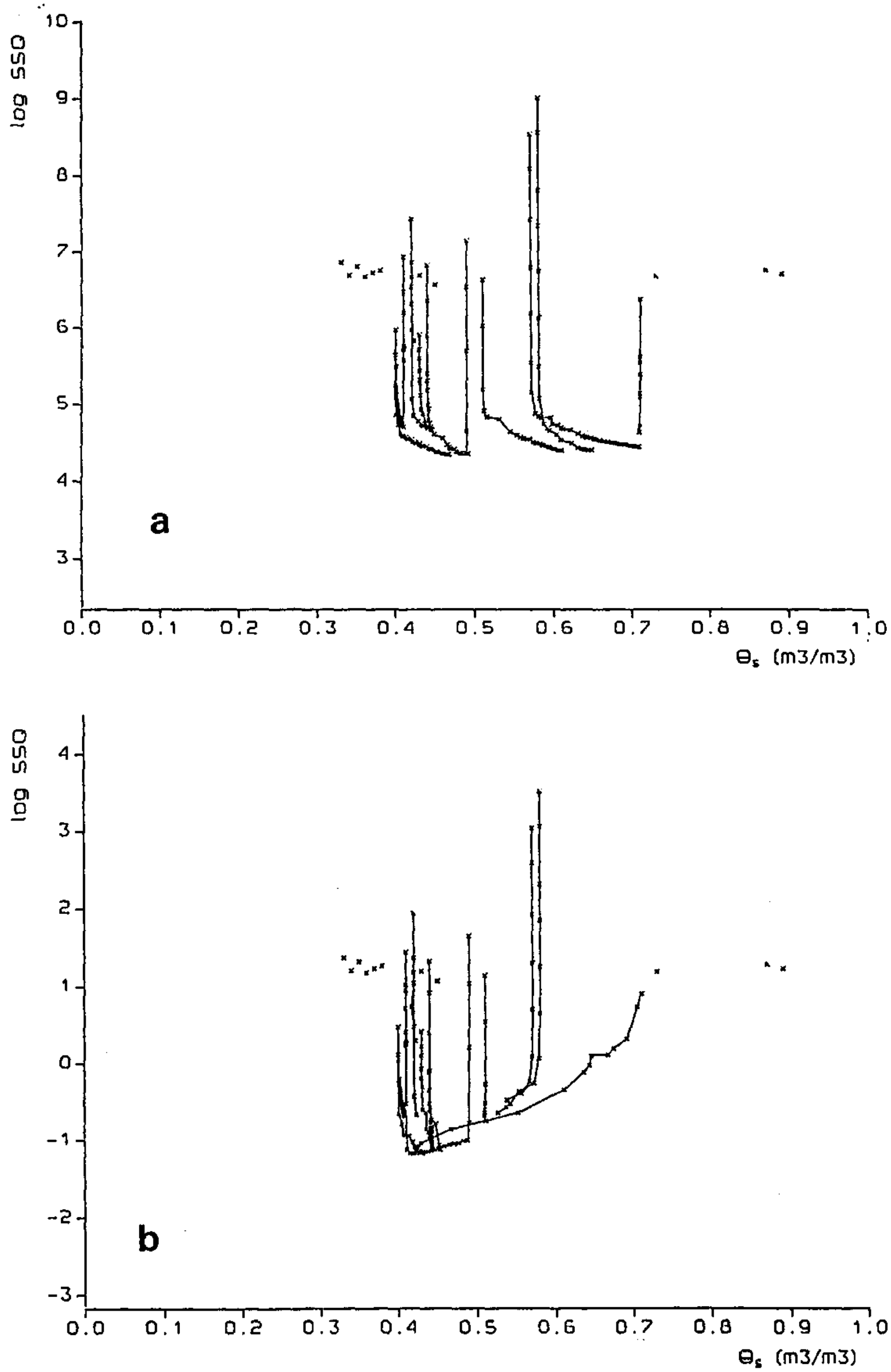

Fig. 3 - Sample 01.040 : nonlinear parameter estimation method. Sum of squares (SSQ) as a function of the parameter Θs .

(a) : observations are the tensiometric data [wi=1]

(b) : observations are the tensiometric data [wi=1] plus $\Theta(h=-3.2cm)$ [wi=2] and $\Theta(h=-15800cm)$ [wi=2]

* Compared to the point of the water retention curve for which h = -3.2 cm (used to define the observation vector), the estimated values of the parameter θs are sometimes not realistic, even with the group of parameter sets for which RSQ is the highest:

1. For the samples 05.040 and 07.040, the estimated value of θs is about 0.04 m3/m3 lower.

2. For the sample 01.038, the estimated value of θs is 0.33 m3/m3 higher.

* For other samples of the same kind of soil, the saturated conductivity has been determined at FYSLAB (see Appendix I). Compared to these conductivities, the values of the estimated parameter Ks are often lower; at least, for the group of parameter sets which corresponds to the highest RSQ, the differences are often 1 or 2 order of magnitude lower.

  Assuming that the experimental saturated conductivities are realistic (although the spatial variability of this parameter is very important), it can be concluded that Ks is not sensitive to the considered problem, or that Ks cannot be considered as a physical meaningful parameter.

* For the samples 01.040, 05.040 and 15.040 (for which there are more than 3 final estimated parameter sets) it can be remarked that the different estimated K(h) curves seem to cross at one point (see Fig.4 and 5).

  This is in agreement with the "numerical experiments", and this phenomenon has been interpreted as an effect of the method of ponderation chosen to solve the generalized least square problem.

23. COMPARISON OF THE TWO METHODS

* At Fig. 4 to 7 is shown the comparison of the soil hydraulic properties obtained with the instantaneous profile method and the nonlinear parameter estimation method, for some samples.

In addition, for each sample, I plotted some points of the water retention curve obtained for other samples of the same kind of soil. These points have been determined with the tension plate technique (range pF 3.0 to 4.2) and the sand box apparatus (range pF 0 to 2.7) (see paragraph [12]).

ADDITIONAL LEGEND TO THE FOLLOWING FIGURES

1. For the instantaneous profile method, the calculated conductivities that are outside of the graphics are not represented.

2. For the nonlinear parameter estimation method, the different lines correspond to the different groups of estimated parameter sets that have been distinguished (maximum 4 groups):

————	: parameter sets of the group 1
——•——	: parameter sets of the group 2
— — — —	: parameter sets of the group 3
-- -- --	: parameter sets of the group 4

231. SAMPLE 01.040

* According to the figure, the unsaturated conductivity curve determined with the instantaneous profile method is unique (Fig.4).

* When the results obtained with the two procedures are compared, the main points are the following:

1. For the water retention curve, the agreement is good (compared to the other cases), and the differences are less than 0.5 order of magnitude for the potential values.

   The best agreement is obtained with the estimated parameter sets of the first group (highest RSQ).

2. For the unsaturated hydraulic conductivity, the agreement is also good, and the differences are less than 1.5 order of magnitude (the maximum differences are encountered for the highest water contents).

   But the estimated parameter sets of the first group do not correspond to the best agreement.

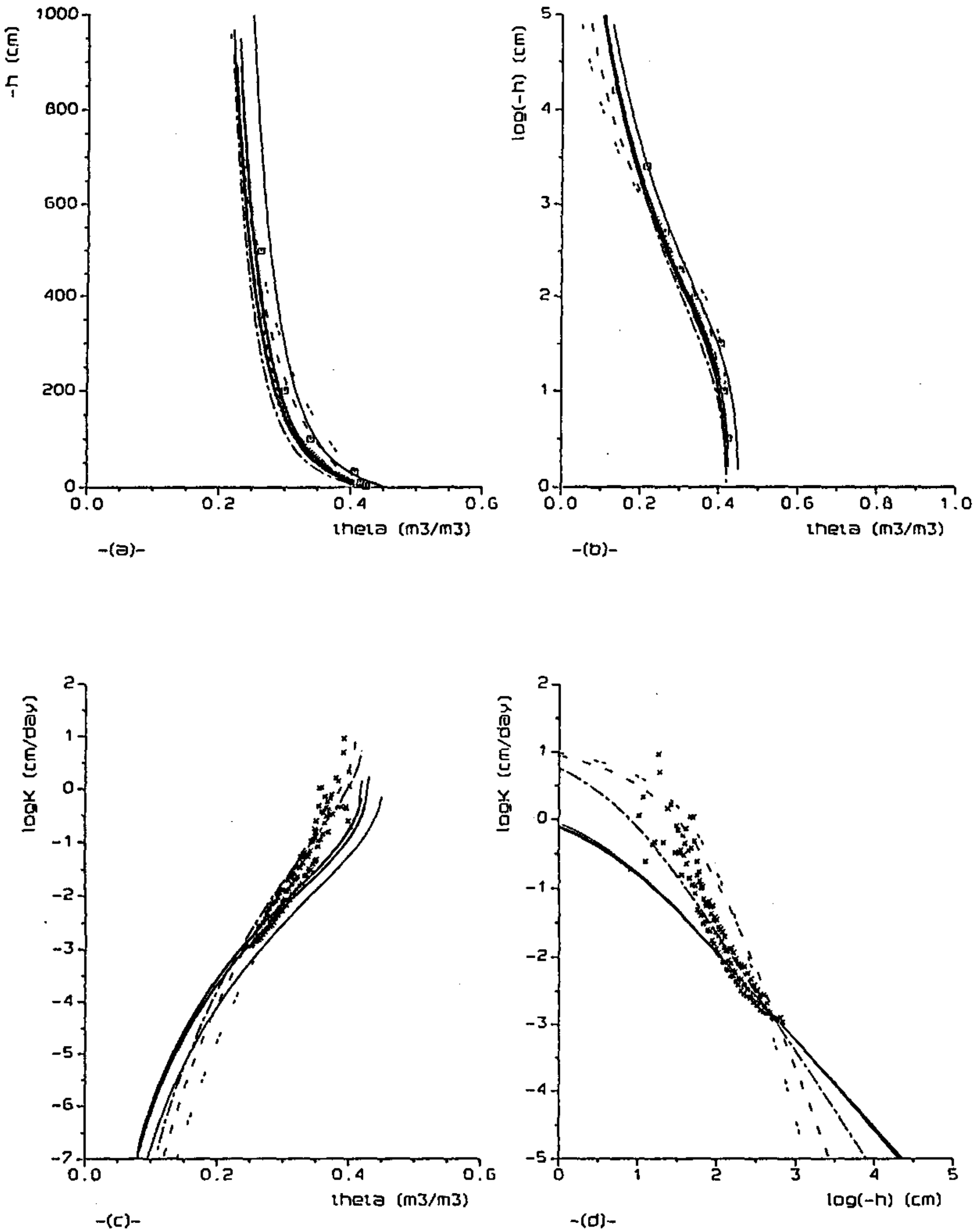

Fig. **4** - SOIL HYDRAULIC PROPERTIES OF SAMPLE 01.040

x : instantaneous profile method

lines : parameter estimation method (maximum 4 groups)

□ : results obtained for other samples (see text)

232. SAMPLES 05.040 AND 15.040

* According to the figures, the unsaturated conductivity curve determined with the instantaneous profile method is not unique (eg. see Fig.5).

* The main points of the comparison of the two procedures are the following:

1. For the water retention curve, the agreement is rather good; the differences are less than 0.5 order of magnitude for the potential values. But the curves predicted with the nonlinear parameter estimation method have a smoother appearance.

2. For the unsaturated conductivity curves, the agreement is rather good; the differences are less than 2 orders of magnitude. But the shapes of the curves are different.

3. For the sample 05.040, the best agreement is not obtained for the first group of estimated parameters (highest RSQ).

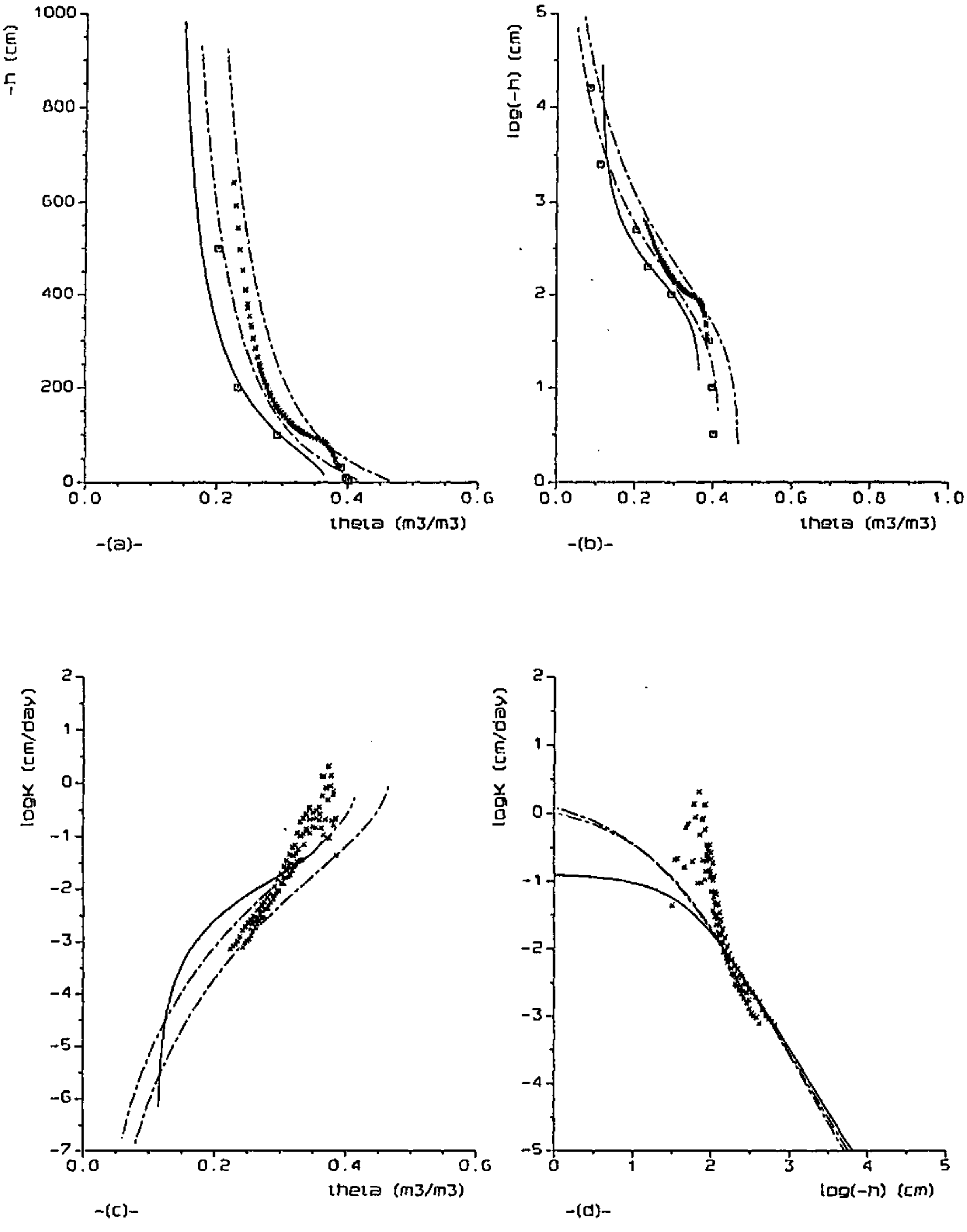

Fig. **5** - SOIL HYDRAULIC PROPERTIES OF SAMPLE 05.040

x : instantaneous profile method

lines : parameter estimation method (maximum 4 groups)

□ : results obtained for other samples (see text)

233. SAMPLES 07.040, 17.040, 01.041 AND 01.038

* According to the figures, it is difficult to distinguish different unsaturated hydraulic conductivity curves determined with the instantaneous profile method, except for the sample 07.040 (eg. see Fig.6).

* With the nonlinear parameter estimation method, only one or two estimated parameter sets are obtained.

* The main points of the comparison are the following:

1. For the water retention curve, the agreement is the best with the parameter set for which RSQ is the highest. But the nonlinear parameter estimation method provides a curve that has a smoother appearance.

   a. For samples 01.041 and 17.040, the agreement is good, if only this parameter set is considered (the differences are $<$ 0.5 order of magnitude for the potential values).

   b. For samples 07.040 and 01.038, there is a poor agreement, and the differences are more than 1.5 orders of magnitude for the potential values.

2. For the $K(\theta)$ relationship, the best agreement is also obtained with the estimated parameter set for which RSQ is the highest. With this parameter set, the differences can be of 2.5 orders of magnitude.

3. For the $K(h)$ relationship, the slopes are different. Even more, for the sample 17.040, the parameter estimation which correspond to the lowest RSQ corresponds yet to a better agreement.

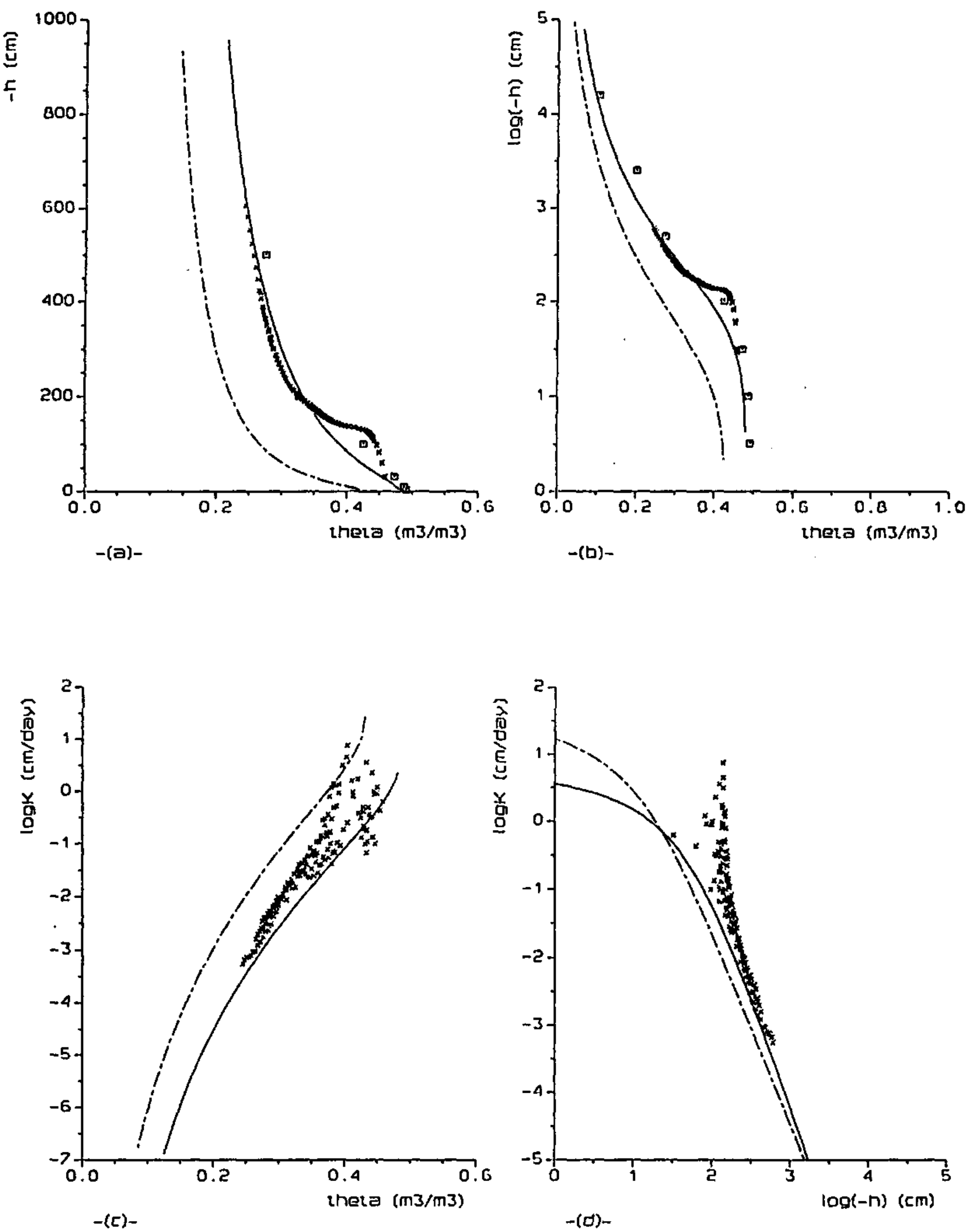

Fig. **6** - SOIL HYDRAULIC PROPERTIES OF SAMPLE 01.041

x : instantaneous profile method

lines : parameter estimation method (maximum 4 groups)

□ : results obtained for other samples (see text)

234. SAMPLES 03.041 AND 05.041

* For these two samples, no final estimated parameter set is obtained (eg. see Fig.7).

* Obviously, the K(Θ) relationships determined with the instantaneous profile method are not unique in both cases.

235. DISCUSSION

* Two cases can be distinguished:

1. The results of the instantaneous profile method do not seem to be biased: the unsaturated conductivity curve seems to be unique (samples 01.040, 17.040, 01.041 and 01.038).

   In these conditions, the results of the instantaneous profile method should be rather accurate at the "low" water contents (see Tamari, 1988c).

   The comparison with the nonlinear parameter estimation shows that:

   a. For the samples which have a zavel texture (01.040, 17.040, 01.041), the soil hydraulic properties determined with the two procedures of calculation are in a good agreement in the "dry" range: for pF < 2, the differences are less than 0.5 order of magnitude for the conductivity.

   b. For one sandy sample (01.038), the K(h) curves are in a rather good agreement, but the water retention curves are in a complete desagreement.

   An interpretation is that the analytical model used for the nonlinear parameter estimation method is not flexible enough, to fit the "real" soil hydraulic properties when there are important changes of slope, as it is the case for a sand.

   For the high water contents, the differences between the results of the two methods can be of 2.5 order of magnitude for the conductivity, and the slopes of the curves are different. Then, it is difficult to conclude which method is the most reliable (see Tamari, 1988c).

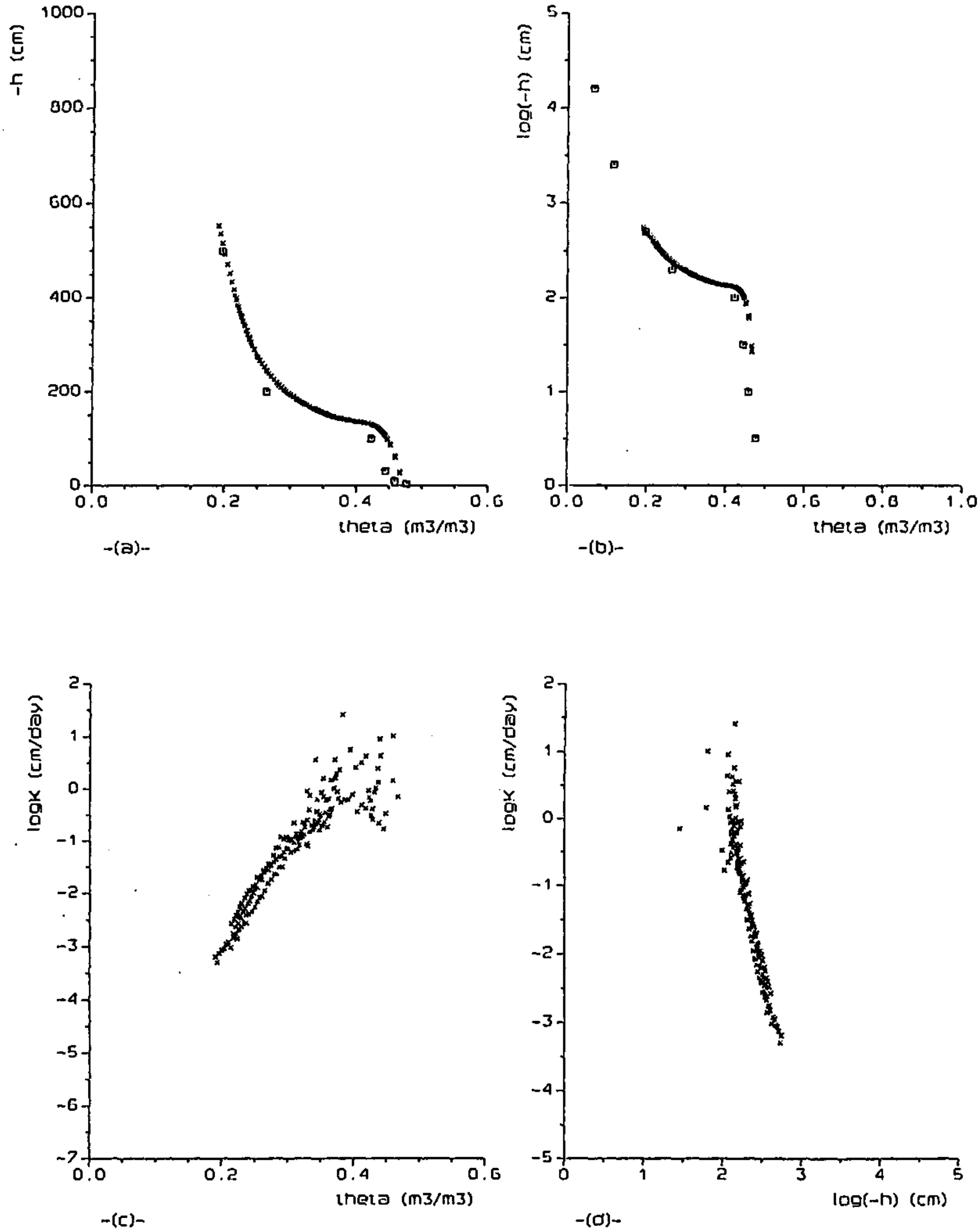

Fig. 7 - SOIL HYDRAULIC PROPERTIES OF SAMPLE 03.041

x : instantaneous profile method

lines : parameter estimation method (maximum 4 groups)

□ : results obtained for other samples (see text)

2. The results of the instantaneous profile method are biased: different unsaturated hydraulic conductivity curves can be distinguished (samples 05.040, 15.040, 07.040, 03.041 and 05.041).

   This situation was not studied with the "numerical experiments" (Tamari, 1988c). So it is not possible to say a priori if the results of the instantaneous profile method are close or not to "reality".

   But with the nonlinear parameter estimation method it can be remarked that:

   a. For the samples 05.040 and 15.040, the results of the nonlinear parameter estimation method are in a rather good agreement with those of the instantaneous profile method. These samples have a zavel texture, and the bias is not very important.

   b. For the samples 03.041 and 05.041, no results are provided with the nonlinear parameter estimation method. These have a sandy texture and the bias is quite important.

   Then, some interpretations are possible:

   a. The nonlinear parameter estimation do not give any results for the samples which have a more coarse texture, because of a lack of flexibility of the analytical model used to describe the soil hydraulic properties.

   b. The nonlinear parameter estimation method do not give any results for the samples for which the bias is quite important (this bias could be due to an instrumental problem or to a non homogeneous soil sample).

   So it is not possible to conclude with these results that the bias observed in the case of the instantaneous profile method has an effect for the nonlinear parameter estimation method.

CONCLUSION

* According to the experimental results presented in this note, the following conclusions can be made for the two procedures of determination of the soil hydraulic properties studied:

1. Sometimes, it seems that the unsaturated hydraulic conductivity curve determined with the instantaneous profile method is not unique, and so, these results are biased.

   But it is difficult to know the origin of this bias and its importance. This point could be clarified with some "numerical experiments".

2. When it is not possible to distinguish a priori some biased results, the same remarks done about the "numerical experiments" can be also applied here (see Tamari, 1988c).

   In particular, the nonlinear parameter estimation method, as it has been defined here, seems to be difficult to use with real data.

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APPENDIX I

SAMPLE DESCRIPTION

sample	01.040	05.040 & 15.040	07.040 & 17.040
place	Lelystad (1984)	Lelystad (1984)	Lelystad (1984)
horizon	Ijsselmeer sediments	Zuiderzee sediments	Almere sediments
code horizon	Ap	C21gp	C22g
depth (cm)	5 cm	30 cm	45 cm
% clay (< 2 μm)	?	≈ 7.0 %	≈ 3.4 %
% loam (2-50 μm)	?	≈ 10.7 %	≈ 25.0 %
% sand (50-2000 μm)	?	≈ 70.0 %	≈ 54.0 %
Staring-series	B8	B8	O10
θ(h=-3.2 cm)	0.424	0.402	0.464
θ(h=-15800 cm)	0.136	0.084	0.107
K sat (cm/min)	?	≈ 0.0206 (1 sample,labo)	≈ 0.0187 (2 samples,labo)

sample	01.041	03.041	05.041
place	Lelystad (1984)	Lelystad (1984)	Lelystad (1984)
horizon	Almere sediment	Almere sediment	Almere sediment
code horizon	C23g ?	C24g ? (or C25g ?)	C25g ?
depth (cm)	60	85	100
% clay (< 2 μm)	≈ 8.7 %	≈ 0.9 %	?
% loam (2-50 μm)	≈ 19.2 %	≈ 16.0 ?	?
% sand (50-2000 μm)	≈ 61.0 %	≈ 74.0 %	?
Staring-series	O8 ?	O9 ? (B8)	O4 ?
θ(h=-3.2 cm)	0.491	0.477	0.471
θ(h=-15800 cm)	0.106	0.067	0.061
K sat (cm/min)	≈ 0.0262 (1 sample,labo)	≈ 0.0123 (1 sample,labo)	≈ 0.0098 (1 sample,labo)

Appendix I

SAMPLE DESCRIPTION (continued 1)

sample	01.038
place	Mariahout (1983)
horizon	"white"
code horizon	Hn21
depth (cm)	60-68
% clay (< 2 μm)	?
% loam (2-50 μm)	?
% sand (50-2000 μm)	?
Staring-series	01,02 ?
θ(h=-3.2 cm)	0.320
θ(h=-15800 cm)	0.012
K sat (cm/min)	≈ 0.0944 (2 samples,labo)

* " K sat " : saturated hydraulic conductivity

* " Staring-series " : classification according to the Staring-series.

Appendix I (continued 2)

REFERENCES FOR THE SAMPLE DESCRIPTION

1. Halbertsma and Veerman (1983,1986):

   Code for the samples, depth below the soil surface.

2. Veerman (1983,1986):

   Place, horizon, $\theta(h = -3.2 \text{ cm})$, $\theta(h = -15800 \text{ cm})$.

3. Veerman (1988, ICW, personal communication):

   Textural analysis, saturated hydraulic conductivities, code horizon for sample 01.038 .

4. de Bakker et al. (1966):

   Code horizon for the samples from Lelystad (experiments 40 and 41).

5. Bannink (1988, STIBOKA, personal communication):

   Code according to the Staring-series.

   The classification according to the Staring-series (see Wosten et al.,1987) must be considered carefully: on one hand because the texture of the soils is not well known, and on the other hand because some soils such as the "Zuiderzee sediments" have not been used to define the Staring-series. Also, at Lelystad, some horizons are not homogeneous (with some bands of gravels, of peat, ...) (Bannink, 1988, personal communication).

Appendix II

INITIAL RECORDED PROFILES OF MATRIC POTENTIAL

sample	h at -1 cm	h at -3 cm	h at -5 cm	h at -7 cm	h at -8 cm
01.040	-11.50	-9.22	-7.94	-5.72	-4.61
05.040	-32.69	-29.47	-26.69	-22.71	-20.72
15.040	-42.65	-40.36	-37.73	-35.16	-33.87
07.040	-19.97	-17.69	-14.92	-12.82	-11.77
17.040	-53.44	-49.84	-47.14	-45.07	-44.03
01.041	-16.07	-13.53	-11.35	-11.46	-11.51
03.041	-13.00	-11.91	-10.00	-8.91	-8.36
05.041	-24.56	-20.64	-18.38	-15.44	-13.97
01.038	-33.34	-31.45	-27.12	-22.72	-20.52

* The h values at -1 cm, -3 cm, -5 cm and -7 cm correspond to the data recorded at the start of experiment (t = 0 min)

* The h value at -8 cm (bottom) has been calculated with a linear interpolation on the h values at -5 cm and -7 cm. This value must be given, to define the initial condition for the SFIT program.

* Note: The second block of data is recorded 240 min after the start of the experiment.

APPENDIX II (continued 1)

FINAL PROFILES OF MATRIC POTENTIAL

sample	h at -1 cm	h at -3 cm	h at -5cm	h at -7cm	t end (min)
01.040	-815.22	-604.05	-473.95	-433.11	10800
05.040	-820.84	-516.08	-333.33	-292.17	9360
15.040	-852.06	-375.20	-273.83	-226.51	11280
07.040	-821.66	-431.76	-390.43	-347.04	11280
17.040	-765.91	-336.68	-286.16	-272.15	10800
01.041	-763.03	-465.91	-396.75	-374.03	13960
03.041	-687.83	-431.96	-389.64	-365.98	17080
05.041	-760.82	-466.53	-392.46	-361.30	17080
01.038	-535.98	-145.48	-127.70	-123.66	17400

* t end : time at the end of the experiment

APPENDIX III

THE INSTANTANEOUS PROFILE METHOD

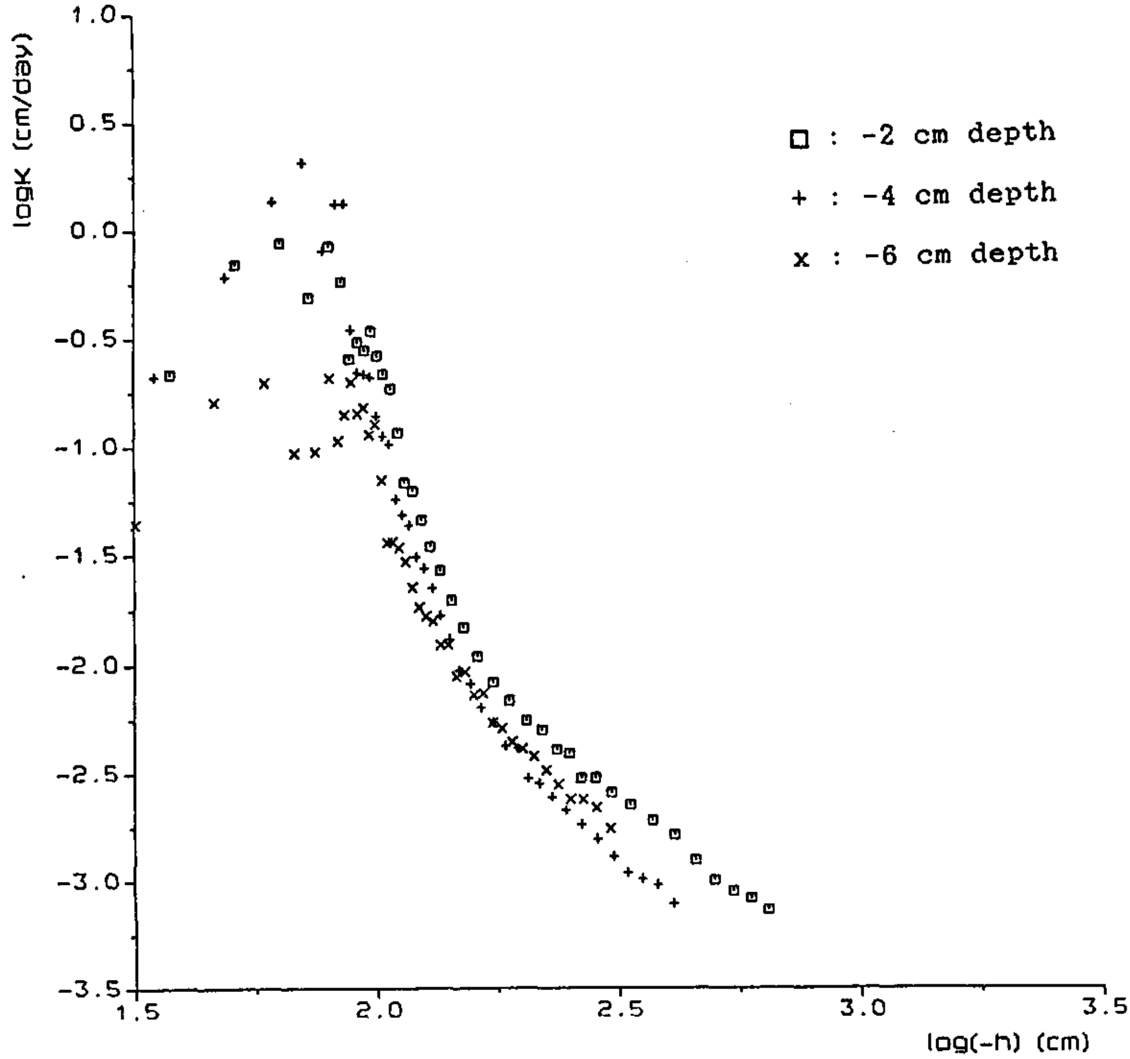

Fig. - Exp **05.040** : instantaneous profile method. Distinction between the conductivity points calculated at different depths.

APPENDIX IV

THE NONLINEAR PARAMETER ESTIMATION METHOD

ESTIMATION OF THE EVAPORATION RATE

sample	nb data	correl.	t at the end (min)	ER at the start (cm/min)	ER at the end (cm/min)
01.040	46	0.99989	10800	-0.0001199	-0.0001073
05.040	40	0.99974	9360	-0.0001489	-0.0001107
15.040	48	0.99995	11280	-0.0001578	-0.0001117
07.040	48	0.99991	11280	-0.0001401	-0.0000984
17.040	46	0.99995	10800	-0.0001399	-0.0000996
01.041	59	0.99996	13960	-0.0001243	-0.0001124
03.041	72	0.99991	17080	-0.0001358	-0.0001105
05.041	72	0.99997	17080	-0.0001311	-0.0001129
01.038	73	0.99915	17400	-0.0001601	-0.0000819

* The load cell data have been fitted with a second order polynomial:

$$\theta = a_0 + a_1 . t + a_2 . t^2$$

* Then, the evaporation rate is calculated with the formula:

$$ER = (a_1 + 2.a_2 .t) . z_{max}$$

* variables:

t : time (=0 at the start) (min)
θ : mean water content (m3.m-3)

zmax : total height of sample (cm)
ER : evaporation rate (cm.min-1)

nb data : number of data for the polynomial regression
correl. : correlation coefficient of the regression

Appendix IV (continued 1)

FINAL ESTIMATED PARAMETER SETS

* Only the final parameter estimations for which RSQ > 0.500 and a convergence test passed are given.

* These parameter estimations are classified according to the RSQ values (from the highest to the lowest).

* Code for the results:

NO : code for the group of parameter sets (1,2,3,...) This classification is empirical.

STAR : STARING-SERIES (for initial estimation of parameters).

RSQ : Square of the linear correlation coefficient between the observations and their prediction.

MSSQ : Minimum sum of squares attained.

MBE(%): Mass balance error during the last iteration (in %)

ITER : Number of iterations

ALPHA : code for parameter α
N : code for parameter N
L : code for parameter l
WCS : code for parameter θs
WCR : code for parameter θr
CONDS : code for parameter Ks

Note : The system of units used here is: cm, min

Appendix IV (continued 2)

* EXP 01.040

NO	STAR	ALPHA	N	L	WCS	CONDS	WCR	RSQ	MSSQ	MBE%	ITER
1	O6	0.04866	1.17121	-5.97327	0.42023	0.00322	0.00630	0.9959	0.6761E-01	0.082	7
	B18	0.04907	1.16931	-6.01101	0.42252	0.00333	0.00559	0.9959	0.6768E-01	0.082	15
	O12	0.05005	1.16485	-6.26606	0.42806	0.00332	0.00384	0.9959	0.6818E-01	0.085	19
	B8	0.04959	1.16476	-6.23953	0.43008	0.00333	0.00504	0.9959	0.6835E-01	0.084	19
	B10	0.05073	1.15182	-6.35860	0.45299	0.00436	0.00151	0.9954	0.7522E-01	0.082	11
2	O11	0.07820	1.15392	-3.46525	0.42325	0.03559	0.00106	0.9870	0.2154	0.054	5
3	O9	0.01337	1.24658	2.61024	0.41030	0.01412	0.00154	0.8952	1.733	0.047	30
4	O8	0.00890	1.29526	6.50587	0.42245	0.01181	-0.01315	0.8817	1.956	0.202	11

* EXP 05.040

NO	STAR	ALPHA	N	L	WCS	CONDS	WCR	RSQ	MSSQ	MBE%	ITER
1	O9	0.01041	1.82531	-2.15716	0.36894	0.00009	0.11251	0.9851	0.9606E-01	0.107	37
	B7	0.01044	1.81917	-2.15795	0.36932	0.00009	0.11206	0.9851	0.9609E-01	0.107	39
	B3	0.01041	1.82552	-2.15704	0.36895	0.00009	0.11254	0.9851	0.9606E-01	0.107	22
	O17	0.01040	1.82628	-2.15695	0.36889	0.00009	0.11259	0.9851	0.9606E-01	0.107	32
2	O12	0.02406	1.25202	-2.30984	0.46765	0.00224	0.00350	0.9698	0.1954	0.113	15
	O6	0.02008	1.30061	-1.96395	0.41999	0.00146	0.00355	0.9667	0.2152	0.113	9

* EXP 15.040

NO	STAR	ALPHA	N	L	WCS	CONDS	WCR	RSQ	MSSQ	MBE%	ITER
1	B16	0.01055	2.02064	-0.78882	0.42587	0.00022	0.10962	0.9706	0.2134	0.692	15
	O16	0.01168	1.86237	-0.69505	0.44468	0.00032	0.10603	0.9662	0.2452	0.622	14
2	O17	0.01919	1.55233	-0.12152	0.50420	0.00205	0.08735	0.9582	0.3033	0.589	8
3	B18	0.03172	1.31124	0.50540	0.59103	0.01530	0.02452	0.9132	0.6305	0.351	8

Appendix IV (continued 3)

* EXP 07.040

NO	STAR	ALPHA	N	L	WCS	CONDS	WCR	RSQ	MSSQ	MBE%	ITER
1	O6	0.03388	1.26210	-3.15619	0.41206	0.00301	0.00223	0.7787	1.841	0.067	26

* EXP 17.040

NO	STAR	ALPHA	N	L	WCS	CONDS	WCR	RSQ	MSSQ	MBE%	ST
1	O16	0.00927	1.69973	0.03094	0.46866	0.00031	0.12217	0.9641	0.2506	0.866	13
2	B16	0.00877	1.28945	6.70400	0.62660	0.00882	0.01507	0.8560	1.004	0.617	4

* EXP 01.041

NO	STAR	ALPHA	N	L	WCS	CONDS	WCR	RSQ	MSSQ	MBE%	ITER
1	O12	0.01350	1.33421	2.06129	0.48250	0.00426	0.01982	0.8573	1.231	0.316	19
2	O15	0.04852	1.28648	1.08563	0.43016	0.03446	0.00143	0.5732	3.681	0.566	4

* EXP 03.041 AND EXP 05.041

-- NO SOLUTION --

* EXP 01.038

NO	STAR	ALPHA	N	L	WCS	CONDS	WCR	RSQ	MSSQ	MBE%	ITER
1	B16	0.03590	1.61295	-0.10850	0.65963	0.00881	0.01418	0.6719	1.731	0.381	5
2	O16	0.04133	1.44143	-0.27905	0.78902	0.01058	0.01293	0.5976	2.123	0.180	20

SOME RESULTS OF THE COMPARISON OF THE TWO STUDIED PROCEDURES

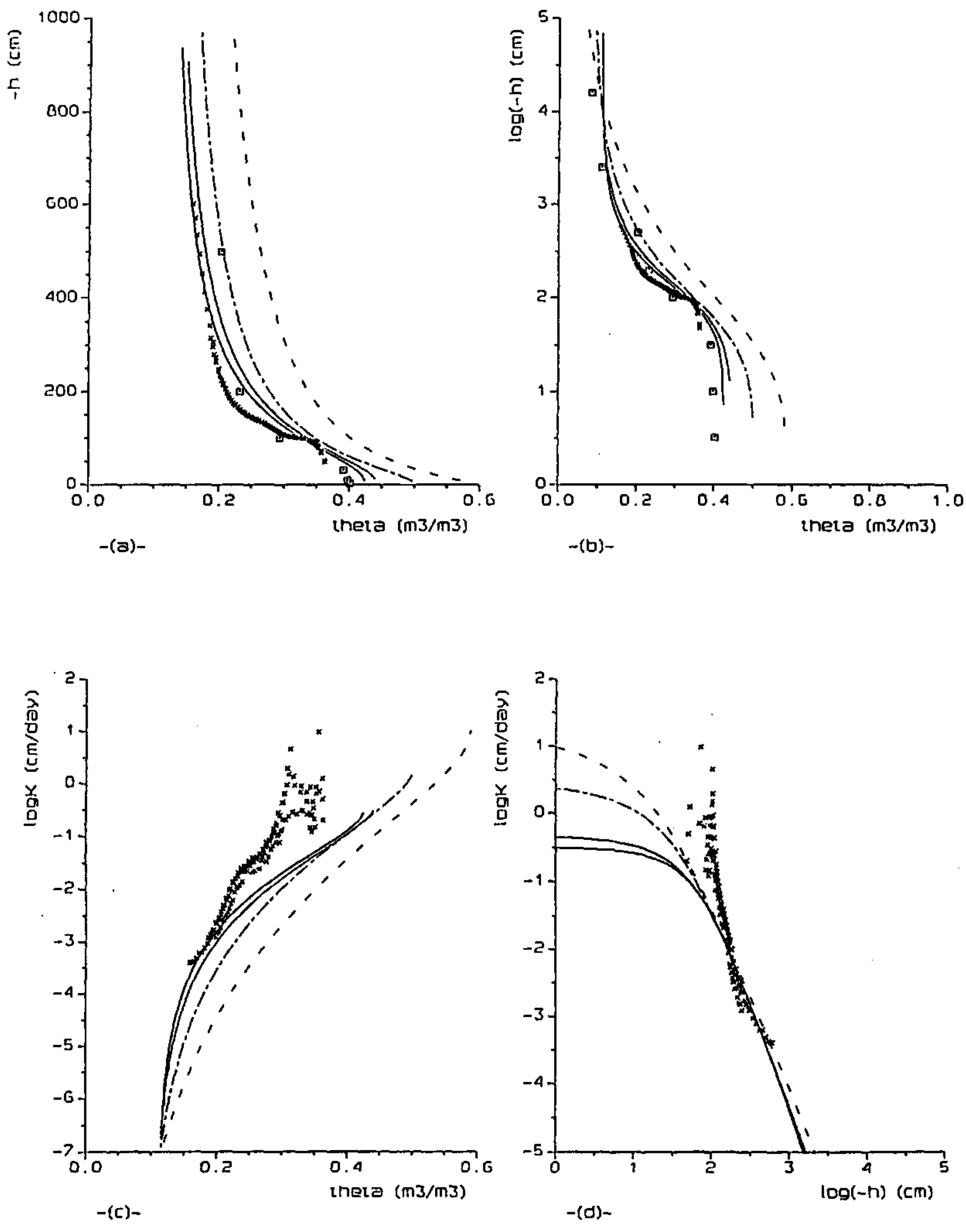

Fig. - SOIL HYDRAULIC PROPERTIES OF SAMPLE 15.040

x : instantaneous profile method

lines : parameter estimation method (maximum 4 groups)

☐ : results obtained for other samples (see text)

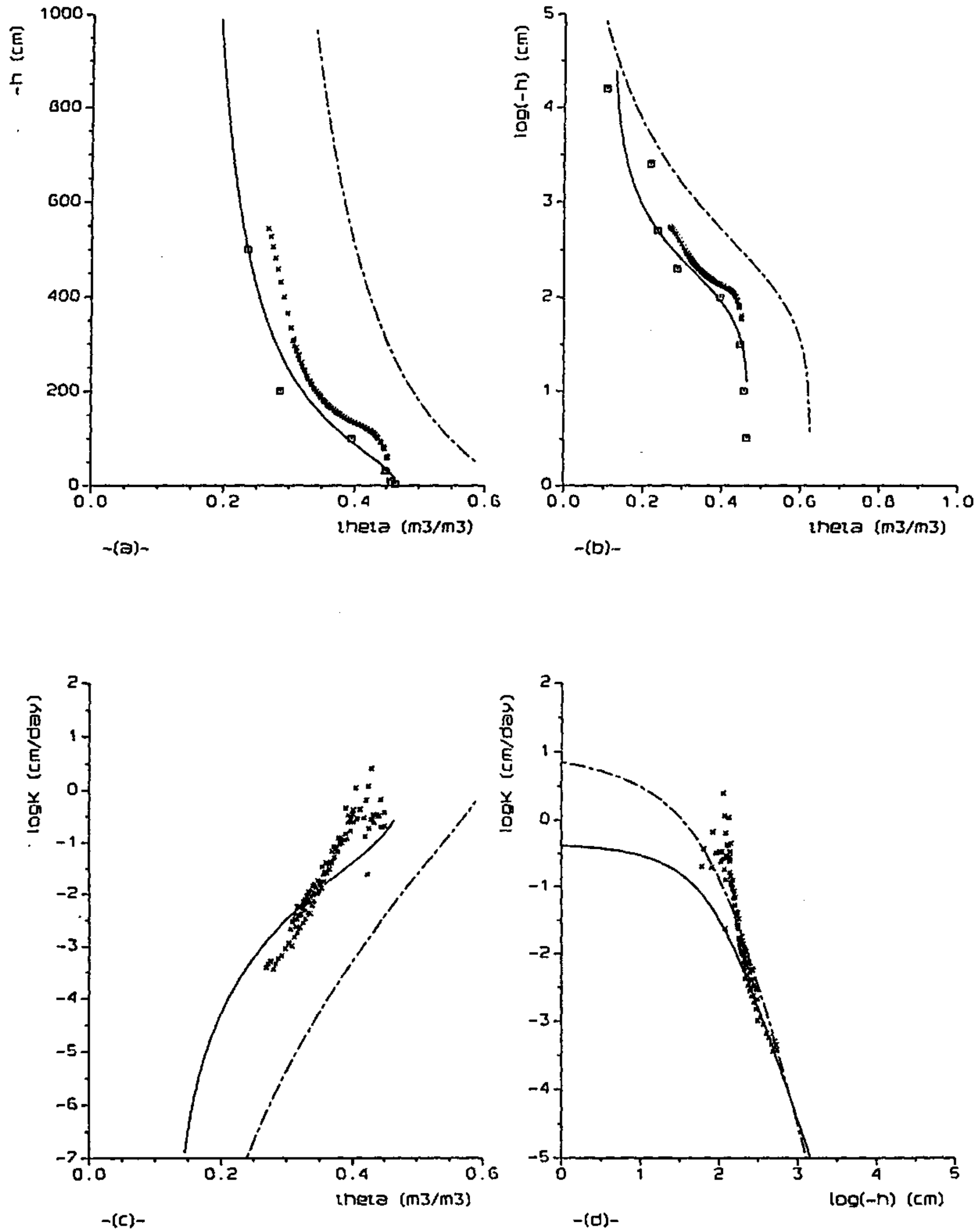

Fig. - SOIL HYDRAULIC PROPERTIES OF SAMPLE 17.040

x : instantaneous profile method

lines : parameter estimation method (maximum 4 groups)

☐ : results obtained for other samples (see text)

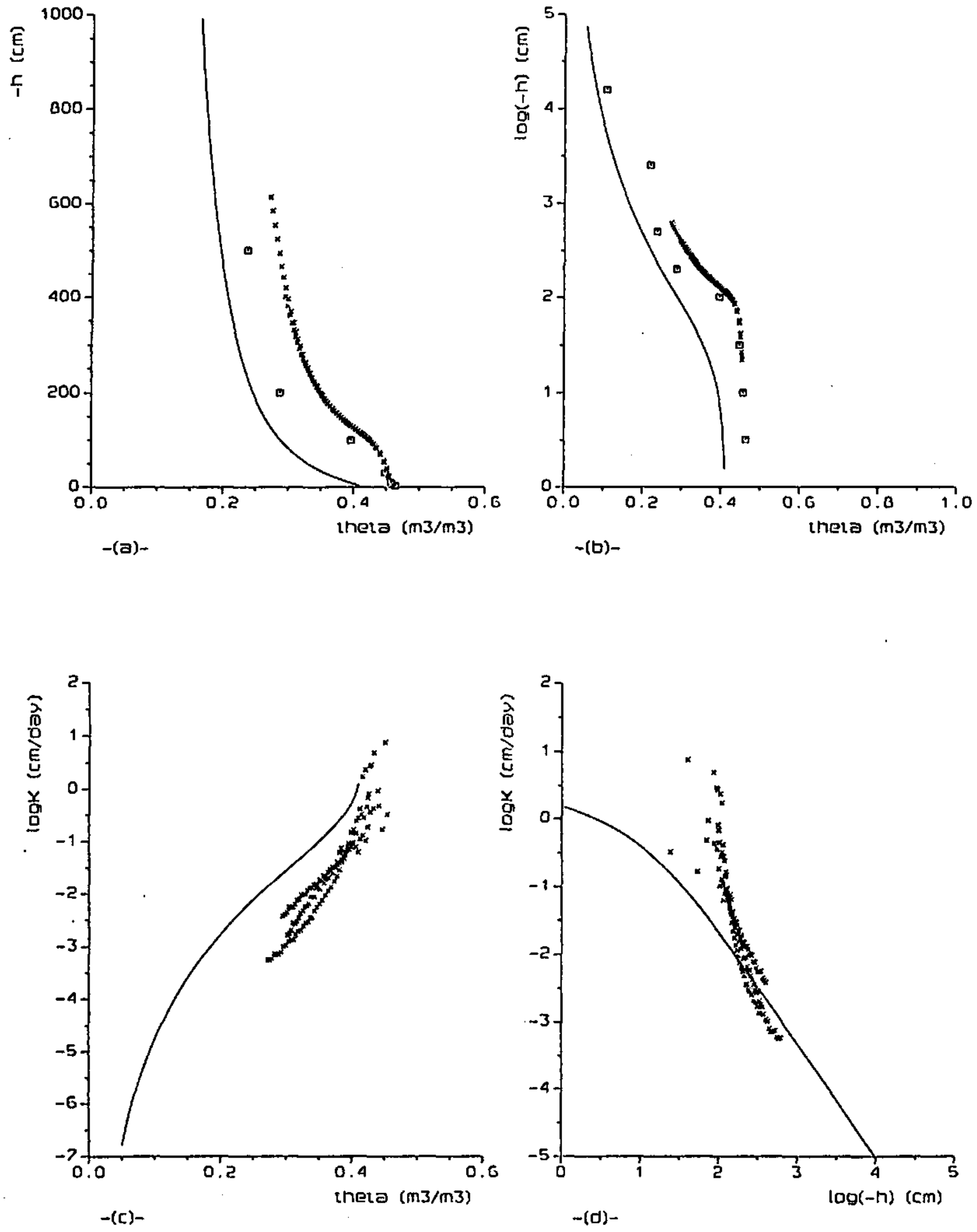

Fig. - SOIL HYDRAULIC PROPERTIES OF SAMPLE 07.040

x : instantaneous profile method

lines : parameter estimation method (maximum 4 groups)

□ : results obtained for other samples (see text)

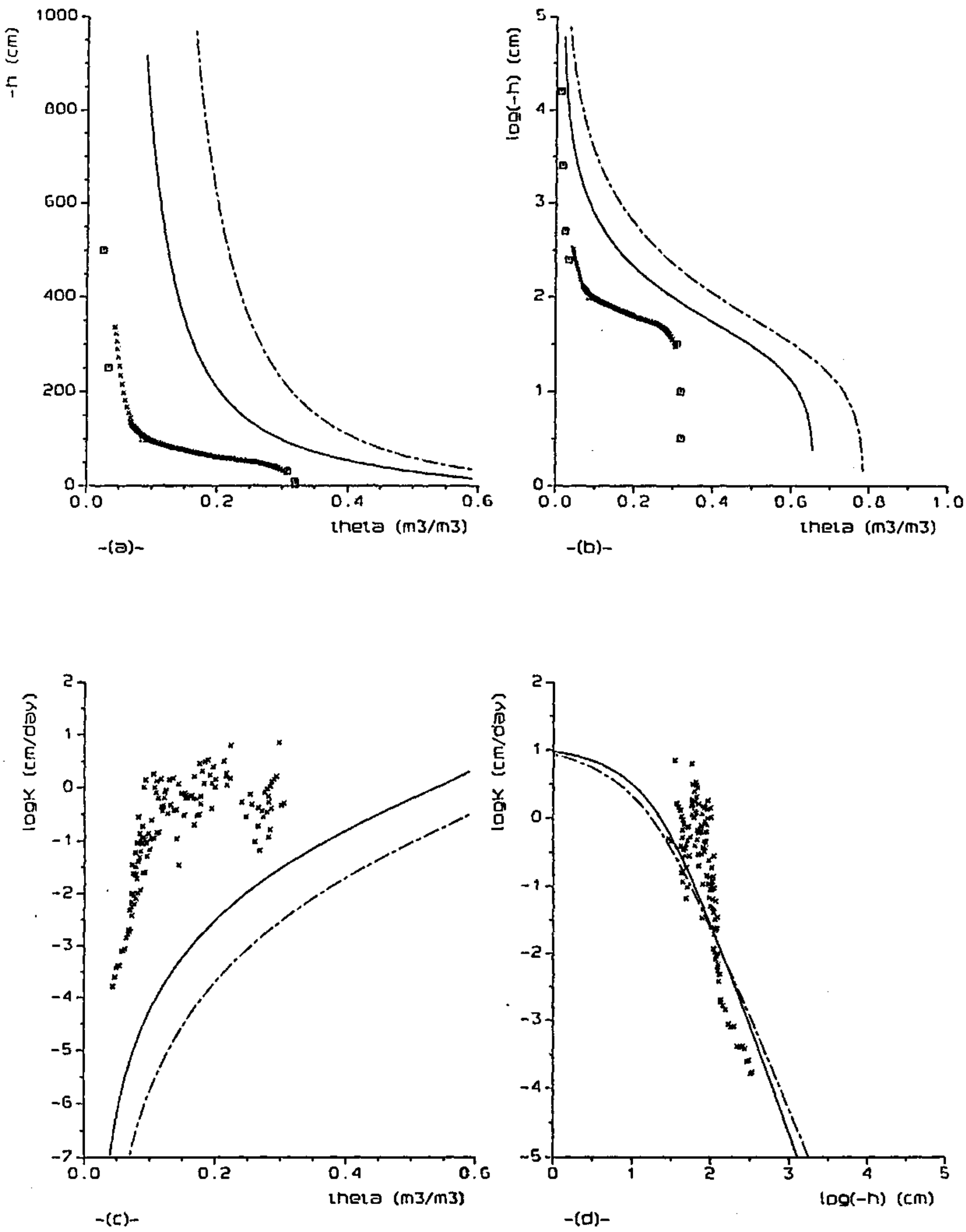

Fig. - SOIL HYDRAULIC PROPERTIES OF SAMPLE 01.038

x : instantaneous profile method

lines : parameter estimation method (maximum 4 groups)

□ : results obtained for other samples (see text)