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CONTROL OF THE IRRIGATION WATER RESOURCES OF THE AL-HASA OASIS

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A Thesis presented in partial fulfilment of the requirements for the Degree of Doctor of Philosophy of the Council for National Academic Awards

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ABSTRACT

This thesis describes the present situation of the Al-Hasa oasis, which is critically dependent on a single over-used water resource.

Evidence is presented to show that water usage is inefficient, and that real improvements are possible, but only if the local farmers are provided with the means of determining the soil moisture levels of their fields.

Simple tensiometers and soil moisture cells are considered for this purpose and both would be effective. Soil moisture cells are likely to be the better choice, but more work is needed to evaluate their response to saline soil moisture conditions.

The thesis shows that the widely used pressure plate (for laboratory evaluations) is less accurate than is the simpler filter paper system. Such laboratory determinations will be needed to ensure that the chosen field instruments are as accurate as is wanted.

An interesting, and still incompletely understood, phenomenon is that the soil grain sizes do affect the accuracy of results from the chosen field instruments. More work is planned on this subject.

A crucial factor also affecting the long term security of the oasis is to improve near surface drainage and evidence is presented that details the adverse effects of the present inadequate drainage system. In view of the vast financial investment already made into the drainage of the oasis, improvements that allow a better drainage of each individual field are seen as sensible.

Evaluations of more modern soil moisture measuring equipment (transducer and psychrometer systems) reveal that these are inappropriate for use at Al-Hasa.

The emphasis of the thesis is on the positive contribution to water use efficiency that can be achieved by the individual farmer. If the thesis conclusions are accepted then the continued prosperity of Al-Hasa can be assured at a very small cost.

SEQUENCE OF THE WORK DONE IN THIS RESEARCH

Oct 1982-June 1984 (Liverpool)	Laboratory evaluation of different types of tensiometers, tensiometer gauges and fittings, etc. Sand box trials and modifications.
June 1984-June 1985 (Liverpool)	Laboratory evaluation of soil moisture cells, gypsum blocks, and psychrometers. Soil column experiments.
June 1985-Jan 1986 (Liverpool)	Analysis of experimental results.
Jan 1986 - Oct 1986 (Liverpool)	Literature survey of technical literature on various aspects of Al-Hasa irrigation practices, water supplies, etc.
Oct 1986-May 1987 (Kingdom of Saudi Arabia)	Field studies at Al-Hasa.
May 1987-Sept 1987 (Liverpool)	Analysis of field results and computer studies.

Thesis presented September 1987

CHAPTER ONE

The Al-Hasa Oasis

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The Al-Hasa Oasis

1.1 Introduction

The Kingdom of Saudi Arabia (Fig. 1.1) is usually seen as an oil-rich state, utilising its wealth to establish a modern industrial society.

Whilst there is obvious truth in this - as can be seen in the vast new petrochemical complexes at Yanbu and the giant steel works at Jubail, it is also true that agriculture is a major pre-occupation with the Saudi Arabian government and with a large proportion of the Kingdom's people (Ref. 1.1). Indeed the growth in agricultural production (Fig. 1.2) and the investment in agriculture has been the most obvious success of the past decade, and the Kingdom is now entirely self-sufficient in many basic foods (e.g. wheat and milk products), (Ref. 1.2).

This has come about despite one of the world's worst climates (Ref. 1.3) for intensive agriculture. The rainfall, as can be seen from Fig. 1.3 and Table 1.1 is sparse and unreliable over most of the country, and

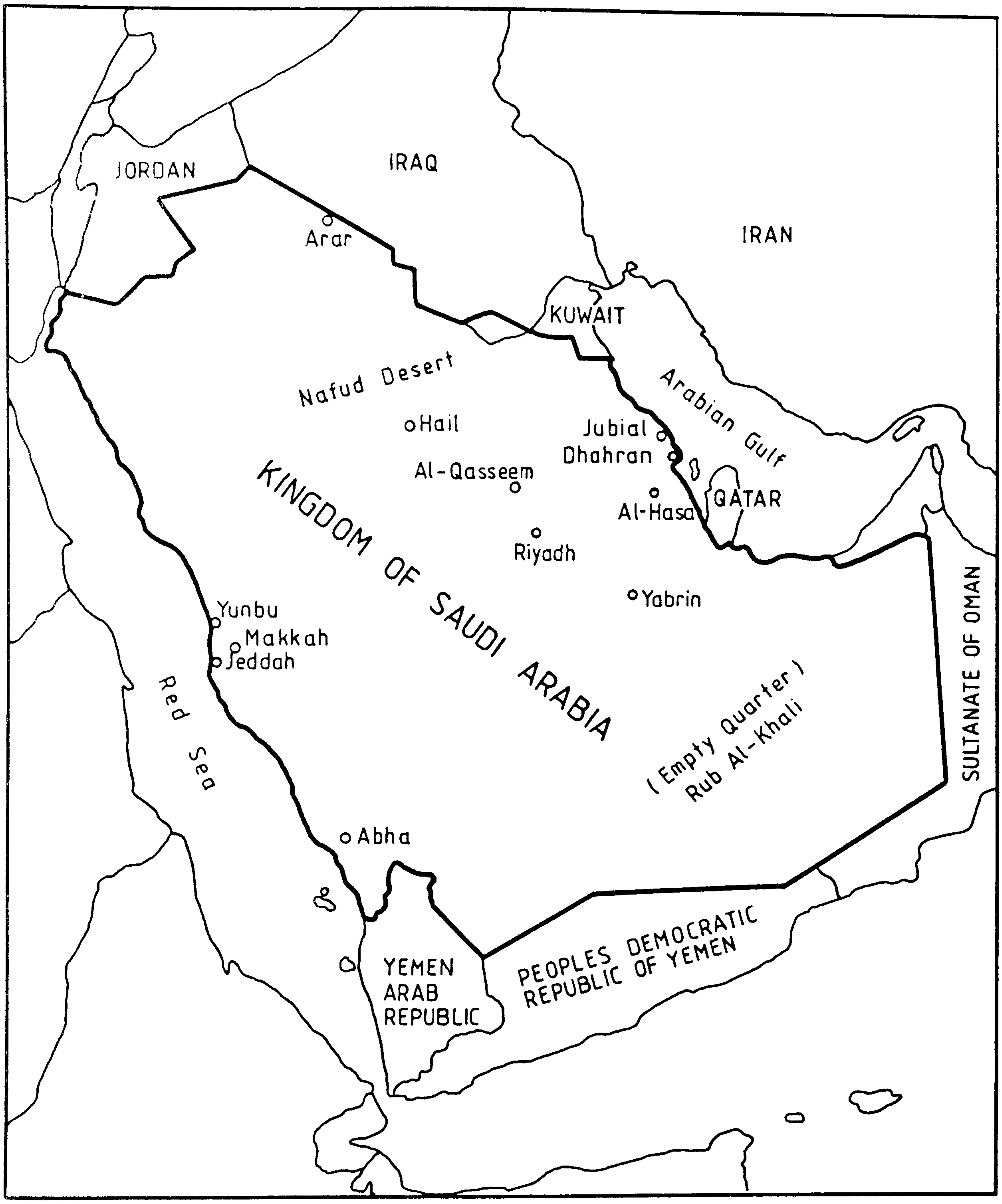
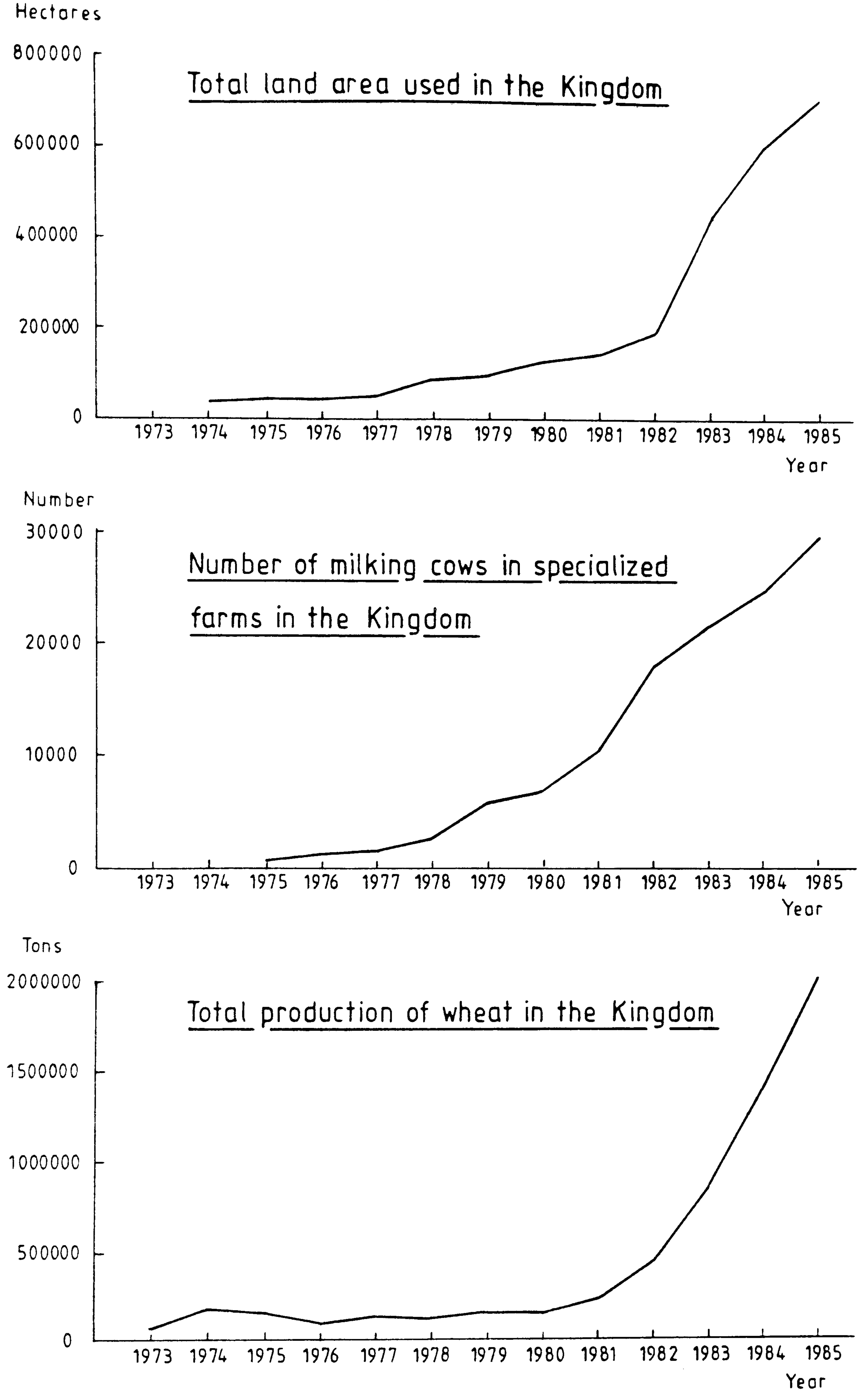


Figure 1·1 GENERAL LOCATION MAP



Total land area used in the Kingdom

Number of milking cows in specialized farms in the Kingdom

Total production of wheat in the Kingdom

Figure. 1·2 AGRICULTURAL DEVELOPMENT

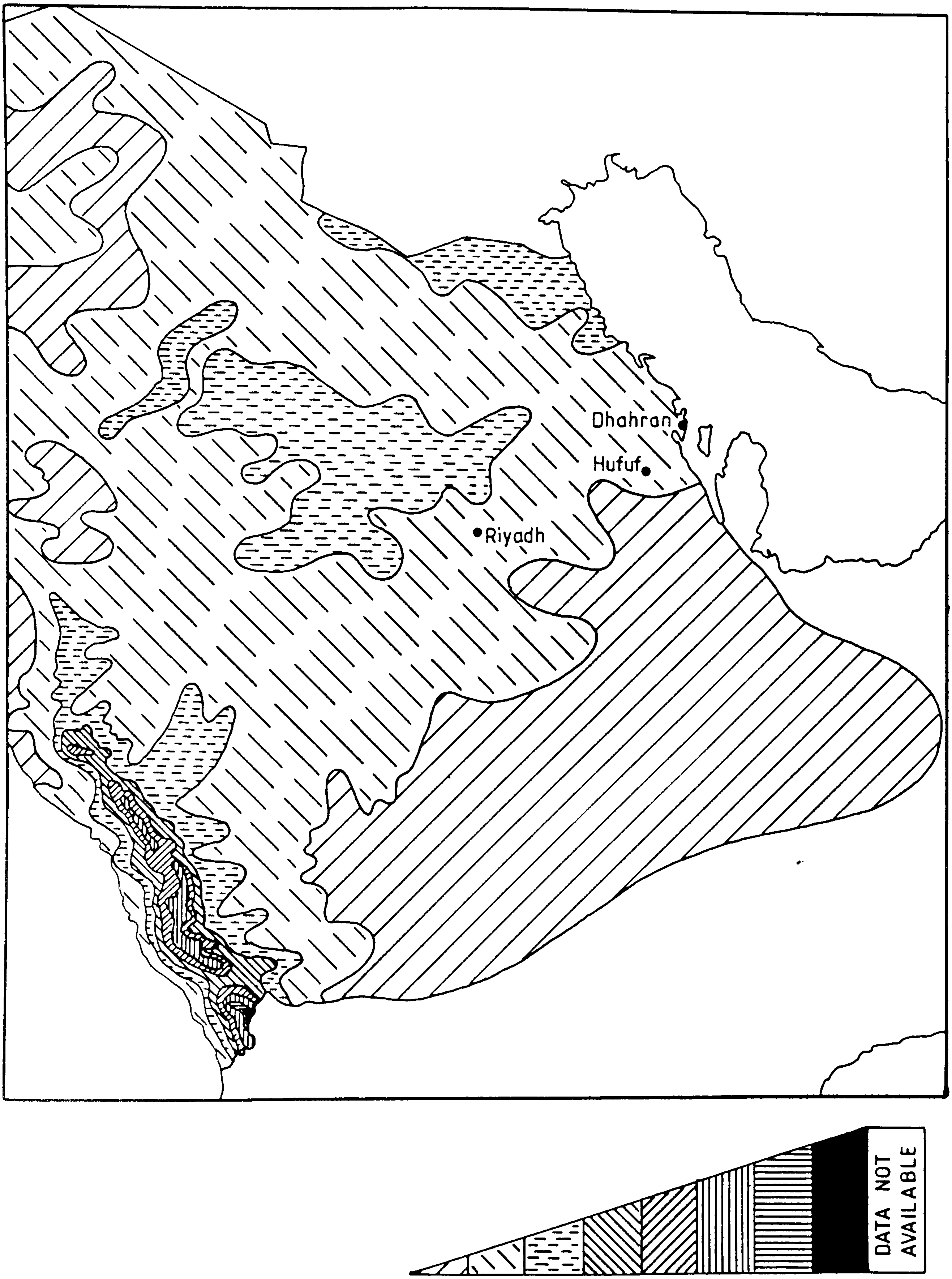


Figure 1·3 AVERAGE ANNUAL RAINFALL

TABLE 1.1

Mean Precipitation Values (mm)

Station	Riyadh	Dhahran	Jeddah	Ta'if	Medina
Altitude (m)	624	23	17	1471	646
Mean monthly totals					
January	18.6	23.5	15.7	10.1	7.5
February	8.8	15.8	9.4	12.8	0.6
March	16.1	3.8	2.2	27.1	6.8
April	24.7	16.2	7.9	27.5	6.4
May	12.8	2.2	2.4	21.9	4.3
June	0.1	0.8	0.4	5.5	0.3
July	0.1	0.0	0.5	3.9	0.1
August	0.1	0.0	0.1	9.4	0.1
September	0.0	0.0	0.0	4.6	0.0
October	0.0	1.4	0.0	6.5	0.4
November	10.3	7.1	14.2	41.7	8.1
December	10.6	3.8	12.5	6.8	3.5
Mean Annual Total	102.2	74.7	65.3	177.8	38.1
Period of Record	1953-71	1959-71	1957-71	1960-71	1956-71

Source:- Data from Kingdom of Saudi Arabia, Meteorological Climate Section evaporation losses from any body of open water (3,600 mm/year on average at Al-Hasa) are extremely high, and the temperature ranges from 0°C to 48°C in most years over much of the Kingdom. In all, the Saudi Arabian climate is kind neither to crops nor to the people who have to tend these.

The obvious question is "how did agricultural output grow so well in such an adverse environment?", and the answer lies in the vast investment made by the Kingdom's government.

Given the fact that surface rivers and springs only exist in the western and southern parts of the country (and these only in the wetter seasons), and that no usable surface water exists over the entire central and eastern regions (Ref. 1.4), the government saw the availability of irrigation water as the main barrier to increasing agricultural output, and - in 1958 - initiated a major groundwater location and evaluation programme. This, at an initial cost of £300 million, proved the presence of enormous groundwater reserves (20,000 cubic kilometres under the Great Nefud Desert alone) and opened the way to the drilling and equipping of many thousand deep wells (Ref. 1.5), and inevitably to a major expansion of almost every pre-existing farming settlement and to the establishment of hundreds of commercial farms in areas which earlier had been able to support only wandering camel herders.

The government's interest in expanding the agricultural sector probably came partly to ensure that the Kingdom would be able to feed itself (and so avoid pressure from foreign suppliers); partly to avoid the unfortunate experiences of many developing countries which had suffered a population drift to the towns and cities where life offered greater opportunities and comforts; but also reflected the intense traditional interest in agriculture which typifies many of Saudi Arabia's people (Ref. 1.6).

Although the development of the groundwater resources seemed to remove the problems of increasing agriculture, two quite separate facts soon emerged to show that other serious difficulties still existed.

The first was the discovery that almost all the groundwater was of fossil water that fell as rain about between 20,000 and 24,500 thousand years ago (Ref. 1.7, Fig. 1.4) and that almost no recharge occurs under today's climatic conditions. Thus the groundwater reserves, whilst huge, are finite and will ultimately be used up.

More immediately, as the groundwater levels fall with abstraction, the costs of pumping the groundwater will increase (since the input power needed by a borehole pump, for any particular water yield and pump mechanical efficiency, depends on the head losses in the pump's rising

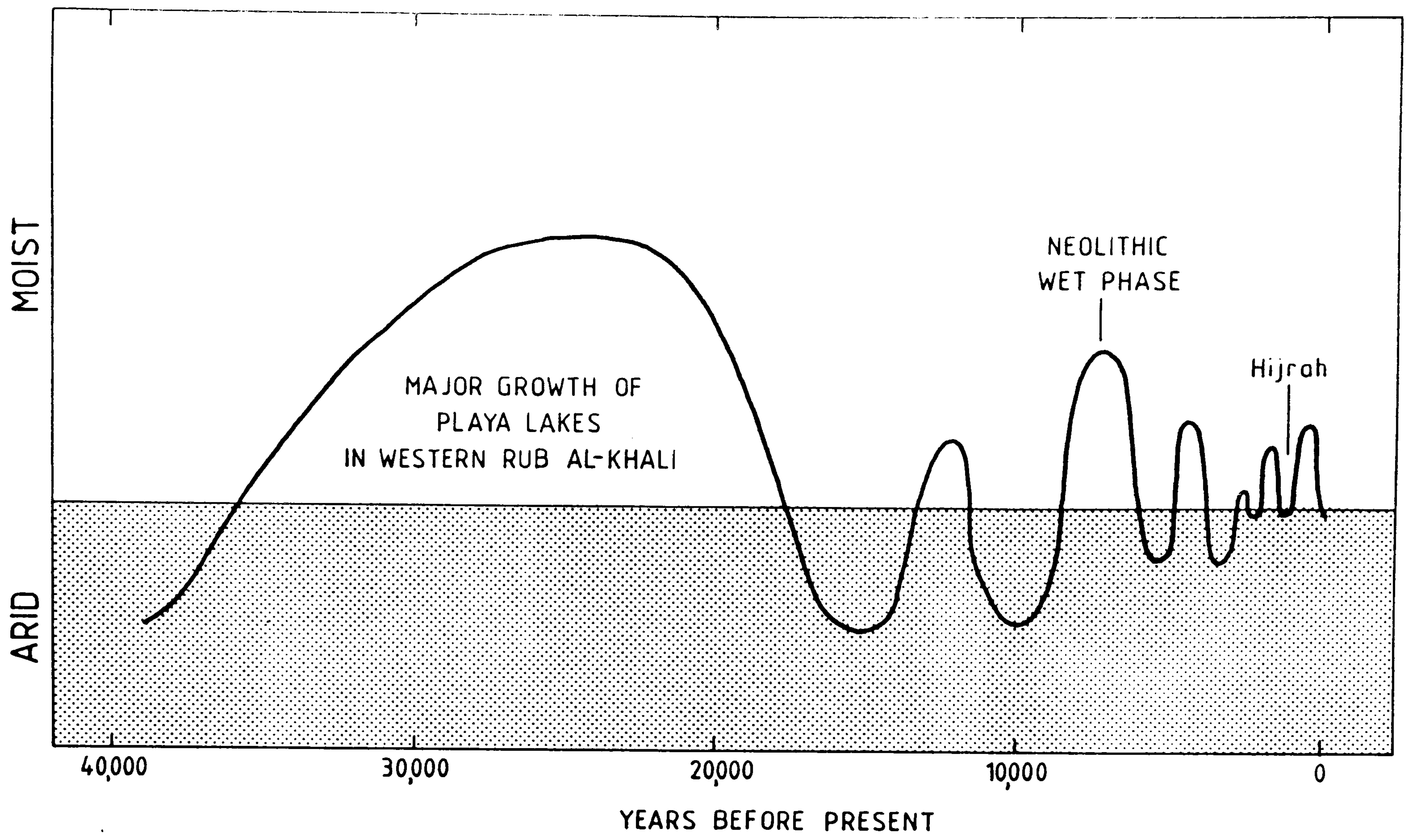


Figure 1·4 RELATIVE MOISTURE – ARIDITY CHANGES IN SOUTH CENTRAL ARABIA

(Adapted from McClure, 1976, 1978; Larsen, 1983) main, and thus on the depth from ground surface level down to the groundwater), until few farmers will be able to afford the water costs. The initial delight at the discovery of the large groundwater reserves soon became tinged with worry over the length of time that these new water sources would be economically available.

The second problem arose quite soon after the groundwater became easily available (through interest free loans for wells and boreholes) to the ordinary farmers. Initially their crop yields increased, but this was shortly followed by an increase in salification and large areas of land becoming poisoned by surface coatings of gypsum and other soluble salts (Ref. 1.1). This problem was widespread over the Kingdom, though best reported in the Al-Hasa and Qatif regions (Ref. 1.6 and 1.8). The reason was simply that the farmers, historically used to having too little water and now having access to much greater quantities, tended to apply more than their crops actually required, and the excess (with the salts it contained) was drawn back up through the soil profiles, by evaporation, to deposit the harmful salt crust over the lands. The effect was especially a problem in those areas where drainage down the soil profiles was impeded by near surface impermeable hard pan layers. Thus deep drainage works had to be considered, and efforts to control irrigation water rates have now been started.

The situation in Saudi Arabia is of an agriculturally minded country that has to make use of non-renewable water resources, and has to refine its water utilisation and management if it is to protect its investment in agricultural expansion and to attain its aim of long term total self-sufficiency.

The oasis complex of Al-Hasa in the Eastern Province typifies much of the national agricultural history, and emphasises the national problems which must now be overcome.

1.2 The Al-Hasa Oasis

The Al-Hasa oasis lies 320 km north-east of the capital, Riyadh, 150 km south of the port city of Dammam (Fig. 1.5), and extends from a latitude of $25^{o}21'$ north to $25^{o}37'$ north and between longitudes of $40^{o}33'$ to $49^{o}46'$ east. In all, the "L" shaped oasis has an area of 320 km^2 (Fig. 1.6).

The oasis is usually approached today from Dammam or Riyadh over a parched scrub and rock desert plateau that dips gently eastwards towards the Arabian Gulf. By no stretch of the imagination are the surroundings hospitable to human life, though they are much more acceptable than is the less used southern route through the Empty Quarter (Al-Rub

Figure 1·5 LOCATION MAP OF AL-HASA REGION

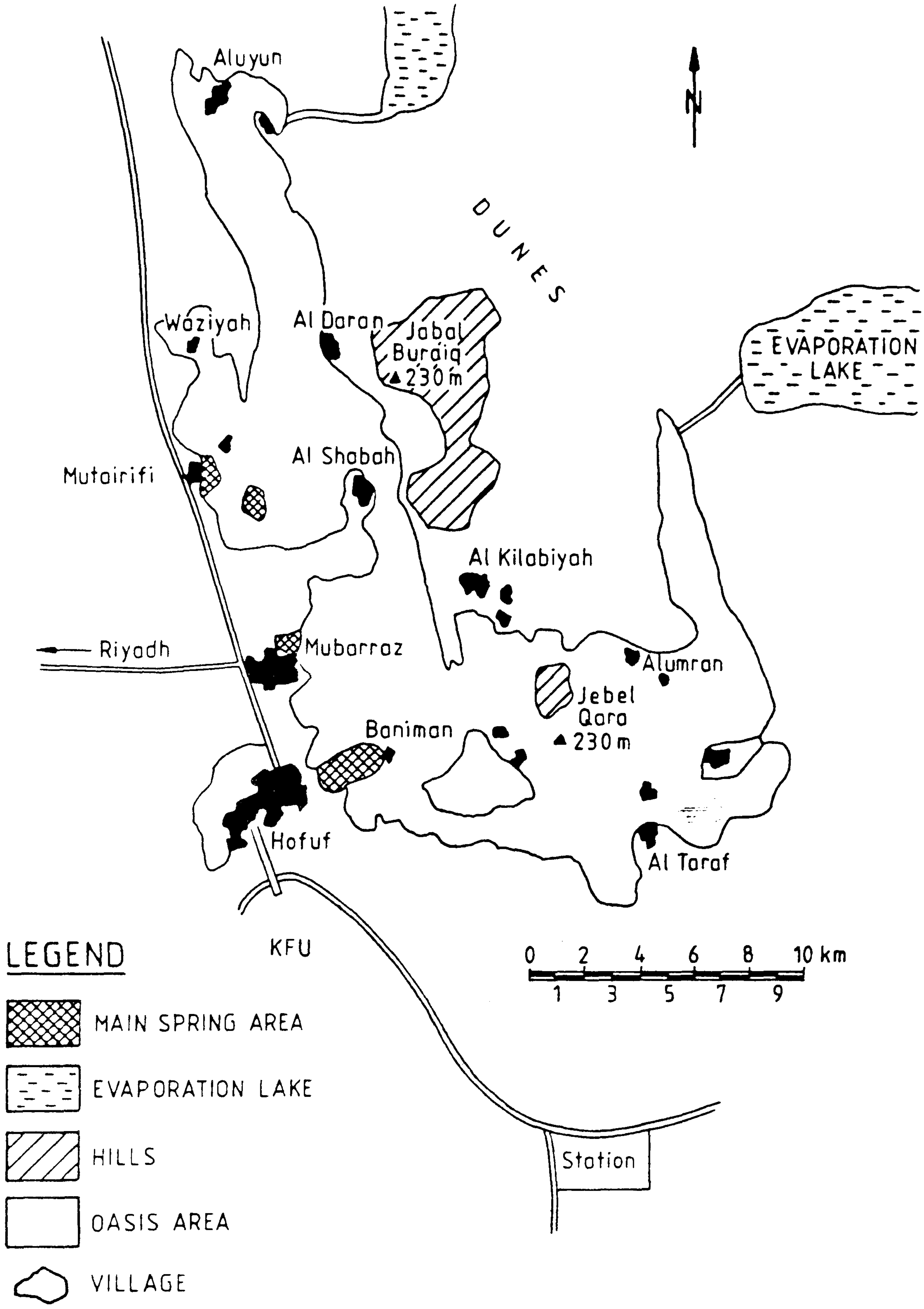


Figure 1·6 PLAN OF AL-HASA OASIS

Al-Khali), where moving dunes, excessive temperatures and salt marshes dominate. By any of these routes, the sudden topographic fall down to the level of the oasis is striking (this topographic change indicates a former coast line of the Arabian Gulf when the oasis lay below the sea and the hills to its north and western margins marked the wave cut cliffs that fronted the Gulf at that time), as is the sight of 172 springs each of which produces clear drinkable water. Many of these springs have such high water flow rates that they have cut swimming pool sized holes in the soft local limestone, and all are surrounded by the shade of the greatest palm oasis in the world. (Plate 1.1).

The dramatic environmental contrast between the oasis and its surroundings explain the great affections with which the local people and the wandering Bedouins regarded - and still regard - the springs, and this affection is often shown in the names given to individual springs (e.g. "Ain Joharya" or "a thing of great value").

The oasis and its springs are the basis on which a major agricultural settlement has existed for perhaps 3,000 years. Certainly Roman travellers - Plinius and Straho - some 2,000 years ago visited the area and described a prosperous transhipment and rest point on the caravan route to Persia, which they identified by the name "Gerrha". At that time Gerrha had a navigable river link to the Arabian Gulf, and

Plate 1.1 View over the Al-Hasa Oasis from the East (Jebel Qara)

this - plus the oasis - gave it its commercial prosperity. The name "Gerrha" appears to Arabic scholars (Ref. 1.1) to be derived from the Arabic word "Qora" (meaning "villages"), and in the southern half of the oasis there still exists a very old village (Al-Qara) with an adjoining hill (Jebel-Qara) in which there are many cave dwellings. This, plus the description of houses being built in the traditional oasis manner from sun dried salty clay suggests that these Roman travellers visited what we today recognise as Al-Hasa.

Throughout its history, the oasis has been dependent on its palm, alfalfa, rice, salad and fruit crops, and has had up to 20,000 hectares of cultivatable land. The cultivated area has varied many times throughout the oasis's history, as climatic and environmental changes (particularly those caused by moving sand dunes) occurred.

Today, the oasis supports a population of about 250,000 people (Ref. 1.9) in the two cities of Hofuf and Mubarraz (Fig. 1.6) and the surrounding 51 villages. Population growth has averaged 2.7% over the past five years, and the greater part of this population is involved in the oasis's agriculture, either on a full-time or part-time basis.

In terms of the Kingdom's total population (about 12,000,000 in 1986), Al-Hasa is thus not an insignificant settlement and its agricultural products (particularly its dates) are an important part of the national crop production.

1.3 Land Utilisation at Al-Hasa

The pattern of Al-Hasa's land utilisation emphasises the problems that the Kingdom as a whole has experienced.

About 2,000 years ago, the cultivated land appears (Ref. 1.10) to have been about 20,000 ha. in extent. The presence of the river link to the Gulf offered easy drainage from the irrigated fields, and salt build-up in the soils is said to have been only a minor problem. This salt build-up comes (Chapter 2) from the high salt content in the oasis's spring waters.

Later, the worsening climate encouraged an increase in moving sand dunes, especially to the north and east of the oasis, and these dunes gradually encroached on the northern edge of the oasis and finally covered the river channel.

With the drainage from the oasis reduced by the dunes, salts could no longer be easily leached out of the soil profiles and salification problems became more obvious. However, the lack of any power sources (except animal powered water wheels and scoops) limited the amount of water (and thus the amount of dissolved salts) that could be added to the fields, and so the salification was not a major difficulty.

By 1951, when modern records began (Ref. 1.1), between 12,000 and 15,000 ha. of land was under intensive cultivation, and the new diesel pumps and drilled wells were making water easily available to every individual farmer. Agricultural production showed a marked short-term increase, and local optimism is said to have been very high (Ref. 1.11).

Within 12 years, a marked worsening however, had taken place. Only 10,000 ha. were still cultivated, and of these 2,400 ha. were in very poor condition with surface salt crusts limiting agricultural output and killing off the more susceptible crops (Ref. 1.1).

By 1970, conditions had become even worse, the area of salt affected land had increased and agricultural yields had fallen still further, despite farmers applying more and more water to their fields in an effort to wash the harmful salts out of the soil profiles (Ref. 1.12).

This worsening situation led to the Saudi Arabian government setting up the Al-Hasa Irrigation and Drainage Authority, (H.I.D.A.), since drainage works of a major oasis-wide nature would obviously be necessary if the oasis were to be saved. (See Section 1.4).

Although the basic cause of the salification is the over use of salt-bearing spring water combined with a poor subsurface drainage, the local and traditional land tenure systems have not helped the situation.

Holdings are usually 2 ha. or less in area (such holdings total 90% of the oasis's cultivated land), with each owned by a peasant farmer and his family. Obviously it is difficult to organise large scale co-operative action (e.g. major drainage or water usage efficiency) with up to 22,000 separate land holders, few of whom are fully literate or educated beyond a basic level.

To make matters worse, some holdings have been acquired through inheritance by people with non-agricultural employment, and these tend to be leased to tenants who thus lack any real incentive to improve the land. These holdings generally are leased for as short a period as two years (another disincentive to improvement) and have rents that are paid in kind. Because of this, most are planted with date orchards, and it is noticeable even today, how poorly cared for are many of the smaller date palm plantations.

Some larger holdings have been bought by the business people, not for income but for the pride of possessing land.

These tend to be run by hired labourers, and few are operated on a share of the profit basis.

Finally a small number of 4 ha. farms have been distributed by the Ministry of Agriculture to the better farmers and these tend to be the most well run (Ref. 1.9).

Of the oasis's current cultivatable area of 25,000 ha., 20,000 are now in production but with a population predominantly of small and technically untrained farmers and tenants. Thus it is not surprising that the salification problems, which are a significant technical problem even to the United Nations Food and Agricultural Organisation (Ref. 1.13), have proved so damaging.

1.4 Drainage Efforts by H.I.D.A.

The H.I.D.A. drainage project is the largest in the Kingdom with about 1,482 km of open concrete channels to distribute the spring waters to the farms over 15,680 ha. A total of 22,000 individual farms were served by the H.I.D.A. system in 1986, (Ref. 1.12 and 1.14).

The origins of H.I.D.A. lie in the appointment of the United Nationals F.A.O. experts in 1960/62 to investigate conditions within the oasis.

This investigation noted the relatively high salt content in the spring waters (Chaper 2), the much higher salt levels in the drainage from the farms, and the fact that the near surface (1 m to 2.3 m below ground level) hard pan layers precluded any fast drainage down many soil profiles and encouraged the formation of a near-surface perched aquifer, from which very salty water could be lifted by evaporation in the hot seasons, (Plate 1.2).

The investigation indicated the obvious need to prevent the fresher irrigation water and the saltier drainage mixing, and thus the need to drain the near-surface perched aquifer. With adequate drainage measures, salts in the soil columns could then be washed out by a controlled over application of irrigation water and salt contaminated land could be brought back into productive use.

W.A.K.U.T.I. (a German/Swiss consultancy organisation) and the Leichtweiss Institute of Braunschweiss University were then (1961/62) engaged to obtain detailed design data and to propose practical solutions (Ref. 1.14).

This led to a final design being accepted in 1965 and to construction contracts (ref. 1.1) being issued in 1966. The final project was completed in 1971 and includes 120 kms of main drains (1.8 m deep), 150 kms of subordinate drains and

Plate 1.2 Salty Near Surface Groundwater Exposed in Excavation

1,000 kms of shallower (1.0 m deep) lateral drains that penetrated into the individual farms. These drains lead to three large evaporation basins, (Fig. 1.7), and the entire network is serviced by a system of asphalted roads.

The 1,482 km of fresh water distributions from the main 32 springs to the farms is built of pre-fabricated "U" section concrete channels (Plate 1.3).

The scale of the project is obviously huge, and very evident benefits (including the drainage of mosquito breeding areas) have been achieved. The simple fact that whilst the spring waters contain approximately 1,400 to 1,550 mg/litre of soluble salts that of the drainage water from the fields averages 5,000 mg/litre alone indicate the need for the vast drainage effort. (Ref. 1.12).

Despite all this expenditure and effort, a basic problem with the farmers still exists. Most still insist in using shallow hand dug drainage ditches within their farms, despite the advice of the Ministry of Agriculture's extension counsellors and the Arabian-American Oil Company's technical advice (Ref. 1.15). These shallow drains (0.5 m or less in depth) are relatively useless and fail to connect to the H.I.D.A. drainage works, and so a high perched water (0.6 m below ground surface) table still exists in the central portion of most of the farms, and the leaching of

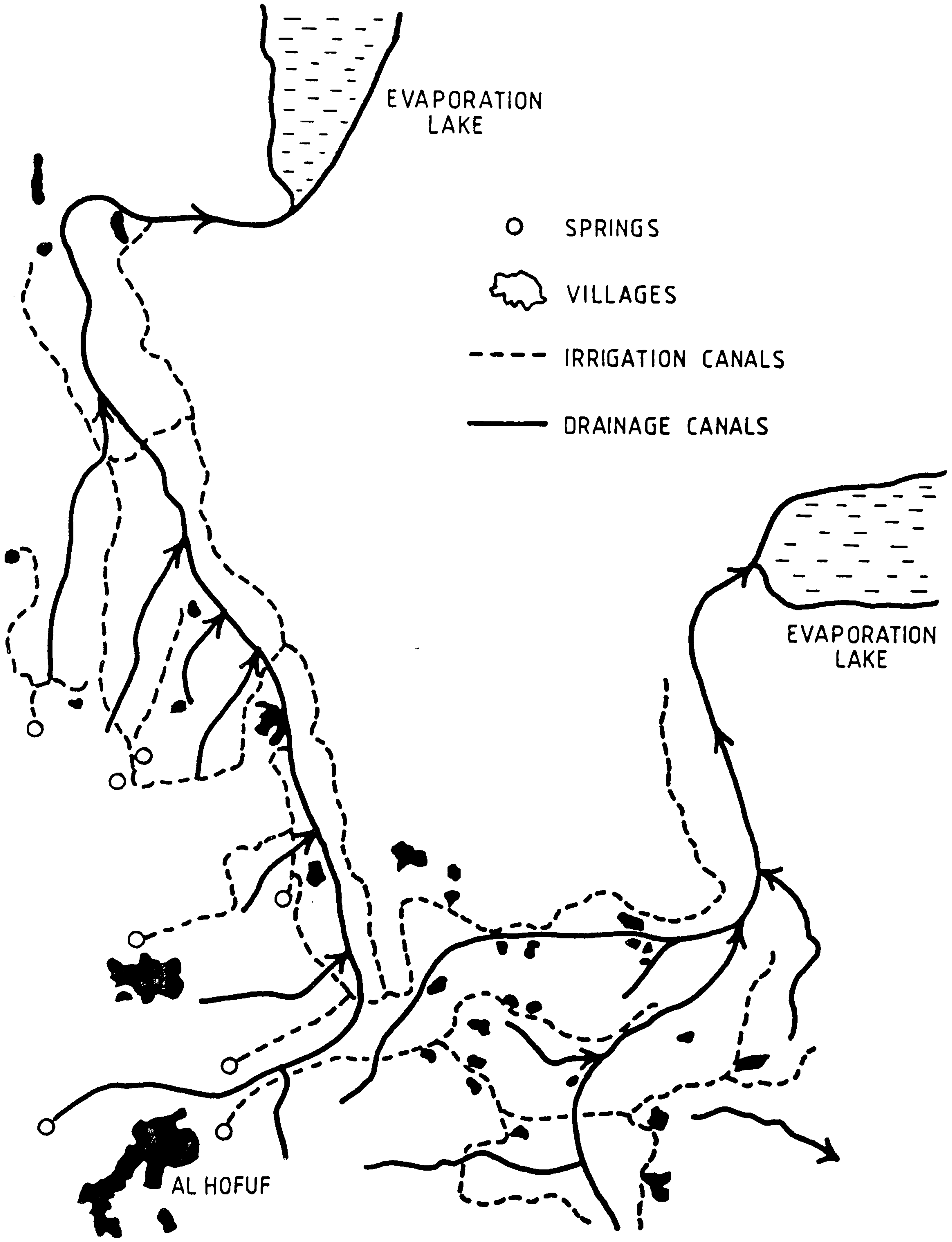


Figure 1·7 AL-HASA IRRIGATION AND DRAINAGE AUTHORITY NETWORK

Plate 1.3 Subsidiary Water Distribution Channel into an Individual Farm

salts out of the soil profiles is far from complete. The land tenure system Section 1.3) obviously has an influence on this (Ref. 1.15), as does the still imperfectly controlled use of water. Some of the local farmers use their own individual supply wells instead of the H.I.D.A. water supplies and so can apply water when the mood takes them and not when the crops actually need irrigation.

1.5 Salification in the Al-Hasa Oasis

The Al-Hasa position is dominated by its excessively high potential evaporation (about 3,600 mm/year), its poor sub-surface drainage, and the presence of salts in the spring waters.

Estimates of the salt content brought into the oasis by the springs vary between 308,000 (Ref. 1.12) and 600,000 metric tonnes per year (Ref. 1.1), since the various authors used different estimates of the amount of irrigation water actually placed on the fields. However, an annual usage figure of 220 million cubic metres now seems accepted, and so at least 350,000 metric tonnes of salt are brought in each year, and this is equivalent to about 15 to 18 tonnes being added to each hectare in a year (Ref. 1.12).

As the oasis is almost surrounded by dunes, through which drainage is slow, the gradual build up of a near surface groundwater of very salty nature is thus understandable. Prior to the H.I.D.A. project, the sole drainage was underground to the small salt marshes ("sabkahs") that lie to the east of the oasis, but these offered only a limited discharge potential.

Even outside of the traditional oasis, where agricultural development of new large farms commenced in the 1960's, salification proved to be a major problem. (Plate 1.4). An example is of King Faisal University Experimental Farm (16 kms to the south west of the oasis), where initial agricultural cultivation had to cease until deep drainage works could be installed (Ref. 1.16). On this farm, a marly hard pan generally occurs at shallow depths below the surface of the fields, precludes drainage of the soil and encourages the formation on shallow salty perched water table. (Fig. 1.8).

The effect of high salt levels on crops can be quite striking. Salts in the soil water increase the energy needed to abstract the water and plants are stunted and of low yield. In the worse cases, plants (such as fruit trees) might survive for up to 5 years and then die. When the roots of these are examined they are usually coated with accumulated salts which have ultimately precluded the movement of moisture into the plants. The sensitivity of plant species to salt levels is of course very variable

Plate 1.4 Salt Crusts on King Faisel University Experimental Farm Fields

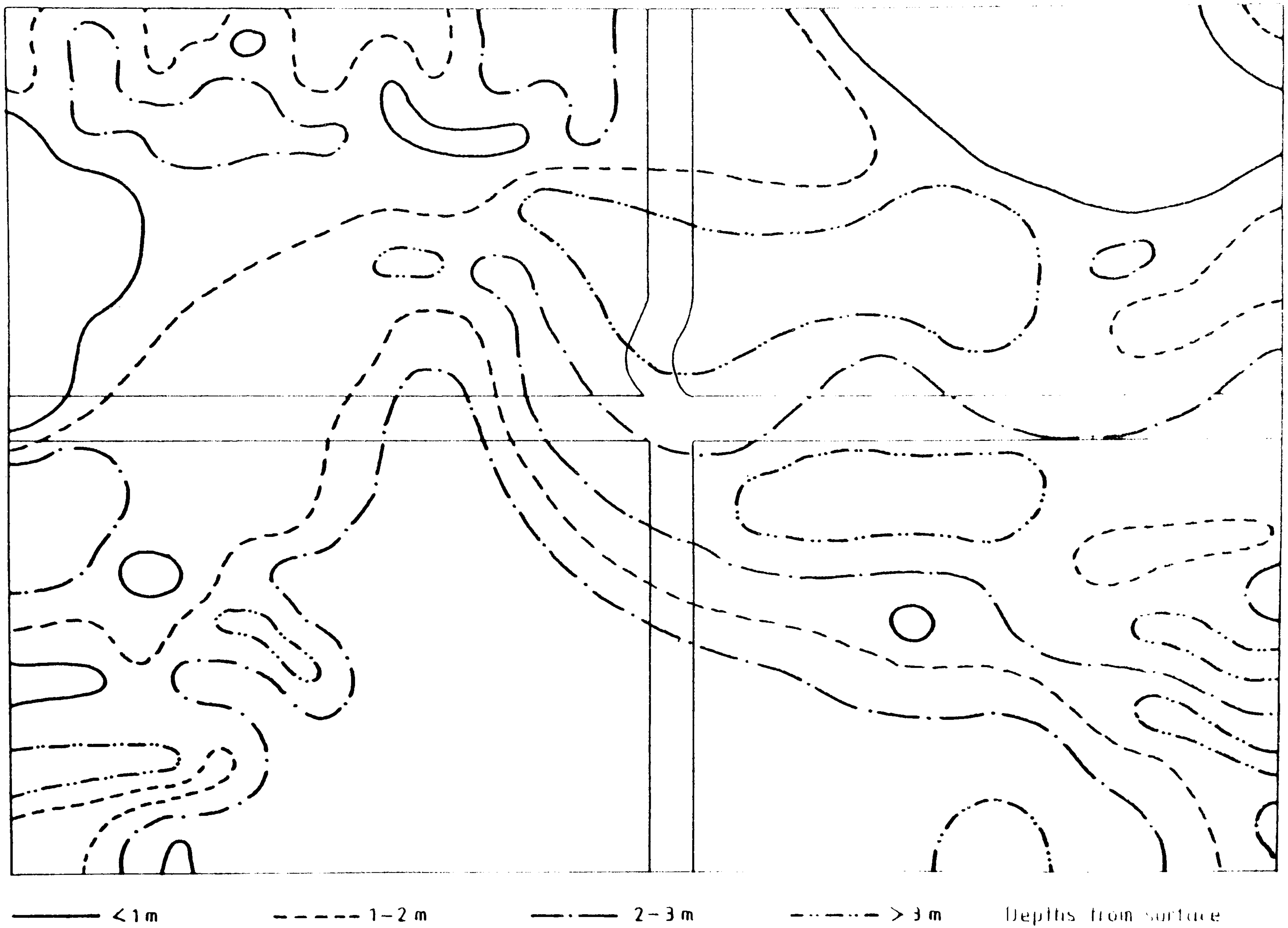


Figure. 1·8 HARD-PAN MAP OF K.F.U. EXPERIMENTAL FARM and many of Al-Hasa's most important crops (e.g. palms, rhodes grass, etc.) are highly tolerant of salts, other important crops (e.g. wheat, rice, alfalfa, vegetables and fruits) are however, much less tolerant and so more liable to suffer damage (Ref. 1.17).

Given that the Al-Hasa soils are usually sandy loams and loamy sands (Ref. 1.18) with a calcium carbonate content that averages 18% at soil surface and increases to 50% at depth, it is not surprising that such salt toxicity effects occur. This situation is even worse in the undrained areas where salt contents of between 37 and 94 millimhos (i.e. equivalent to 23,680 to 60,160 mg/kg) still occur. (Ref. 1.18).

The obvious benefit of the H.I.D.A. drainage works is that the oasis's soils on average now have between 1,000 and 2,000 mg/kg of soluble salts, a very marked reduction indeed over the figures quoted immediately above.

However, the salt content in the soils is still extremely high by international standards, and the spring water salt content is about twice the level that would be seen as appropriate in most other countries.

Thus it is obvious that drainage works (whilst essential and valuable) are not the ultimate answer to controlling salification at Al-Hasa or in most of Saudi Arabia. What is required is an irrigation management that precludes over addition of the salt bearing irrigation water to the fields and this requires some simple and obvious method which the farmers (few of whom are technically educated or even fully literate) can use to judge the need to irrigate their fields.

1.6 Consumptive Use Data for Al-Hasa

In order of importance, the crops of the oasis are

date palms (often with an alfalfa sub growth)
alfalfa
various salad and vegetable crops
rice
various fruits.

Wheat, maize and sorghum are generally grown outside of the main oasis on the newly developed farms.

Dates are traditionally the major crop, and still cover 68% of the oasis. Over 1,200,000 individual trees exist, of which about 250,000 are in the die-back stage because of water shortages, saline water logging of the soils or various disease and pest problems.

Although dates provided the staple diet of both people and livestock and formed the basis of a major export trade to India, the current low market value of the crop has reduced its importance and has led to much less care than formerly being given to the trees. (Ref. 1.6).

Alfalfa is another traditional crop and still commands a good market price since the Kingdom's increased livestock farming has generated a great need for fodder crops.

The other crops tend to be grown for local consumption.

Consumptive water use data is of course crucial to any area that requires irrigation water for its agriculture. Such data, plus estimates of the areas covered by each crop type are the basics on which irrigation systems are sized, designed and managed (Ref. 1.19).

Two quite separate approaches to estimating crop's consumptive water uses are possible, by a theoretical/ empirical evaluation of the climatic factors (evaporation, solar intensity, wind speed, soil type, etc.), and by field trials. Both approaches have been carried out for Al-Hasa.

A theoretical evaluation (Ref. 1.20) of the crop water requirements for

wheat
barley

tomatoes
potatoes
onions
melons
dates
citrus fruits
grapes
alfalfa
rhode grass
and sorghum

was completed to allow the amount of various qualities of irrigation water (from salt contents of 500 mg/litre up to 4,000 mg/litre) to be estimated. The study allowed for various crop planting times and for various irrigation types (i.e. surface flooding, sprinkler systems, trickle systems). For the typical Al-Hasa waters (with a total salt content of 1550 mg/litre) this revealed the following data (Table 1.2).

Whilst such work is generally useful to water resources planners, it is of little real benefit to agriculturalists since it does not allow for the varying needs of crops as they grow and mature. Additionally such estimates are based on climatic and vapour flow/heat balance studies and so have to be practically confirmed by field trials, especially since these theoretical approaches often have to be applied to climatic and agronomic conditions very different from those from which they were developed. Thus the theoretical approaches are usually seen as "stop gap" measures until more factually based data can be obtained. (Ref. 1.21).

TABLE 1.2

Estimated Gross Seasonal Water Needs of Important Crops

Crop Type	Water Need (m^3/ha/year) by		
	(a) Surface Flooding	(b) Sprinkler Application	(c) Trickle Application
Wheat (October Planting)	9,360	7,275	-
Barley (October Planting)	9,160	7,121	-
Tomatoes (September Planting)	11,291	7,886	6,494
Potatoes (October Planting)	11,713	6,982	5,750
Onions (October Planting)	12,952	6,058	4,989
Melons (February Planting)	10,907	7,452	6,137
Dates	34,782	26,120	20,865
Citrus	51,568	30,875	25,423
Grapes	30,444	17,738	14,608
Alfalfa	57,575	37,862	-
Rhodegrass (April Planting)	29,745	22,617	-
Sorghum (April Planing	31,494	22,141	-

More useful are the results gained from controlled field trials, especially since these can identify the benefits and disadvantages of various irrigation schedulings.

The first such studies in Al-Hasa (Refs. 1.22, 1.23, 1.24 and 1.25) were based on a well managed experimental plot system, with water conveyed by open ditches to the crops. These revealed (taking the sorghum study as an illustrative example) that:-

(a) the theoretical estimates of consumptive needs overestimated irrigation water needs

(b) crop water needs differ quite markedly through the growing season

(c) irrigation on the loamy sands of Al-Hasa is better carried out on a time interval of 2 or 3 days, rather than at less frequent intervals. Crop dry weights fell by 33% if a 6 day interval between irrigations replaced the preferred 2 or 3 day interval

(d) irrigation is best carried out by making enough water available to bring the soils up to their water field capacity in a single irrigation event. Applying less amounts of water (even on the same irrigation scheduling) resulted in markedly less successful crops with much lower protein levels

(e) irrigating at rates above the soil's water field capacity did not give any advantage in crop yield or health and merely resulted in a wastage of water.

This pioneer work pointed the advantages of factual consumptive use data and led to the major study by Asseed, Turjoman and Etewy (Ref. 1.3).

This covered a reasonably wide crop range - i.e.

wheat
onions
lettuce
alfalfa

- and included comparisons of all the theoretical approaches against field trial results. The main conclusions of the work are -

(a) that the Al-Hasa rainfall is able to supply a mere 2% of the water requirements of the crops in the trials

(b) that the saline content of the groundwater forces the addition of extra water (above that required by the plants) to leach salts down to the field drains. This leaching requirement was found to be 29% of the applied water for sensitive crops (lettuce), and 16% of applied water for moderately tolerant crops (onion, alfalfa, wheat)

(c) that water consumption - as would be expected - varies markedly with the amount of irrigation water added and that crop yields fell dramatically if irrigation rates were too low. A 32% drop in crop yield was associated with irrigation at only 5% lower than the field capacity value

(d) that irrigating at rates below the field capacity results (for lettuce) not only in crop weight losses but in a produce of far inferior taste (the phrase "sour" is used by the authors)

(e) that predictable relationships of the type

$$ET_a = K_c . ET_p$$

were achieved. The actual annual crop consumptive use (ET_a) could be related to the values of potential evapotransportation (ET_p) given by the various empirical methods (i.e. modified Blaney-Criddle method, Jensen-Haise method, Penman formula, Turc and Thornthwaite formulae) by factors (kc) they are respectively 1.26, 1.05, 1.24, 1.56 and 2.69. Factors to allow the relating of the peak consumptive use values also proved achievable.

This work provided useful guidance for the personnel who control the H.I.D.A. irrigation water supplies and forms the basis on which future work will inevitably take place.

Currently such work is being continued at the Al-Hasa Agricultural Research Centre.

Thus, whilst Al-Hasa has yet to have available the accuracy and detail of crop consumptive use values that are normal in the developed world, enough detail is available on which to have irrigation planning and the on-going research seems likely to yield the data that will be practically required within a few years.

Soil water retention data and soil studies (Fig. 1.9 and Ref. 1.26) are also widely available and, as detailed later in this thesis, a good knowledge of typical soil profiles is to hand.

1.7 Summary of Relationship to this Research

The Al-Hasa oasis is crucially dependent on the water from its springs and boreholes and has a large and traditionally established population whose livelihood must be protected.

As Chapter 2 will detail, the long term reliability of the oasis's water supplies are now in some doubt, and conservation of the groundwater has to be brought about soon.

More immediately crucial, the salt problem and the poor natural drainage of the area makes the need for effective irrigation management important, though the typical farmers have not yet the educational background to operate complicated irrigation practices or even to appreciate the

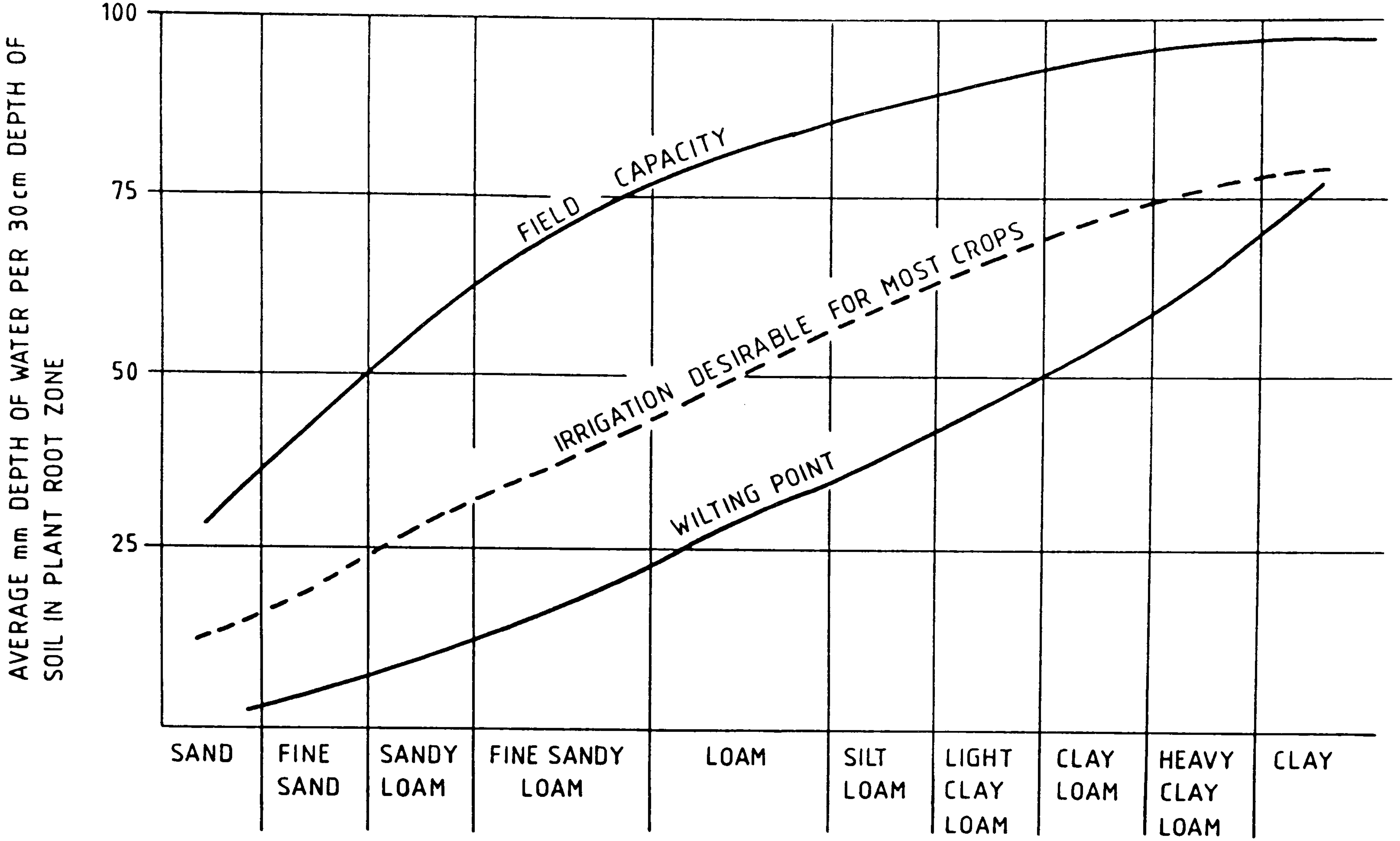


Figure 1·9 WATER HOLDING CHARACTERISTICS OF AL-HASA SOILS full potential for damage that over-irrigation will cause.

Consumptive use data is partly available and will soon be much more complete. Thus - in theory - each farmer should soon know how much water he should add to a field of a particular crop to maximise his yield and avoid the risk of increasing the soil's saline content.

What is obviously lacking in this search for water conservation and good irrigation practices is some simple and cheap method of indicating a soil's state of dryness. The chosen method has to be able to be used effectively by the area's typical farmers and so no method which requires technical expertise or experience can be successful. The indicating method will be needed since farmers - unless they can be assured that their fields are adequately watered - will simply reject any official assurance that this is the case or that any official consumptive use irrigation flows are actually reaching their personal fields.

The aim of this research is to determine which type of indicating device is

(a) accurate when compared to the range of laboratory and scientific techniques

and

(b) is useable by a population of partially educated peasant farmers.

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CHAPTER TWO

Water Supplies and Usage at Al-Hasa

CHAPTER TWO

Water Supplies and Usage at Al-Hasa

2.1 Introduction

As stated in Chapter 1, the oasis has always relied on the water flow from its 32 main springs and 140 smaller springs. Today some 565 boreholes are also used to give a more convenient distribution of groundwater on the larger farms and in the areas remote from the H.I.D.A. distribution canals.

Best estimates (Ref. 2.1) are that the area's limited and unreliable rainfall (a mean of 62.8 mm/year) account for as little as 2% of the oasis's irrigation water needs.

The springs have always been artesian and rise up to the land surface through caverns eroded in the soft local limestone. Usually the springs have cut large surface pools in the bases of which are the flow supply caverns. Diving investigations (Ref. 2.2) show that the oasis's past inhabitants attempted to control the flow into the surface pools by building crude throttles and dams of palm logs. (Fig. 2.1) in the necks of these inlet passages.

Many of the springs are cool (24°C on average), whilst others are much hotter (40°C), and this temperature difference is explained as a function of the directness of the water flow paths from the source aquifer to the land surface. The hotter springs have a more direct flow up geological fissures, whilsts the cooler springs are the result of the rising groundwater entering subordinate higher aquifers and flowing sub-horizontally through these before being able to burst upwards to the ground surface. (Fig. 2.2).

Whilst all the springs are artesian, some are much more so than others and provide enough hydraulic head to allow gravity drainage from the spring pools to the surrounding fields. Invariably these springs with the greatest artesian head also provide the largest flow rates.

All the springs and boreholes show a seasonal variation of water level, partly the result of the limited rainfall recharge in the winter and partly the consequence of the heavy abstraction of water in the summer months. Superimposed on this cyclic trend is a marked fall of the water level in the oasis due to water usage out-stripping the safe yield. These two effects are well shown by the water level records of two boreholes in the Umm Er Radhuma aquifer. (Fig. 2.3).

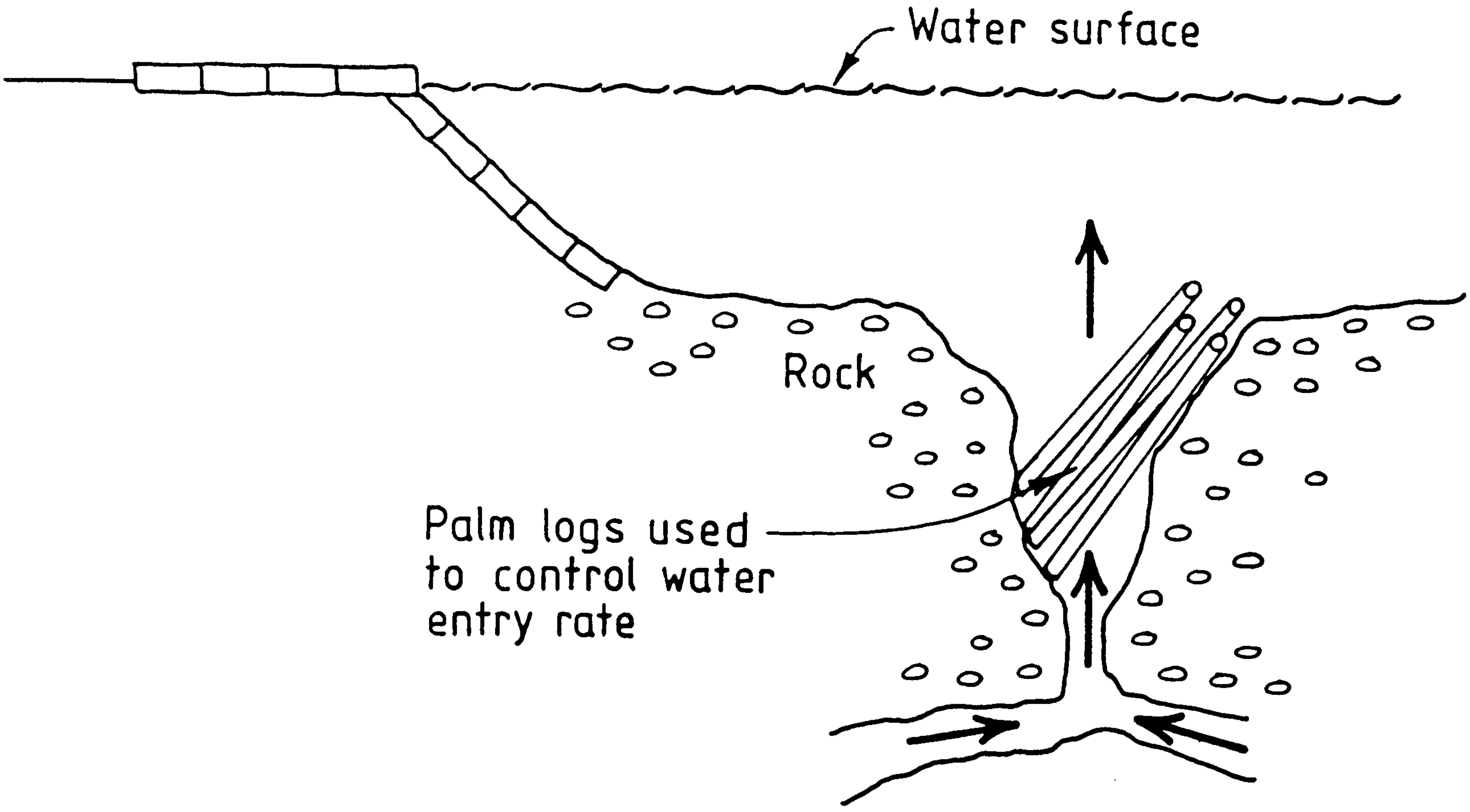

Figure. 2·1 TYPICAL CROSS-SECTION THROUGH THE LARGER SPRINGS AT AL-HASA

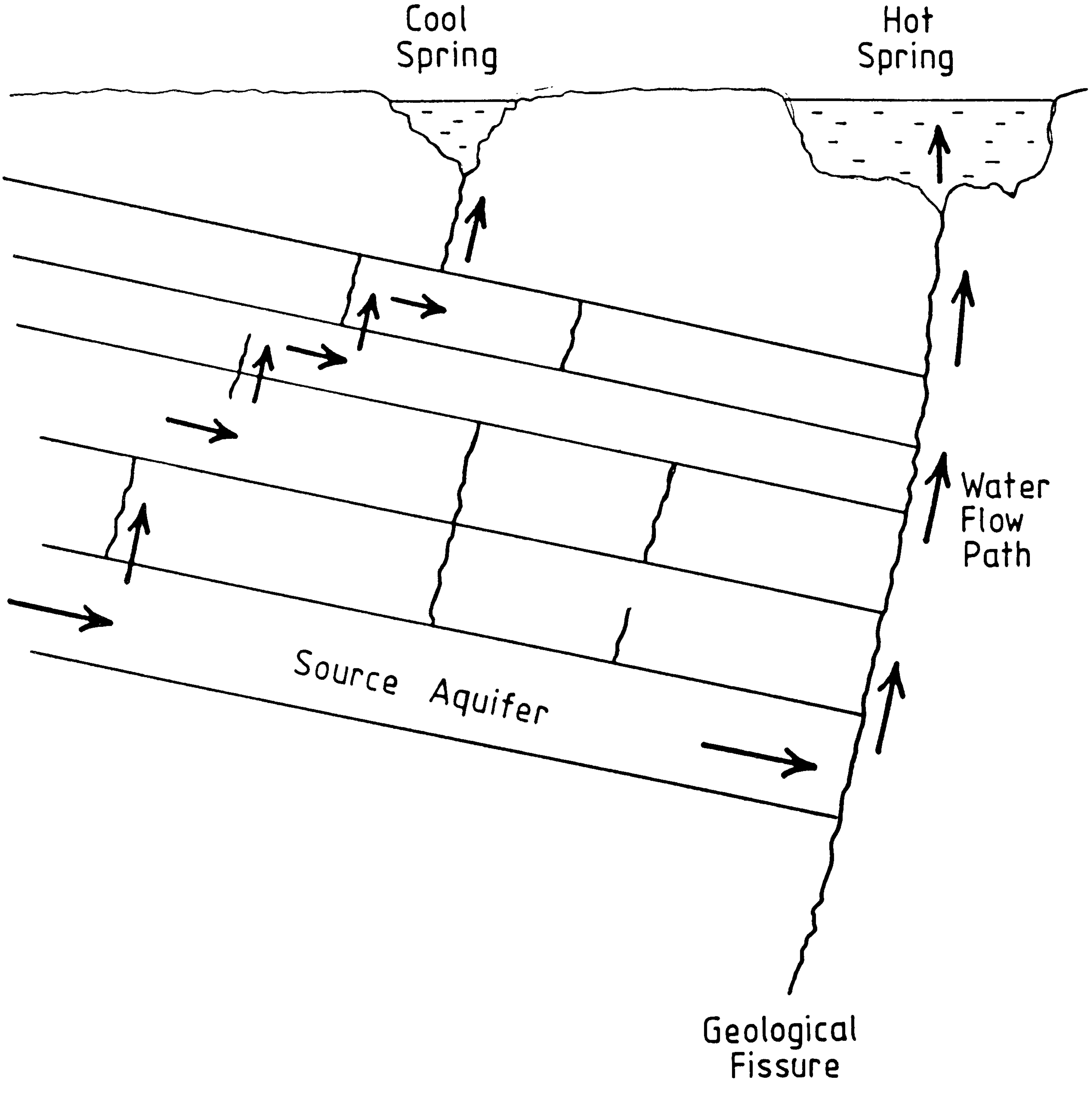

Figure 2·2 EXPLANATION FOR TEMPERATURE VARIATIONS OF DIFFERENT SPRINGS

(after work of Leichtweiss Institute)

Well HD-4-U in the centre of Al-Hasa shows a 7.5m downdraw between 1978 and 1982, whereas Well HA-1-U's water level has an almost insignificant fall of 0.2m in the same period. This second well is 50 kilometres from Hofuf and in an area where no utilisation of groundwater yet takes place.

The practical consequences of the decline in the ground water level will be discussed below.

2.2 The Geological Aquifers

The work of oil companies and of consultant hydrogeologists has revealed that the most productive aquifers are in the sedimentary rocks that underlie two thirds of the Kingdom, and dip east and north-east towards the Gulf of Arabia. (Fig. 2.4).

Of these, three:

the Neogene
the Dammam
the Umm Er Radhuma

are of direct interest to the Al-Hasa oasis. (Fig. 2.5).

The Neogene, from which all the oasis's springs actually emerge, is a very variable aquifer both lithologically and

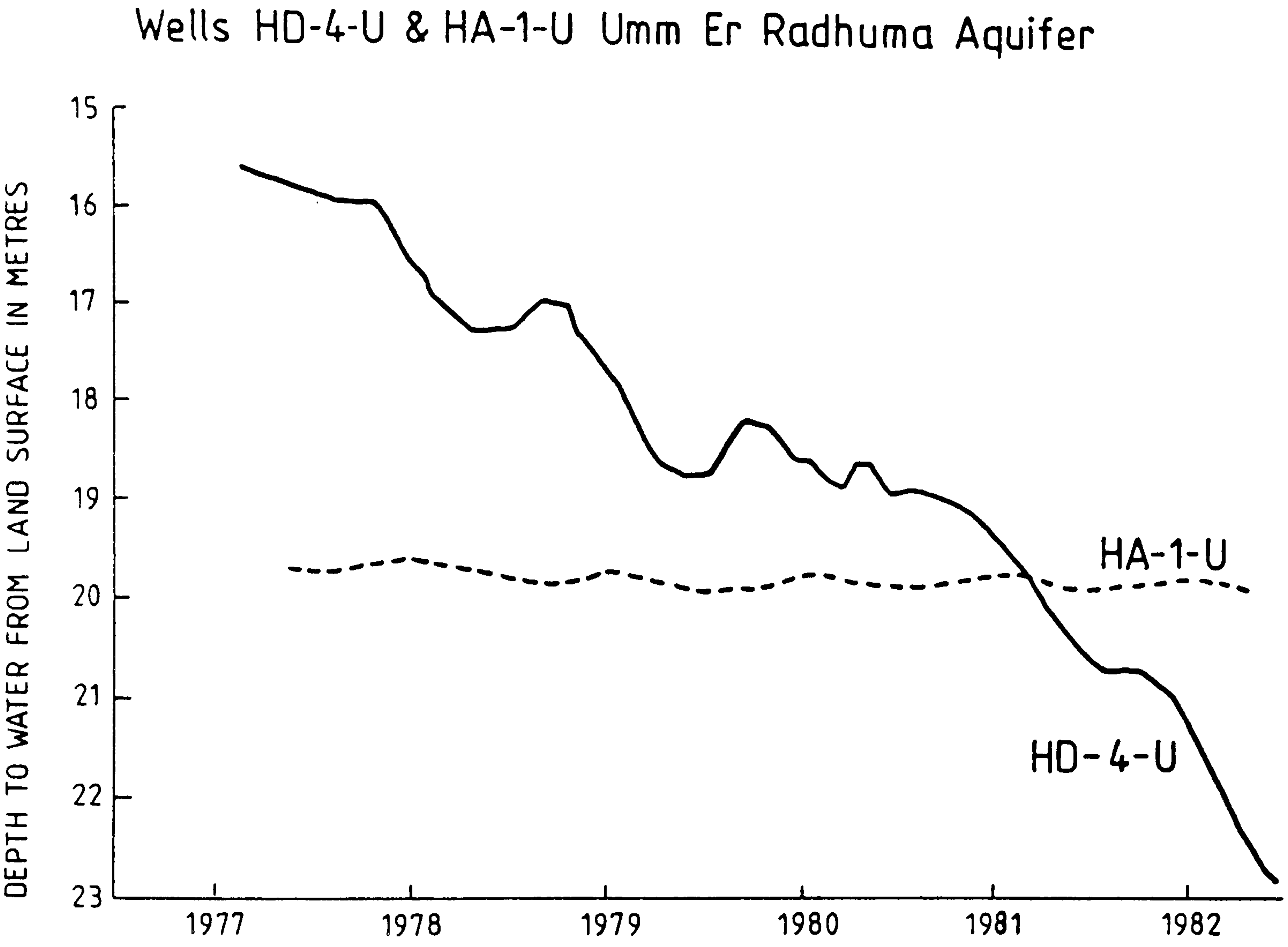

Figure 2·3 GROUNDWATER LEVEL VARIATIONS IN THE UMM ER RADHUMA AQUIFER

Figure. 2·4 PRINCIPAL AQUIFERS OF SAUDI ARABIA

AGE		FORMATION	MEMBER	GENERALISED LITHOLOGIC DESCRIPTION	RANGE OF THICKNESS	HYDROGEOLOGY
Quaternary		Surficial deposits		Gravel, sand and silt	Generally less than 30 m	Variable productivity, depending on recharge
Tertiary	Neogene	Hofuf		Sandy marl and sandy limestone	0-95 m	Generally called Neogene Aquifer.
		Dam		Marl and shale; subordinate sandstone; limestone	0-125 m	Irregular occurrences of water.
		Hadrukh		Marly sands, siltstones and sandy limestones	0-90 m.	Prolific aquifer in Al Hasa.
	Eocene	Dammam	Alat	Limestone with sandy fissures; orange marl at the base	0-85 m	Moderate aquifer
			Khobar	Skeletal-detrital limestones, dolomitic limestones; marls at the base	0-60 m	Aquifer
			Alveolina Limestone	Limestone interbedded with marls or shales	0-20 m	Aquitard
			Saila Shales	Dark-coloured fissile shales and marls with small gypsiferous lenses	0-25 m	Aquitard
			Midra Shale			
		Rus		Marl, chalky limestone, anhydrite	10-200 m	Aquitard
	Paleocene	Umm Er Radhuma		Limestone, dolomitic limestone and dolomite	200-600 m	Aquifer
Cretaceous		Aruma		Limestone; subordinate solomite and shale	400-600 m	Poor aquifer

FIGURE 2.5 Geological succession in the Al-Hasa Area

hydrologically, and is unconfined and unproductive except around Al-Hasa. The Dammam aquifer is much more persistent and uniform and contains two thick limestone aquifers separated by shaly aquicludes. The deep Umm Er Radhuma aquifer is by far the thickest, most uniform, and most highly productive.

Geologically, the Kingdom's Eastern Province is underlain by these sedimentary beds, which while dipping initially to the Gulf are now contorted by folds (trending to the north-east). (Fig. 2.6). The presence of these cross folds and their associated geological fissures complicates the hydrological framework of the Province and of the Al-Hasa oasis in particular.

The water storage in the Kingdom's aquifers is enormous and is said to be between 2% and 5% of the entire world's sub-surface water. As a single example of scale, the Wasia Aquifer, on its own, has been estimated to hold more water than does the modern Gulf of Arabia. (Ref. 2.3).

Although the Al-Hasa springs all emerge from the Neogene beds, there is evidence, from water level monitoring and well pump tests, that vertical interconnection between it and the lower aquifers exists. (Refs. 2.4 and 2.5).

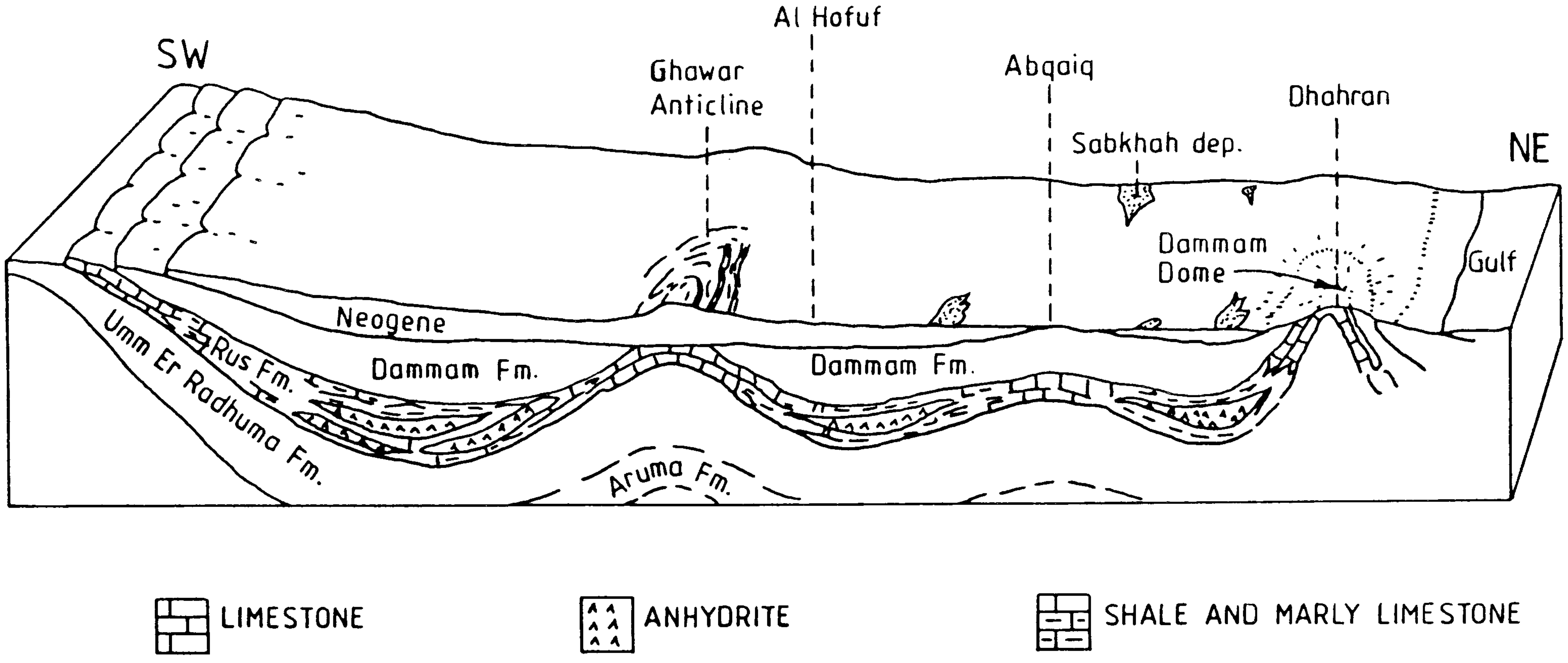

Figure 2·6 GEOLOGICAL CROSS-SECTION OF EASTERN SAUDI ARABIA

Thus it is not entirely clear which aquifer or aquifers actually feed the oasis. This is a point of some significance when the consequences of the groundwater level decline is considered below.

The actual age of the groundwater is also less than fully known. Whilst all workers who have published on the subject accept that the bulk of the spring water is from a past geological wetter climate, (between 20,000 and 25,000 years ago), the amount of modern recharge is debatable. The French consultants, B.R.G.M. (Ref. 2.5) claimed that only 5% of the springs' discharge was recent rainfall and the rest of fossil origin, whilst the German Leichtwess Institute workers (Ref. 2.6) carried out radiological studies which suggested that as much as 20% of the spring flows came from modern rainfall. Doubtless future work will resolve this uncertainty, but it is of interest to note that not only is the source aquifer uncertain but so also is the amount of aquifer recharge that occurs under today's climatic conditions.

2.3 The Long Term Security of the Oasis's Water Supplies

Given the uncertainties of the aquifer source and the recharge that takes place, most workers have turned to mathematical model studies to establish the overall groundwater situation, and to attempt to decide what safe yield can be taken from the oasis's springs and boreholes.

The earlier work was by the foreign consultants engaged to establish the Kingdom's groundwater resources. The first Al-Hasa study in 1975 (Ref. 2.5) grew from the work of the French consultants B.R.G.M. and was based on a digital model, calibrated by a 108 day borehole pumping programme. In 1980, a five layer digital model (to model the supposed interconnection of the Umm Er Radhuma, Dammam and Neogene aquifers) (Ref. 2.7) was developed by another firm of consultants. More recently (Ref. 2.8) local investigators also found it necessary in models to interconnect the area's three aquifers to generate the known groundwater levels and to model the calculated and measured aquifer properties.

One gain from these model studies is that a reason for the existence of the Al-Hasa springs is now apparent. Figure 2.7 shows clearly that contours of groundwater are quite widely spaced to the west of Al-Hasa, but more closely

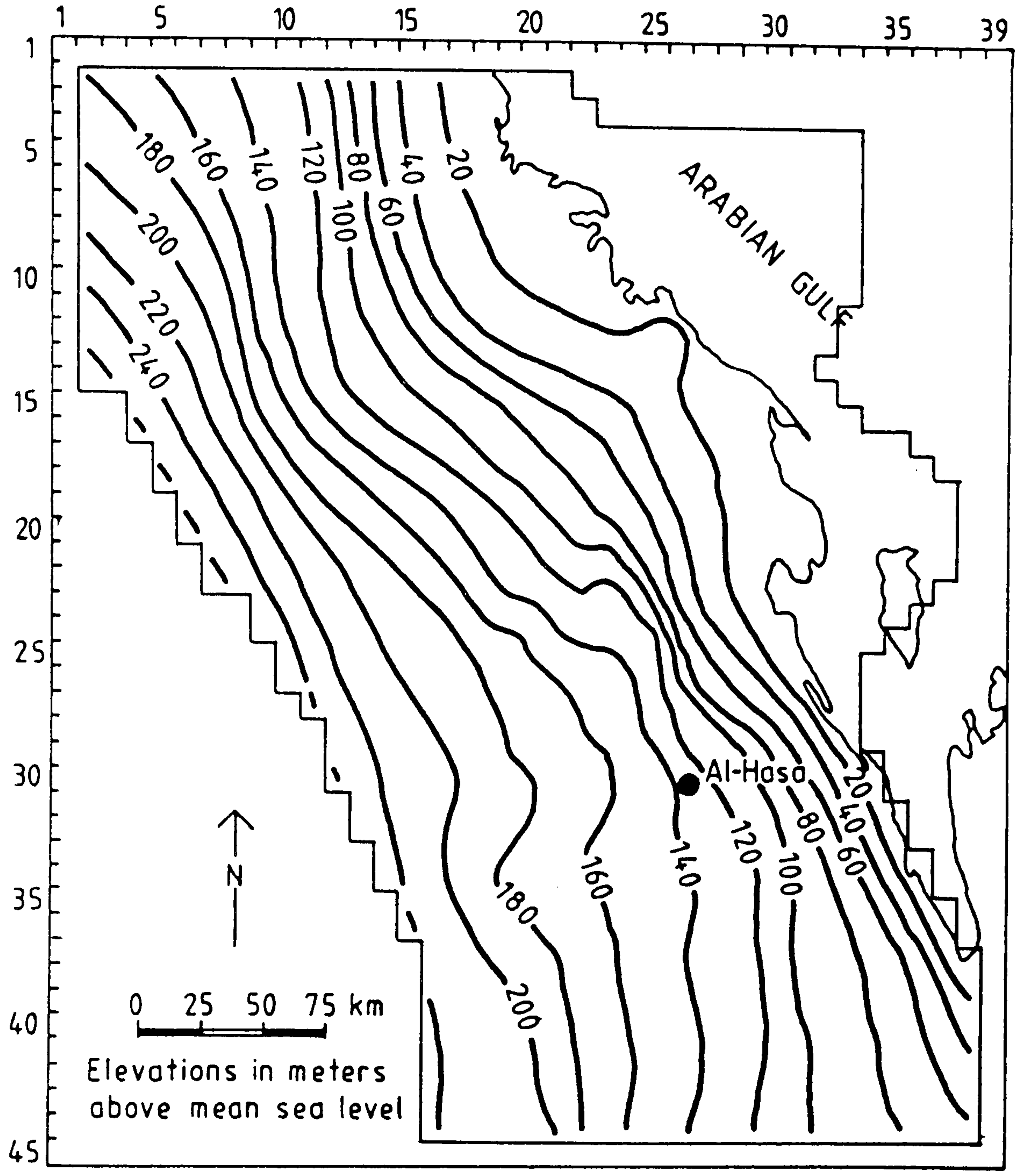

Figure. 2·7 GROUNDWATER LEVEL CONTOURS IN 1970 packed to the east of the oasis and model studies showed that this contour spacing was a result of a marked decline in aquifer transmissibility to the east of the springs. Thus groundwater flowing down to the Gulf finds its path eastwards restricted, and instead rises up the easier hydraulic pathways (the fissures and faults associated with the N.E. cross-folding) to emerge as the area's springs.

The main results of the model studies are that the safe yield of the Al-Hasa springs is estimated as about 10.125 m^3/s (Refs. 2.5, 2.8 and 2.9) and that if abstraction, for agriculture and other uses, continues at its present level, then the springs will cease to be artesian within 15 years and will become totally depleted soon afterwards. Simulations of the groundwater contours for 1995 (Fig. 2.8) show clearly how the oasis's abstractions will result in a marked hollow in the groundwater surface.

Whilst all such model studies have to be seen as initial conclusions, (especially in view of the uncertainties of the actual aquifer (or aquifers) involved and the doubts over the current rainfall recharge rates) the recent decline in the groundwater levels (Fig. 2.3) is factual and has indeed worsened since 1982. Additionally, the Al-Hasa Drainage and Irrigation Authority estimates (Ref. 2.10) that current water usage is 11.338 m^3/s and that this is continuing to increase. (Ref. 2.9).

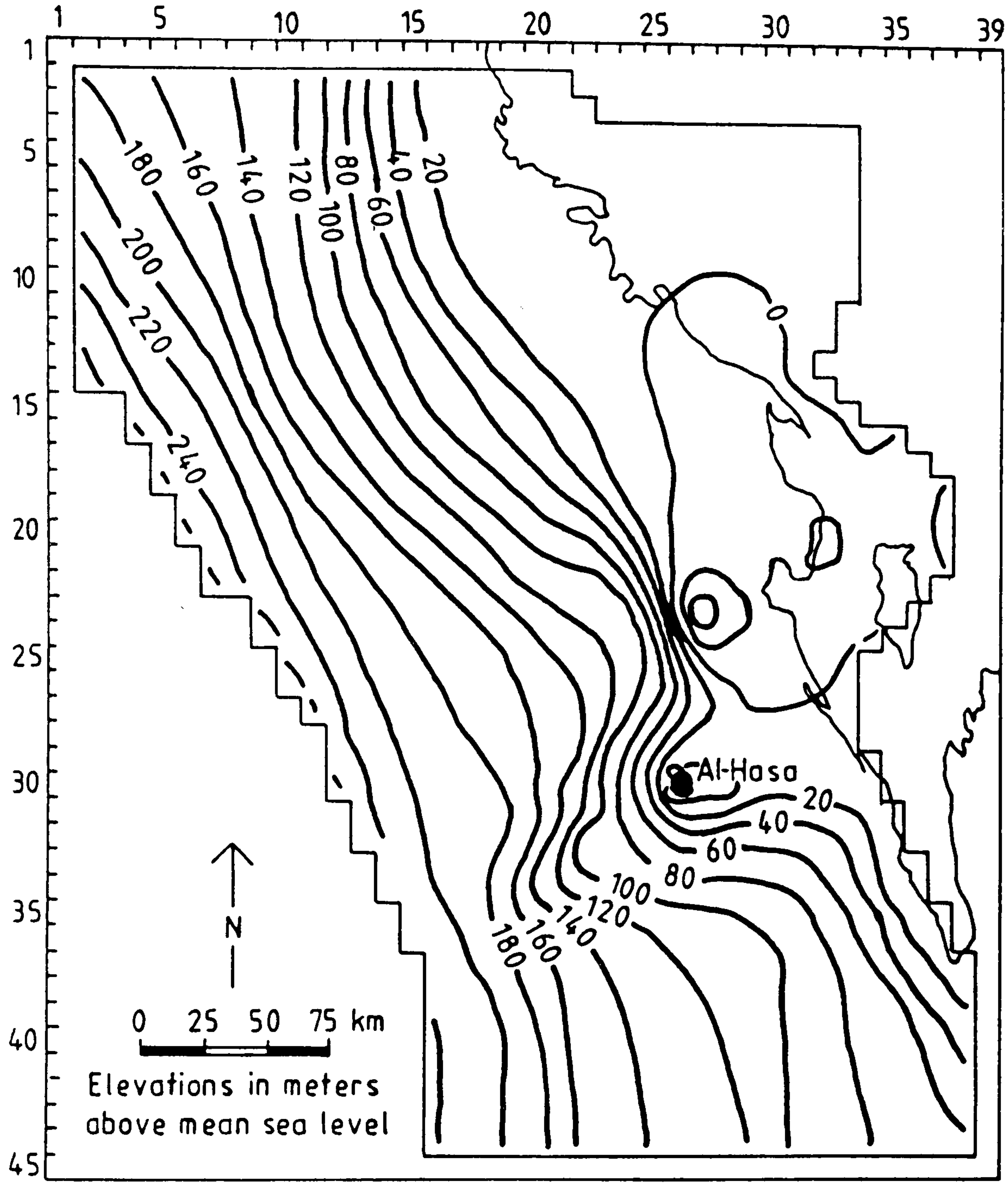

Figure. 2·8 SIMULATED GROUNDWATER CONTOURS FOR 1995

Thus the evidence is clearly that the aquifer(s) that serve the Al-Hasa springs is being over-used and that a water shortage will become inevitable if remedial action is not taken soon.

2.4 Water Use Efficiency in Al-Hasa

As stated in chapter 1, the Government of Saudi Arabia has invested considerable sums in providing water supply channels, major drainage and a controlling body (H.I.D.A.) for the oasis's water usage. It therefore could be assumed that water use in Al-Hasa is now reasonably efficient.

However, H.I.D.A.'s own reports indicated that a marked imbalance exists between the water demands from their customers and the supplies that H.I.D.A. is actually able to provide. The seasonal climatic factors (see Table 1.1) indicate that farmers would prefer to receive more water in the summer months than they do in the winter, and studies (Ref. 2.11) indicate that a winter supply of 174×10^6 m^3 occurs, whilst the summer supply rate is only 154×10^6 m^3. Thus 53% of supply being available in the winter and 47% in the summer, is in conflict with United Nations Food and Agricultural Organisation guidance on the water requirements of crops in Al-Hasa's climatic conditions (Ref. 2.12) which indicate that 68% of the available water is actually needed in the summer months.

The practical consequence of this imbalance is that a severe water shortage already exists in the summer months, and that newly opened land can, at present, only be used for winter crops. A large area of potentially usable land (4,438 ha.) lies unused since no irrigation water supplies are available.

Abderrahman (Ref. 2.11) also examined the efficiency of H.I.D.A.'s irrigation management and obtained first estimates of the field application efficiency (54%), the measured water conveyance efficiency (88%), and the water supply operational efficiency (80%) and evaluated the overall project efficiency from these parameters as 38%. This value is obviously on the low side, and suggests that of the total 328 x 10^6m^3 supplied each year only 124.6 x 10^6m^3 of water is used effectively.

Part of this inefficiency results from the difficulty of controlling the unsteady water flow rates in the complicated distribution canal network, with the hundreds of sluice gates and valves, and H.I.D.A. is currently involved - with the University of Petroleum and Minerals in Dhahran - in evolving computer controlled water release management (Ref. 2.13).

On the basis of F.A.O. guidance data (Ref. 2.12) Abderrahman predicted the actual water needs of the oasis's crops as 208.6 x $10^6 m^3$/year, a figure well within the supply level that is currently possible. Whilst this study can be criticised as theoretically biased, in that it makes use not of the known crop water consumptive requirements (see Section 1.6) but of potential evapotranspiration indices that are certainly not factual in the Al-Hasa context, it is of interest in indicating the need for efficiency and the likelihood that the oasis has the water to meet its requirements.

The aim of improving the irrigation project efficiency from its 38% low level to a more reasonable 57% value, and of similarly improving the performance on the larger new farms outside of the old oasis, however does call for modern technology, since (see Section 1.3) the land tenure system and farmers' educational levels will preclude any efficiency increase that stems from "grass roots" action.

Abderrahman (Ref. 2.14) has indicated how this can be done by utilising computer models and telemetric links and it does seem inevitable that such improvements will be implemented under the pressure of water shortages.

2.5 Water Demand Growth Rate

The safe yield of the total groundwater resources at Al-Hasa is accepted as about 10.125 m^3/s and currently this is being exceeded.

On the best predictions of population and types of water use (Table 2.1), Abderrahman (Ref. 2.9) believes that water consumption will be 20.689 m^3/s by the year 2000, if no increase in water use efficiency takes place.

This indicates the scale of the oasis's problem and suggests that either

(a) a greater irrigation efficiency has to be implemented

or

(b) that other water sources have to be developed.

In fact, it would not be difficult in theory (though very expensive in practice) to develop additional water resources.

An examination of Figs. 2.7 and 2.8 reveals that the Al-Hasa problem is simply one of over abstraction in one locality, and that groundwater a few tens of kilometres from Al-Hasa by-passes the oasis and flows to be wasted in the Arabian Gulf. The French investigators (B.R.G.M. - Ref. 2.5) in

TABLE 2.1

Water Use for Domestic, Industrial and Irrigation Purposes in Al-Hasa Region 1977 - 2000

Year	Domestic Purpose		Industrial purpose m^3s^{-1}	Domestic and Industrial purpose	Irrigation		Required irrigation water in m^3s^{-1}	Grand Total demand m^3s^{-1}
	Population	Total Demand m^3s^{-1}			Irrigated areas in hectares	Increase in Irrigation water demand m^3s^{-1}		
1977	350,000	0.565	-	0.565	8,000	-	9.6	10.125
1980	477,000	1.181	0.1	1.281	8,000	-	9.6	10.881
1982-1983	535,000	1.408	0.3	1.708	8,000	-	9.6	11.308
1985	610.000	1.687	0.6	2.287	9,000	1.56	11.162	13.449
1990	740,000	2.235	1.2	3.435	12,000	6.25	15.850	19.285
1995	860,000	2.712	1.4	4.112	12,000	6.25	15.850	19.962
2000	970.000	3.239	1.6	4.839	12,000	6.25	15.850	20.689

1. From Abu-Butain (1980)
2. Personal Survey

fact determined that 3.75 m^3/s could be abstracted from a site 55 kms south-west of Al-Hasa without adversely affecting the flows to the oasis.

Additionally it should be possible to make use of the discharges from Al-Hasa's 3 sewage treatment plants. Currently these discharge flows of 1.716 m^3/s to waste and should increase their discharges by the year 2000 to 3.629 m^3/s. Obviously the quality of the sewage water would be important if salinity and disease problems were not to accompany any use of this water.

Finally, the area's agricultural drainage (about 2.693 m^3/s) which currently flows to the evaporation lakes, (see Fig. 1.7) could be used. This water has a high salinity (about 3,500 mg/litre in summer and 2,000 mg/litre in winter) and so would have to be blended with fresher spring water to ensure that the salination problems were not worsened by its use.

All of these options for additional water supplies have practical and financial problems and would be difficult to implement until the technical manpower of the area is increased.

2.6 Summary

The water source(s) that supply the oasis are as yet imprecisely defined, but enough knowledge does exist to show that the safe water yield for the oasis is less than the current level of water use. If current usage rates, and the predicted increase in these, continue then an extremely serious shortage is inevitable by or before the year 2000.

Whilst ideas have been suggested for developing other new water sources, these do seem to involve technical, social and cost penalties and it seems better to improve the irrigation efficiency to well beyond its present low level.

Work is started to allow the H.I.D.A. to improve the efficiency of its releases into the distribution network and it seems inevitable that evaporation losses from the open canals (that cause the 88% water conveyance efficiency) will ultimately be reduced by the relatively cheap method of capping these.

When Abderrahman's estimates (Ref. 2.11) are considered it is, however, obvious that the greatest inefficiency is in the field application (stated as only 54%) and this is the area where the individual farmer (and not H.I.D.A. or scientific specialists) is most obviously involved. If the farmer had a method of determining when his fields needed water and how much was actually wanted to push crop yields up to the best levels, then it could be feasible to improve the field application efficiency to perhaps 80%. If this were possible, and if H.I.D.A. succeeds in its improvements in operating the supply and in reducing evaporation from the canals, then a project efficiency of perhaps 72% - a doubling of the current efficiency of water use could be achieved.

Such a gain in efficiency would mean that the oasis could continue to be served by its present springs and that the development of other water sources need not be developed until the oasis's technical manpower is increased. Abderrahman's ideas of improving irrigation efficiency by telemetric and computer aids could play a crucial role in buying time and conserving water, though even these will need a supporting technical manpower and an industry geared to service and repair and electronic devices. At present, neither of these needs could be met from the oasis's population.

It thus seems crucial to involve the individual farmer in conserving water, and this can best be done by showing that crop yields are highest when irrigation follows a particular scheduling (see Section 1.6) and that over-application of water and irrigating more frequently than the optimum bring no advantages. If this educational process can be achieved (as should be possible if the field crop trials reported in

Chapter 1 are publicised) then the individual farmer can be enrolled to improve the efficiency of water application in the field.

At that stage, each farmer will need access to simple and cheap methods, by which he can judge the moisture level in his fields and whether or not he needs to make use of irrigation water.

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2.9 Abderrahman, W. and Ukayli, M. (1984) "Strategy for groundwater use in Al-Hasa Region of Saudi Arabia". Water Resources Development. Vol. 2, 1, pp45 - 59.

2.10 Al-Hasa Irrigation and Drainage Authority (1982) Annual Report. Water Research Department, Hofuf, Saudi Arabia.

2.11 Abderrahman, W. (1987) "Water Management plan for the Al-Hasa Irrigation and Drainage project in Saudi Arabia". Journal of Agricultural Water Management, (in press).

2.12 Food and Agricultural Organisation (F.A.O.) (1977) "Crop water requirements". F.A.O. Irrigation and Drainage Paper No. 24, pp3 - 82, F.A.O. Rome, Italy.

2.13 Al-Hasa Irrigation and Drainage Authority (1986) Personal communication with H.I.D.A. officials.

2.14 Abderrahman, W. and Ukalyi, M. (1984) "A proposed water operation plan for irrigation projects in Saudi Arabia". Arabian Journal for Science and Engineering, Vol. 11, 4, pp381 - 388.

CHAPTER THREE

The Role of Laboratory Methods in Improving Irrigation Efficiency

CHAPTER THREE

The Role of Laboratory Methods in Improving Irrigation Efficiency

3.1 Introduction

As the first two chapters should have emphasised, Al-Hasa is a traditional farming centre whose existence is now directly threatened by an inefficient use of the available water resources.

Since the main area of inefficiency comes when the individual farmer applies irrigation water to his personal fields, it seems obvious that improvements can only come with the co-operation of the farmers. These people however are not especially educated and will have to be persuaded that the best crop yields will be achieved when irrigation is on a frequent scheduling (i.e. a 2 or 3 day interval between applications) and when only enough water is added to raise the soil moisture state to its "field capacity"* level. Obviously this is a public relations task and one that the H.I.D.A. organisation hopes to commence soon with the initiation of an Agricultural Advisory Service.

This seems likely to be a successful effort, since the farmers - although they lack higher technical education - are practical and sensible businessmen who will accept provable advantages, such as those contained in the various crop water consumption publications (Refs. 3.1, 3.2, 3.3).

The introduction of terms such as "field capacity" and "wilting point"* should not present any insupperable difficulty, but the practical difficulty of giving each farmer an accurate method of measuring soil moisture state in his fields will have to be faced.

In more developed societies, irrigation users make use of "available moisture depletion curves" for their particular soils, (Fig. 3.1). Such curves are in fact derived from the "water content-suction curves" obtained as a soil dries out (Fig. 3.2), and the only difference is that the "field capacity level" is taken as the zero moisture depletion level and as the soil moisture content that occurs at a suction of 100 cm of water head, and that the "wilting point" is seen as 100% moisture depletion and equal to 2000cm of suction. These rather arbitrary suction equivalents were first proposed by Richards and Marsh, (Ref. 3.4), but seem to be reasonable from the published crop consumption research (Refs. 3.1, 3.2, 3.3).

* For definition of these technical terms see Appendix 1

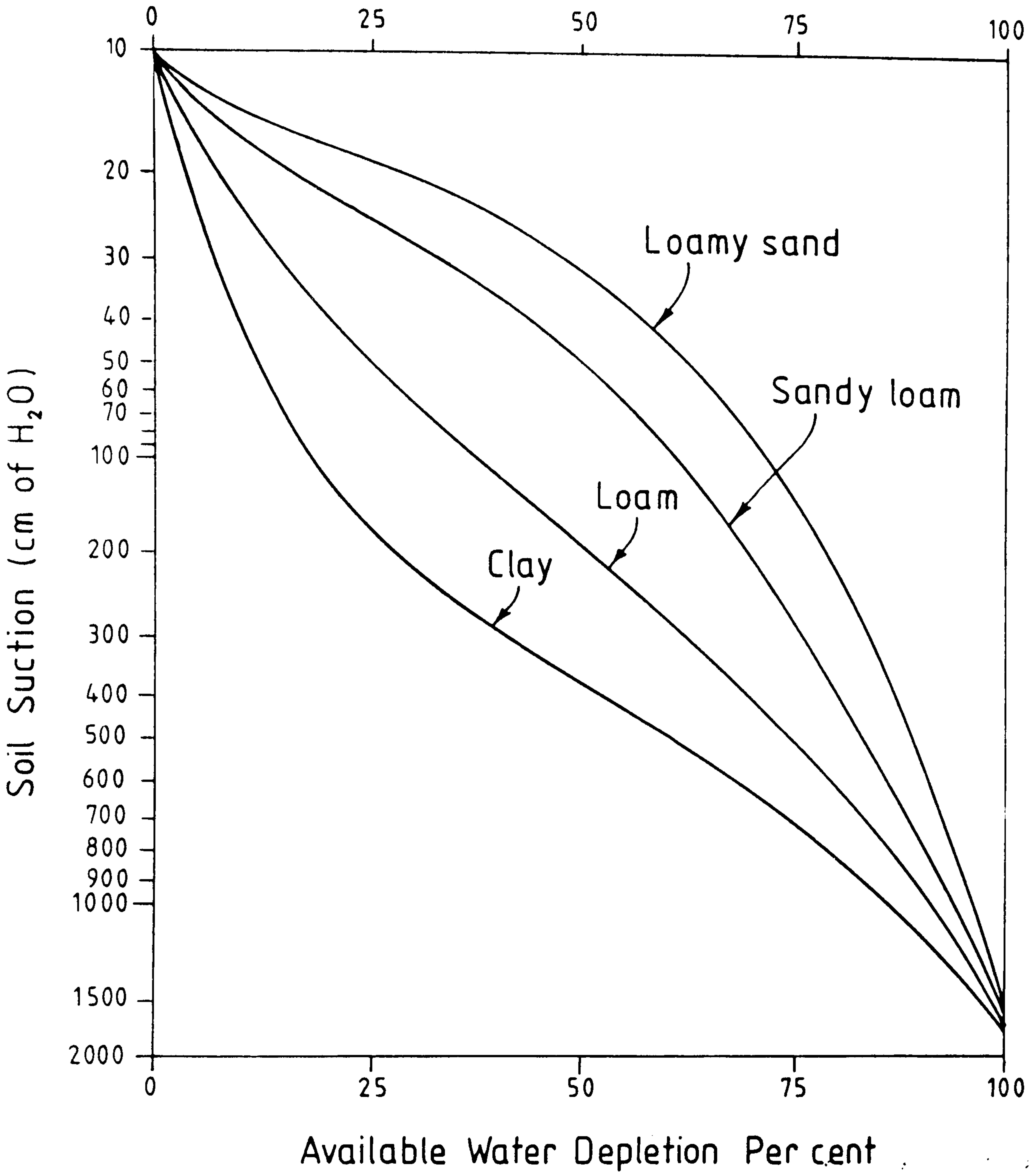


Figure 3·1 WATER RETENTION CURVES FOR SEVERAL SAUDI ARABIAN SOILS

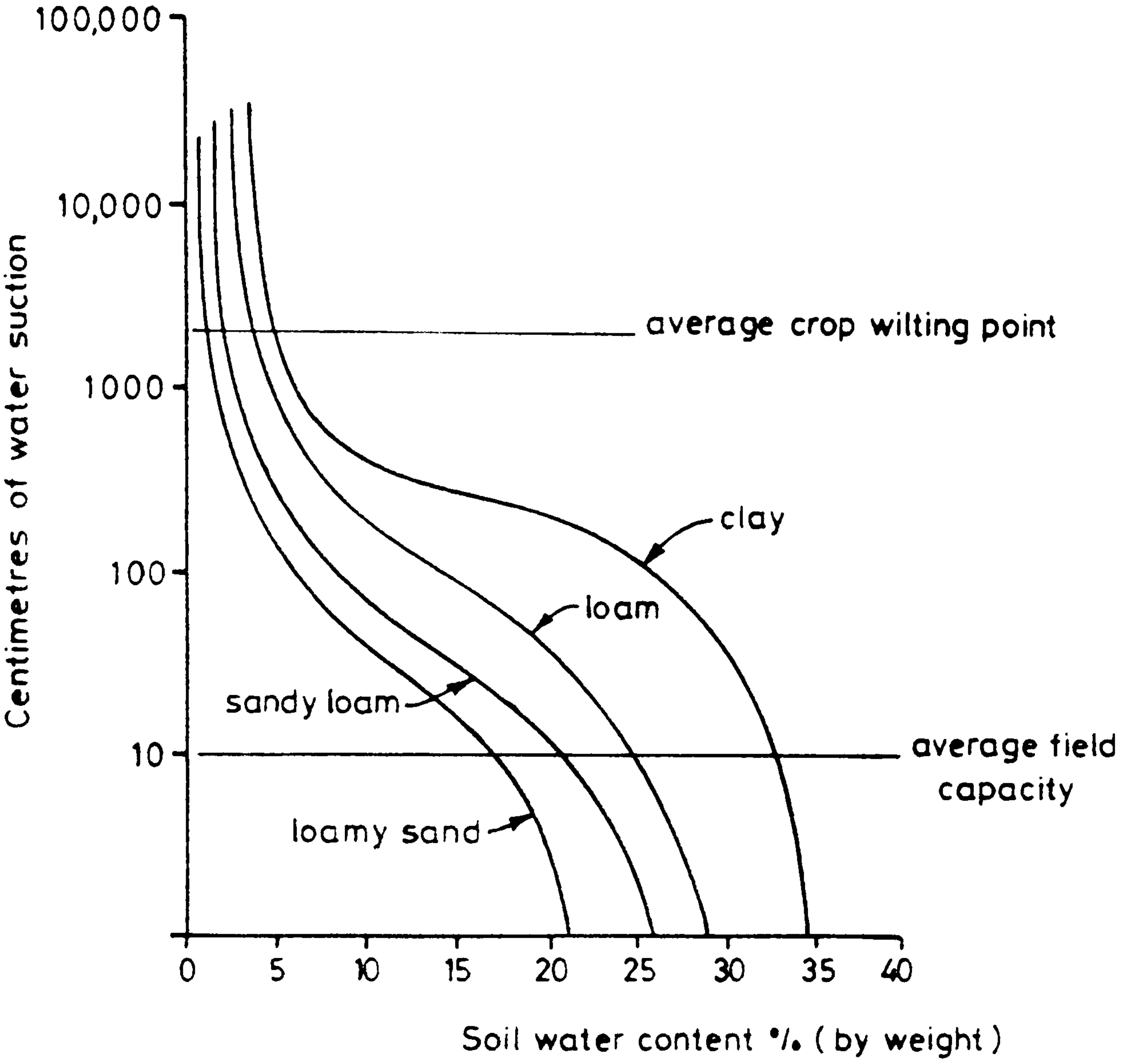


Figure 3·2 WATER CONTENT-SUCTION CURVES OF SOILS FROM AL-HASA IRRIGATION SCHEME

King Faisal University

It obviously would be extremely difficult to explain "soil suction" concepts to a typical Al-Hasa farmer, but this need not be attempted once it is appreciated that the real aim is to give the farmers a visual indicator of soil moisture state so that they can irrigate to just bring this up to the desired "field capacity" level.

However, if this approach is to be followed, then the H.I.D.A. organisation and its Agricultural Advisory officers need to have factual soil moisture depletion data for every soil type that occurs in and around the oasis.

Thus a basic investigation into the methods of providing this data was undertaken. Of course, there are two distinct approaches available:-

(a) laboratory testing of typical soil samples

and

(b) field monitoring and experimentation.

Whilst both have been followed, this chapter will be biased to the laboratory methods, since the availability of technically trained manpower in the oasis is limited and quite inadequate to carry out large numbers of field trials on the various soils that occur.

3.2 Derivation of available Moisture Depletion Curves by Laboratory Methods

Data of the type shown on Fig. 3.1 is obtained from the water content/suction relationships, (Fig. 3.2) that occur as a soil dries out.

Thus the problem is to produce the water content/suction curve that applies as each soil type dries out, and three laboratory based methods of doing this are available, i.e.

(a) pressure plate
(b) filter paper
(c) computer assisted analysis.

Prior to a discussion of these three methods, it should be noted that a number of other laboratory approaches (e.g. the sand table method, Ref. 3.5) have been utilised by some workers, but are unsuitable in the Al-Hasa context since they either lack the required suction range (from a pF of 2 to a pF of 4.2) or call for greater laboratory expertise than is likely to be available.

3.2.1 The Pressure Plate Method

This is internationally perhaps the most widely used method to derive a soil's water content/suction relationships as it dries out from its saturated state, and a number of suppliers can provide the necessary apparatus and technical manuals at relatively cheap prices - about £2,000.

In the oasis, pressure plate facilities are available both at the H.I.D.A. laboratories and at King Faisal University's Department of Soil and Water and, in both establishments, trained technical staff familiar with the method are in post.

In its simplest form, a pressure plate apparatus consists of a method of applying a positive gas pressure (either oxygen or nitrogen or an air compressor is used) to a pressure tight container within which saturated samples of the soils are placed. In response to the gas pressure, moisture is forced out of the soil samples and escapes from the seepage drain pipe. When the seepage rate ceases (for whatever positive pressure has been applied to the soil samples) the assumption is made that the remaining soil moisture content (which obviously must be in equilibrium with the applied gas pressure) is in equilibrium with a suction equal in magnitude to the applied positive pressure.

A crucial component of all pressure plate equipment is the porous disc on which the soil samples are placed. This disc has to have a known air entry value (see Appendix 1) to

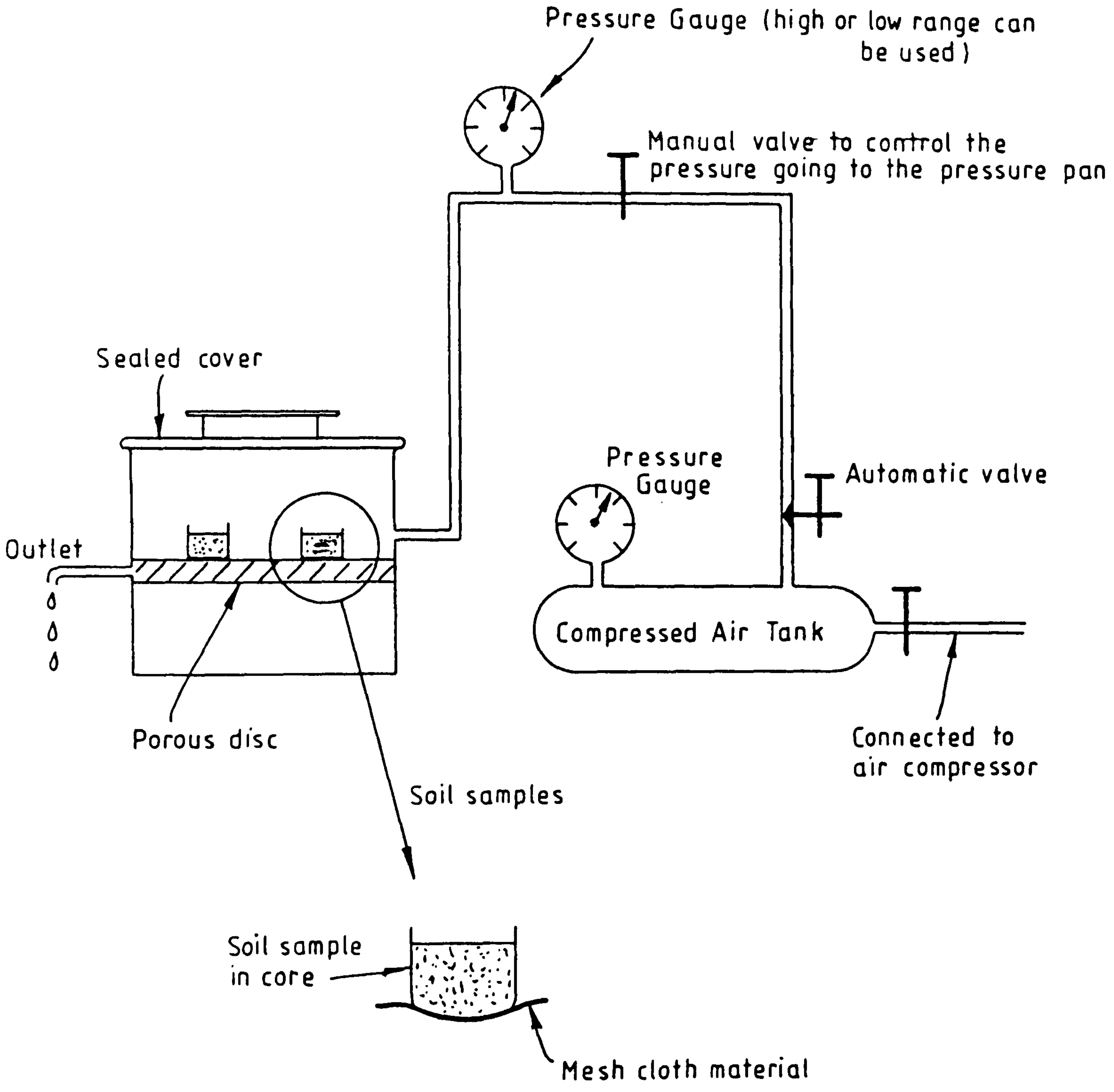


Figure 3·3 PRESSURE PLATE APPARATUS

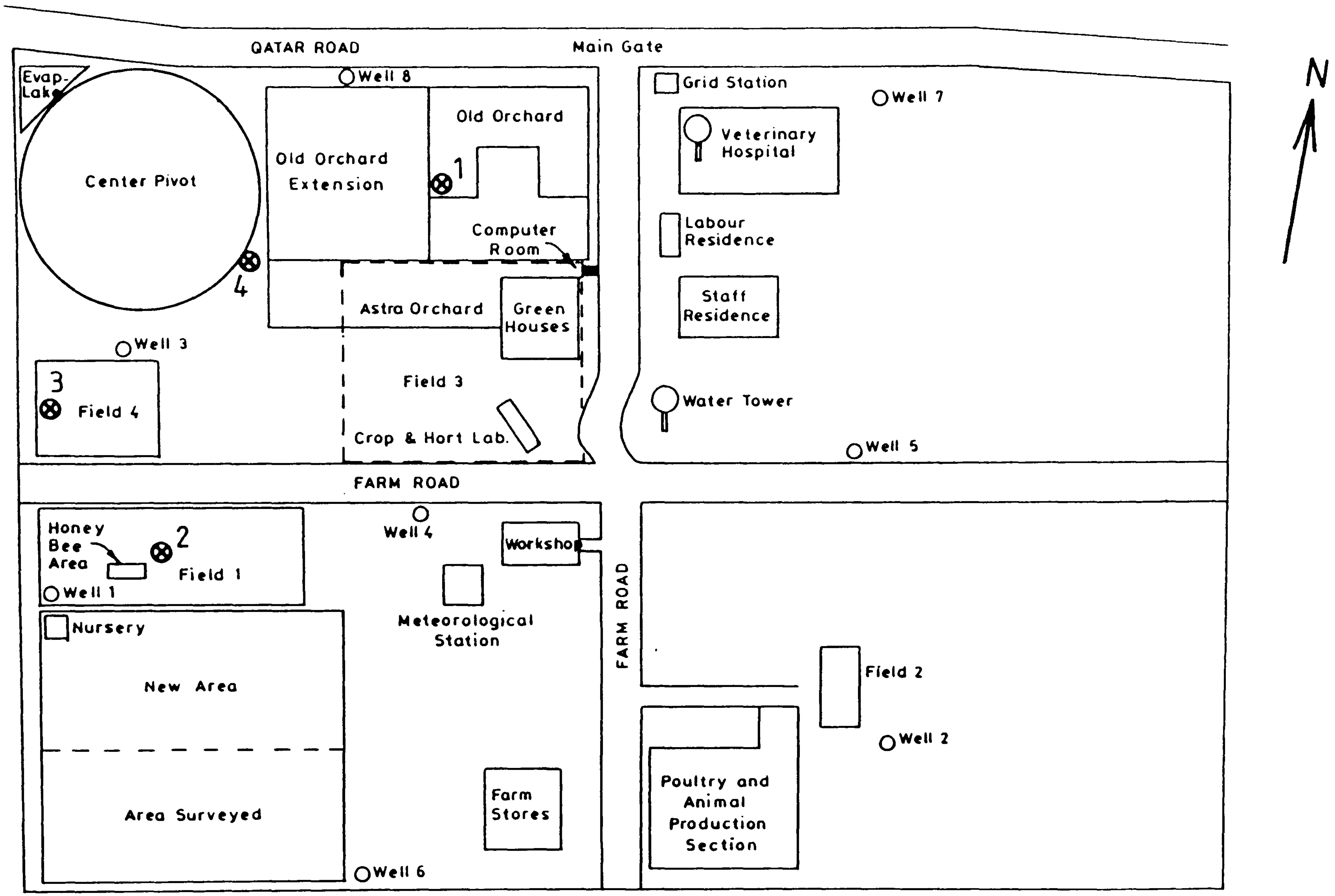
ensure that atmospheric air does not enter the pressure tight container. (Fig. 3.3).

The method was first described by Richards (Ref. 3.6) to overcome the difficulty of earlier suction methods, which could not work beyond a 1 bar suction, at which "cavitation" (i.e. the nucleation of bubbles of dissolved air and water vapour from the soil sample's pore spaces) would disrupt the experiment.

To evaluate the possible methods of producing the laboratory aids to improving irrigation efficiency, four soil profiles were excavated on the King Faisal University Experimental Farm (10 km from the centre of the oasis - see Fig. 1.6). These profiles were chosen to take in the variation in soil type known (Ref. 3.7) to exist over the farm (Figs. 3.4 and 3.5), and revealed the horizons listed in Table 3.1.

Fuller details of the profiles and the soil survey data on the oasis and its surrounds will be detailed in Chapter 4. Particle size analyses are listed in Table 4.1. (p 134)

Samples typical of each of the 10 identified horizons (all the hard pan layers were excluded) were taken, oven dried, packed to their field dry density values in open ended sample tins and then water saturated and placed on the pressure plate's porous disc. The positive gas pressure was then set at a chosen value, the gas valves opened, and the



⊗ Pits of Soil Profiles taken for analysis

Figure 3·4 LAYOUT MAP OF THE KING FAISAL UNIVERSITY ~ AGRICULTURAL AND VETERINARY TRAINING & RESEARCH STATION, AL-HASA

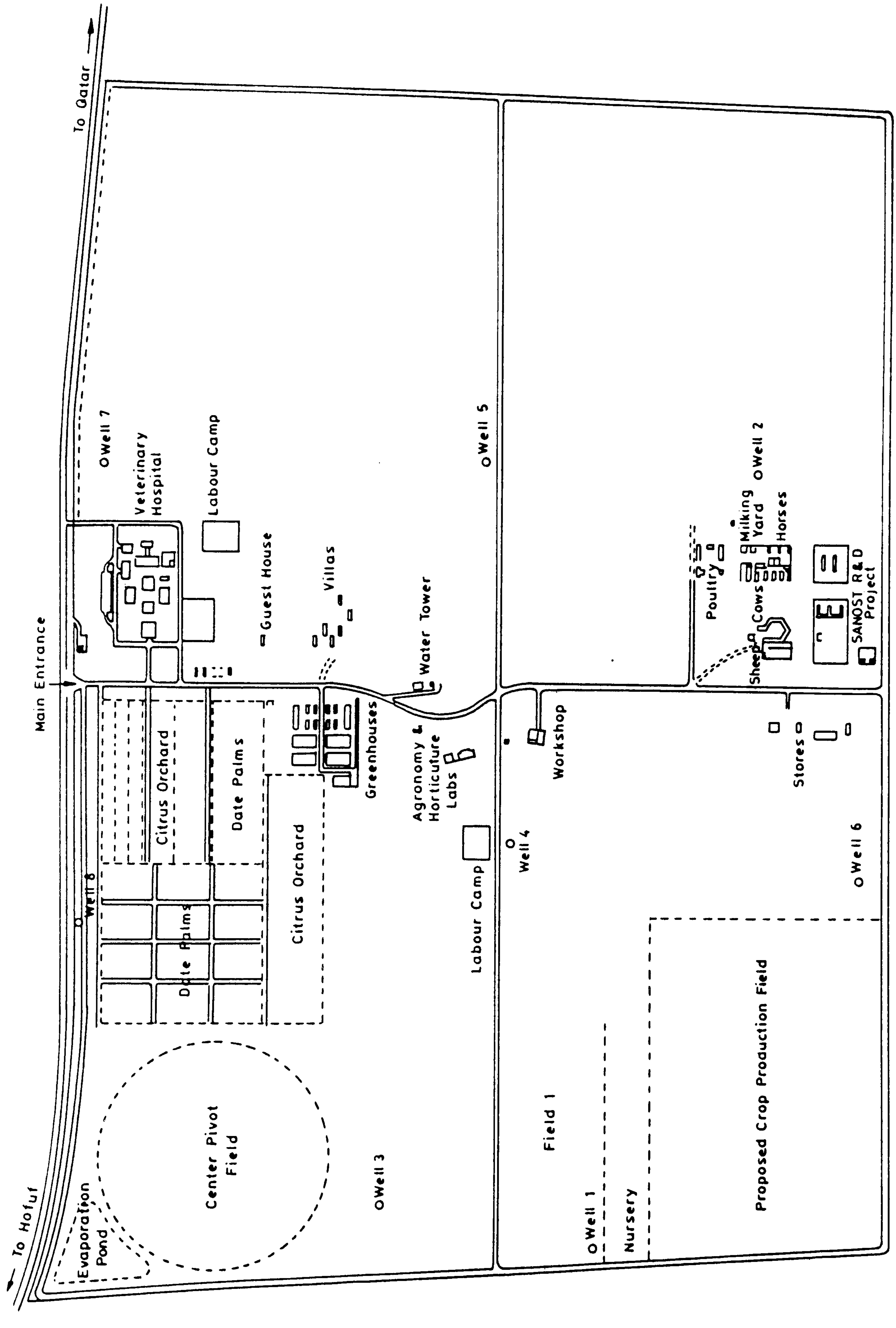


Figure 3.5 KFU EXPERIMENTAL STATION - SITE PLAN

TABLE 3.1

Soil Profiles Typical of the King Faisal University Experimental Farm

Profile	Horizons Encountered	Dry Densities (gm/cm³)	Water Table Depth(s)
No. 1	Sand (0 to 30 cm) Loamy Sand (30 to 150 cm) Hard Pan (150 to 160 + cm)	1.81 1.91	117 cm to 140 cm
No. 2	Sandy Loam (0 to 20 cm) Silty Loam (20 to 55 cm) Hard Pan (55 to 75 cm +)	1.46 1.38	50 cm to 55 cm
No. 3	Sandy Loam (0 to 15 cm) Loam (15 to 60 cm) Sandy Clay Loam (60 to 100 cm) Hard Pan (100 to 120 cm +)	1.53 1.43 1.54	No water table encountered
No. 4	Sandy Loam (0 to 18 cm) Loamy Sand (18 to 75 cm) Sandy Loam (75 to 130 cm) Hard Pan (130 to 160 + cm)	1.57 1.56 1.66	130 cm

samples left in the pressure plate until all seepage from them had ceased.

Once this has been achieved, a simple reweighing of the sample tins showed the amount of soil moisture lost and thus the moisture content in equilibrium with the applied gas pressure. By progressively increasing the gas pressure (after equilibrium has been attained at each earlier setting) it was possible to derive a curve describing the change in soil moisture content with suction.

Apart from the obvious need for careful handling of the sample tins and for accurate weighings, the major factor to note is that the porous disc on which the samples stand has to be changed if pressures above its air entry value are to be applied. In this research use was made of 2 different porous discs (one with a 5 bar air entry and the other with a 15 bar air entry value).

The other major precaution - and one that appears often to be overlooked - was that the pressure gauges on the apparatus were periodically checked and recalibrated against a mercury manometer system (Plate 3.1) to ensure that accurate data was actually being obtained.

On average it tended to take 15 days to establish the entire water content/suction curve for a soil and to establish the

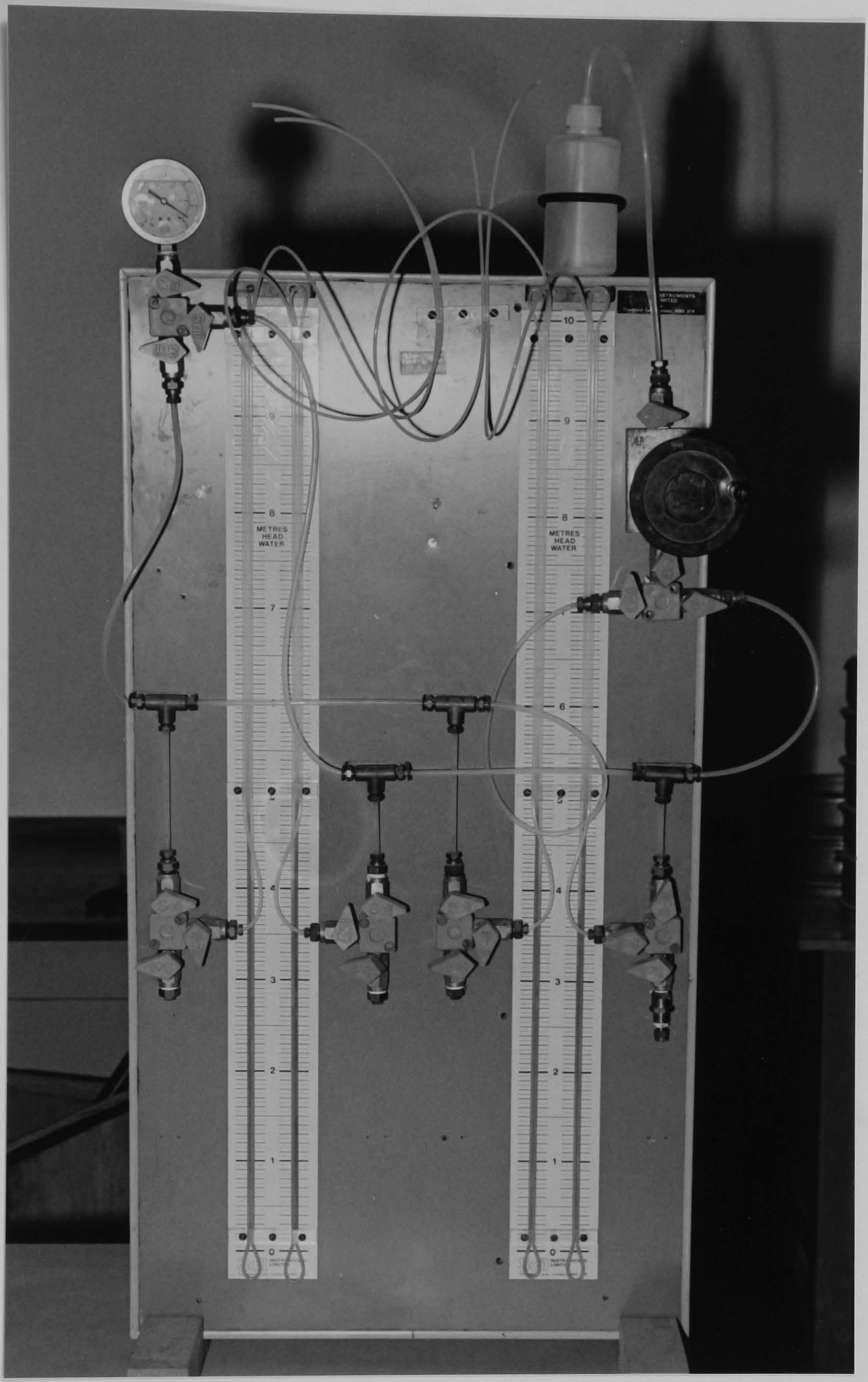


Plate 3.1   Method of Calibrating Bourdon Dial Gauges

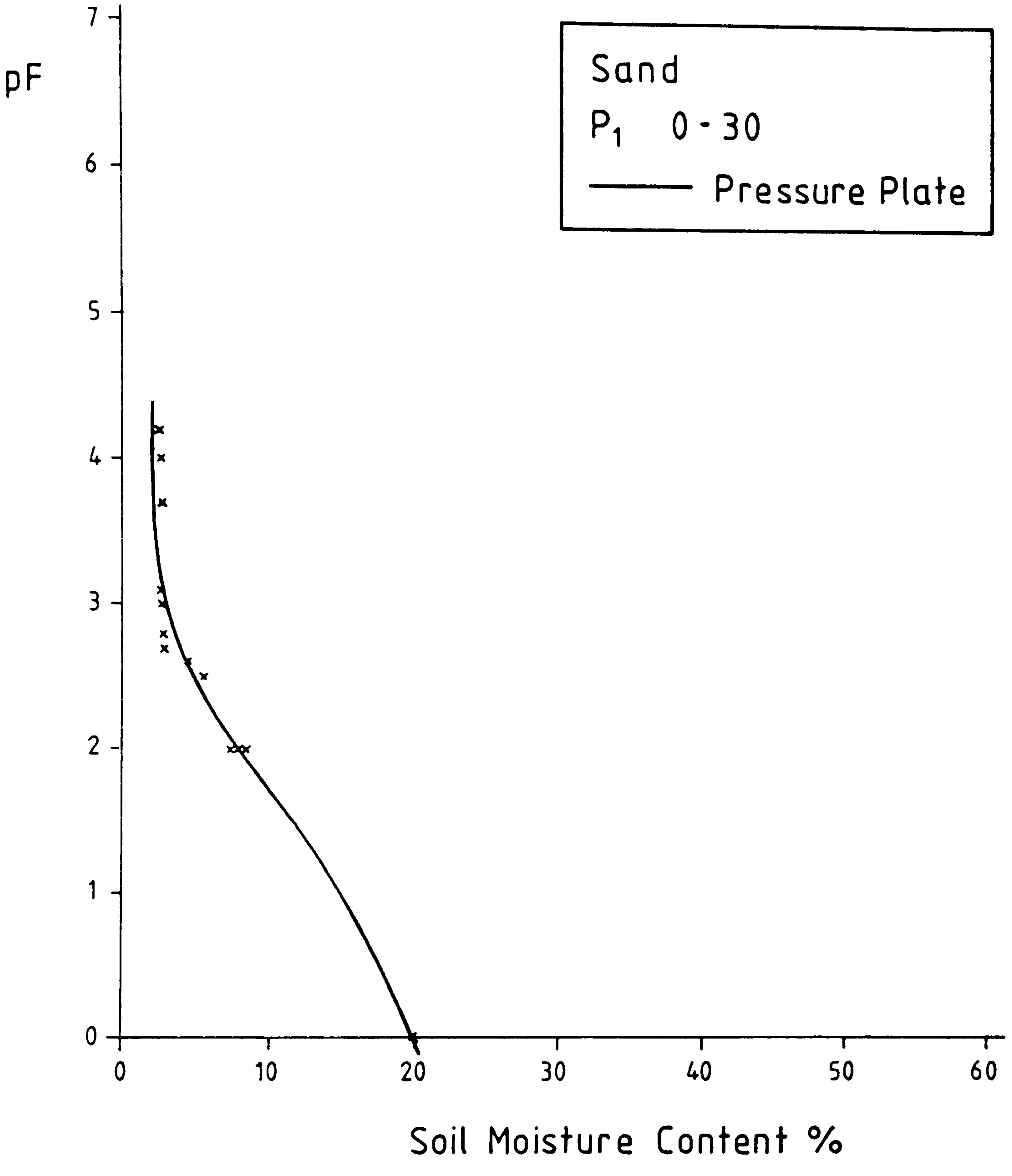

pF
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
Soil Moisture Content %
Sand
P_1 0 - 30
Pressure Plate

Figure 3·6

water contents in equilibrium with applied pressures of 0.1, 0.3, 0.4, 0.5, 0.6, 1.00, 1.30, 5.00, 10.00 and 14.00 bars (i.e. pF values of 2.00, 2.50, 2.60, 2.70, 2.80, 3.00, 3.10, 3.70, 4.00 and 4.20).

Three replicates of each soil sample were tested in each experiment.

Whilst the experimental work proved simple to carry out, it is worth noting the real difficulty that was found in setting the positive gas pressures at values below 1 bar (i.e. below a pF of 3). This showed itself in situations such as when a gas pressure of 0.3 bar (a pF of 2.5) was chosen and this would fall within a few hours to perhaps 0.002 bars. Obviously this stemmed from the insensitivity of gas pressure control valve. Other workers have encountered similar difficulties (Ref. 3.8). In the Al-Hasa context, this inadequacy of the pressure plate apparatus was more than a minor nuisance, since the crop water consumption experiments (Refs. 3.1, 3.2, 3.3) show that accuracy near the field capacity level (pF 2) is especially important if irrigation control is to achieve the highest possible crop yields.

The results (Figs. 3.6 to 3.15) gained from this work showed a high degree of repeatability and only rarely did replicate sample water contents differ by more than 2% where such

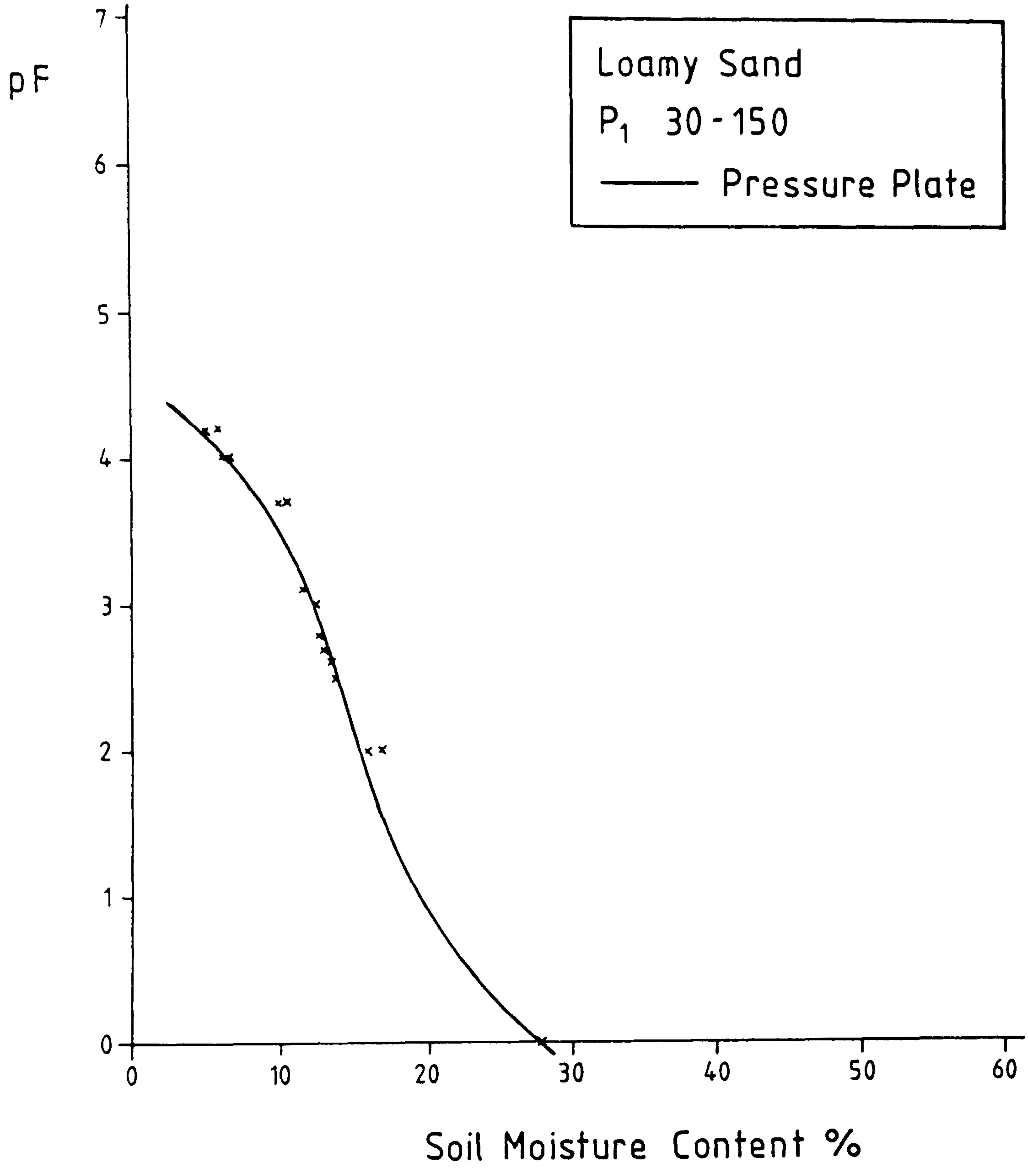

pF
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
Soil Moisture Content %
Loamy Sand
P_1 30-150
Pressure Plate

Figure 3·7

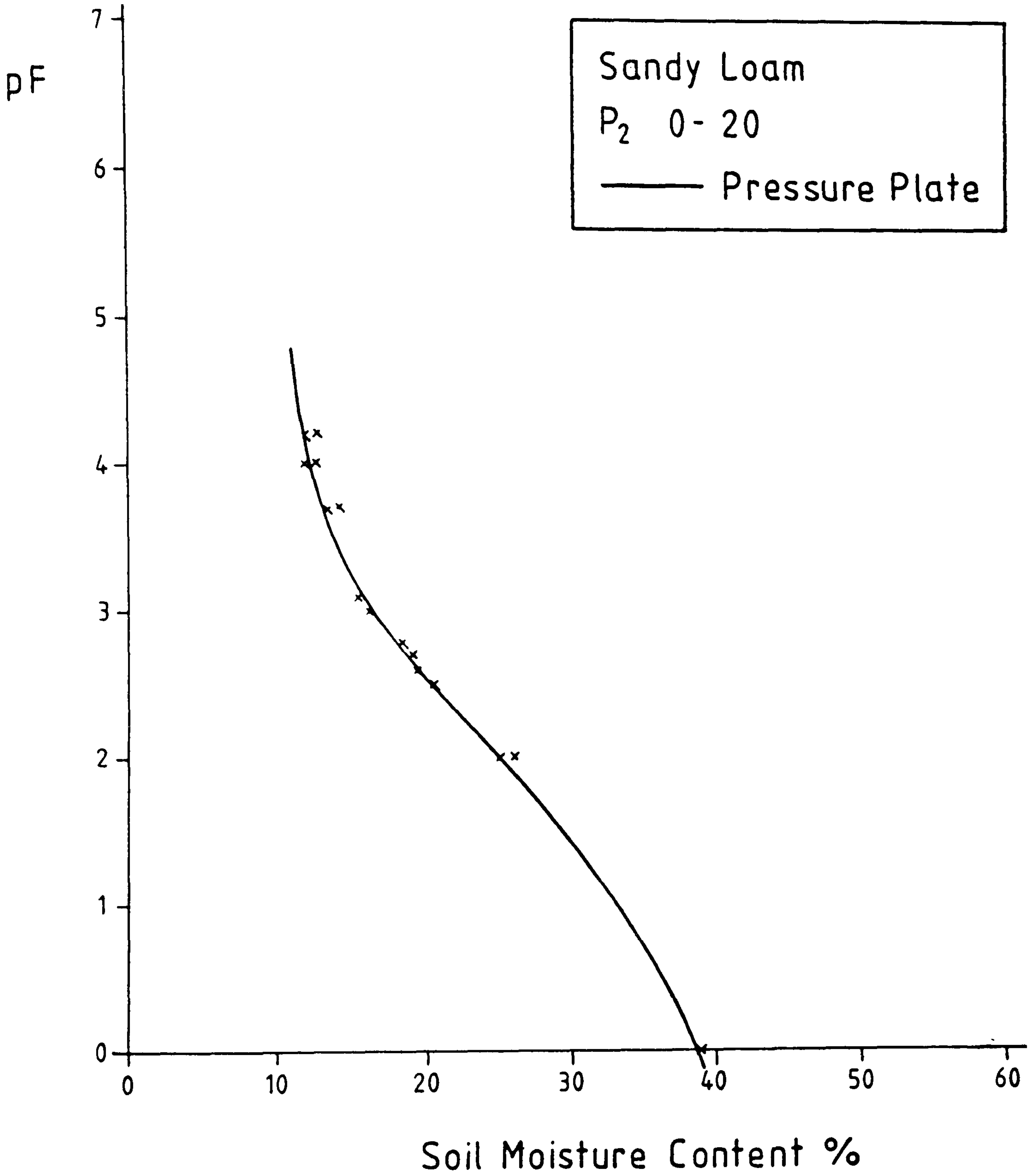

pF
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
Soil Moisture Content %
Sandy Loam
P_2 0- 20
—— Pressure Plate

Figure 3·8

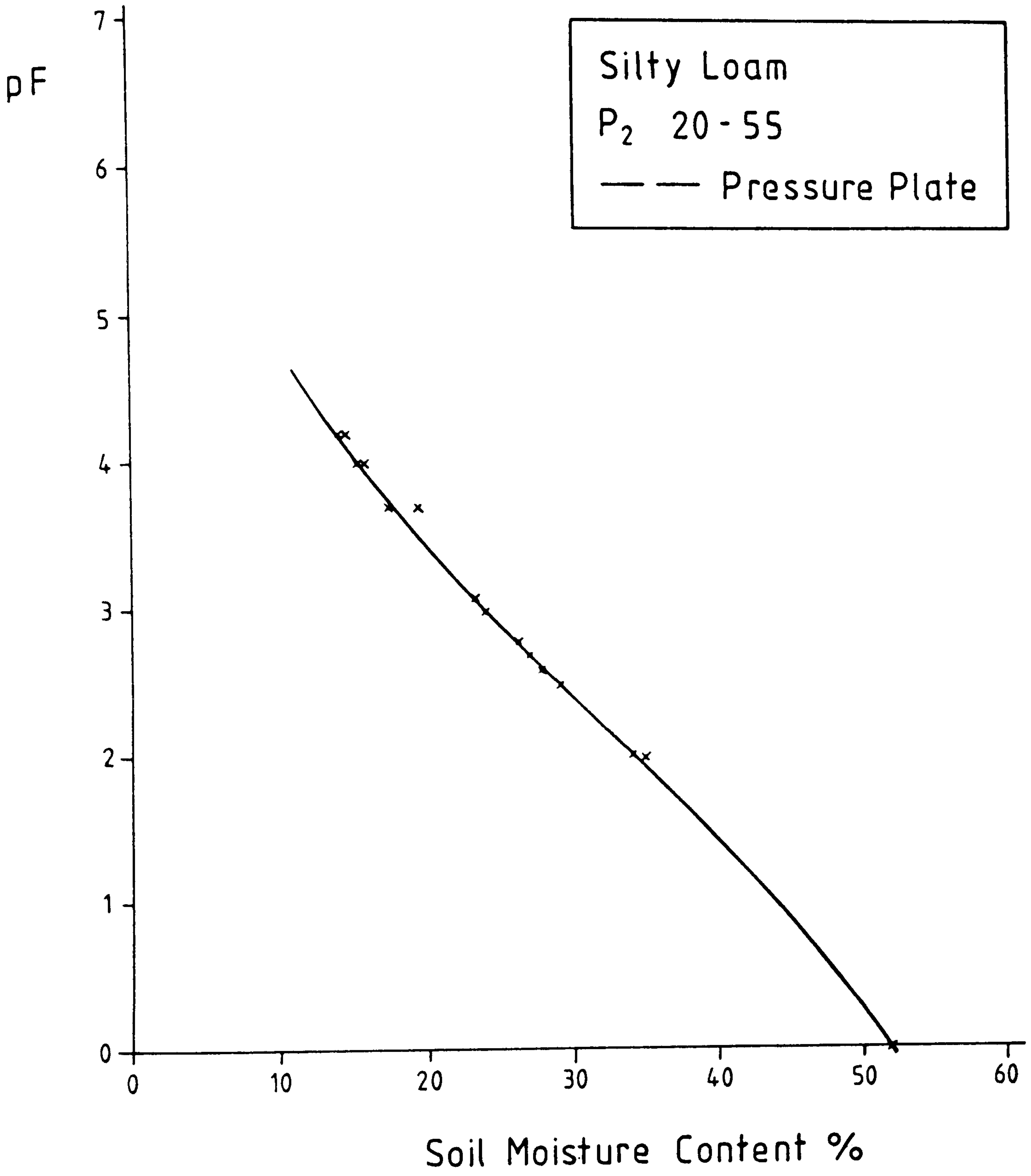

pF
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
Soil Moisture Content %
Silty Loam
P_2 20 - 55
—— Pressure Plate

Figure 3·9

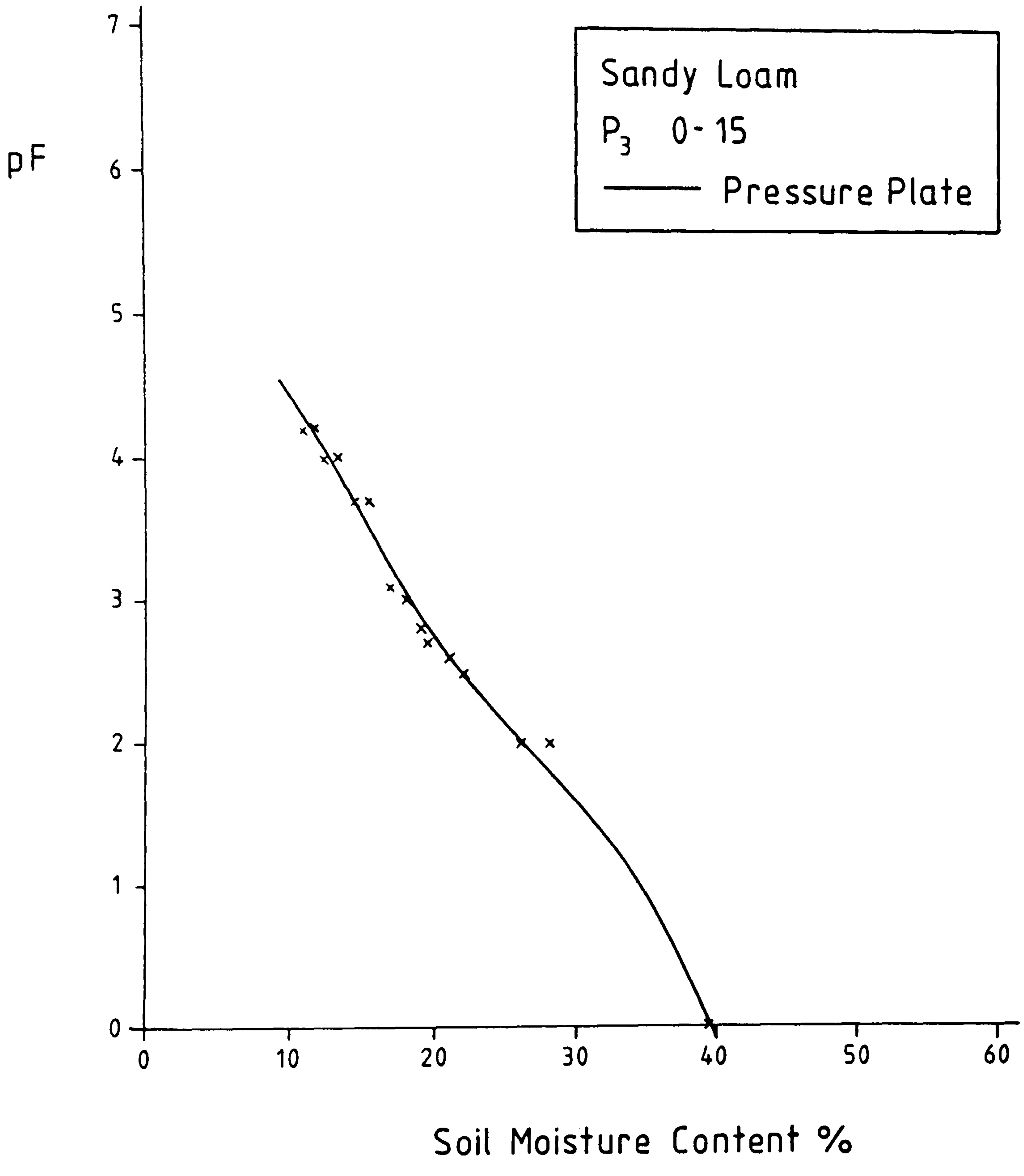

pF
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
Soil Moisture Content %
Sandy Loam
P3 0-15
Pressure Plate

Figure 3·10

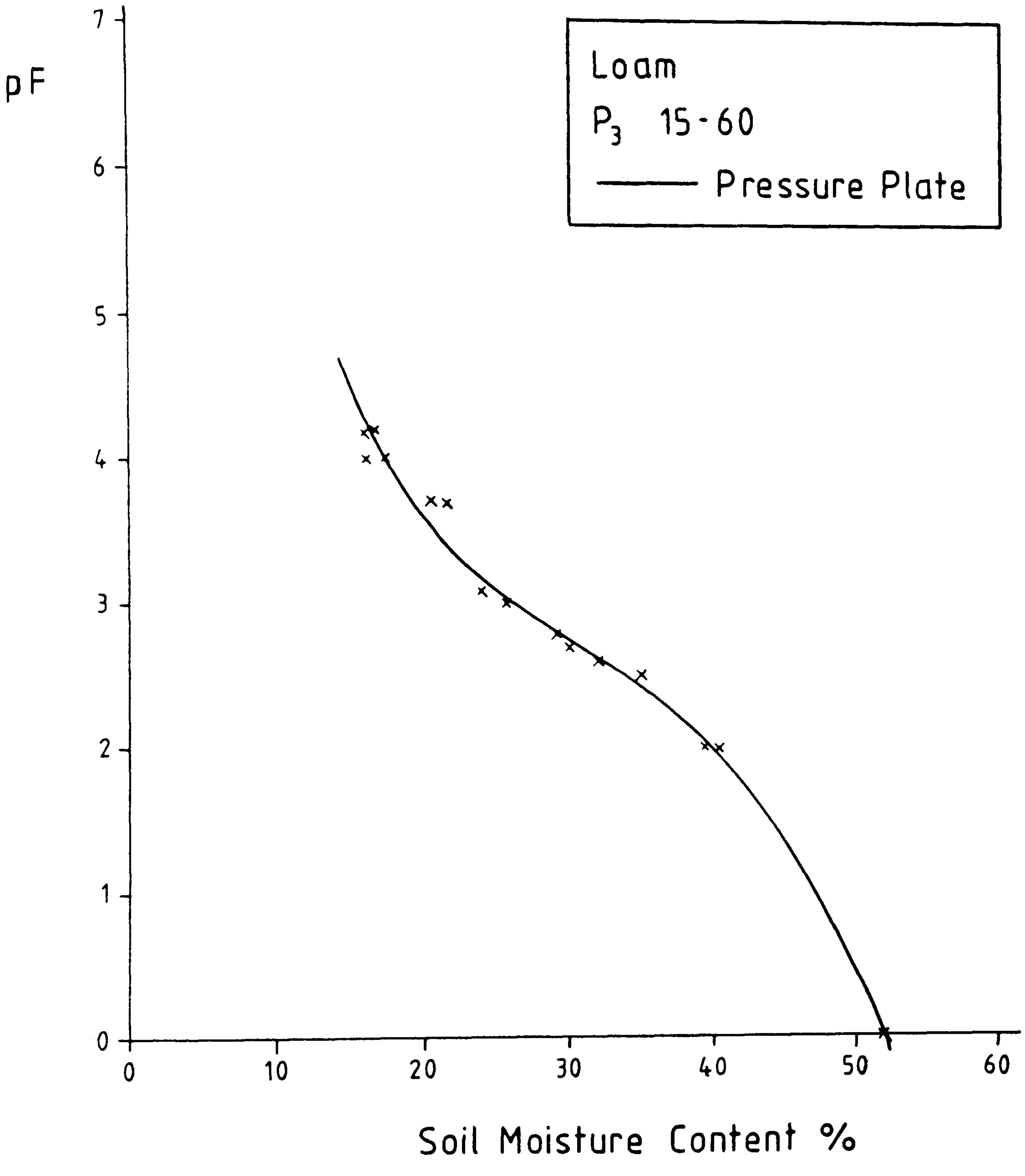

pF
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
Soil Moisture Content %
Loam
P3 15-60
Pressure Plate

Figure 3·11

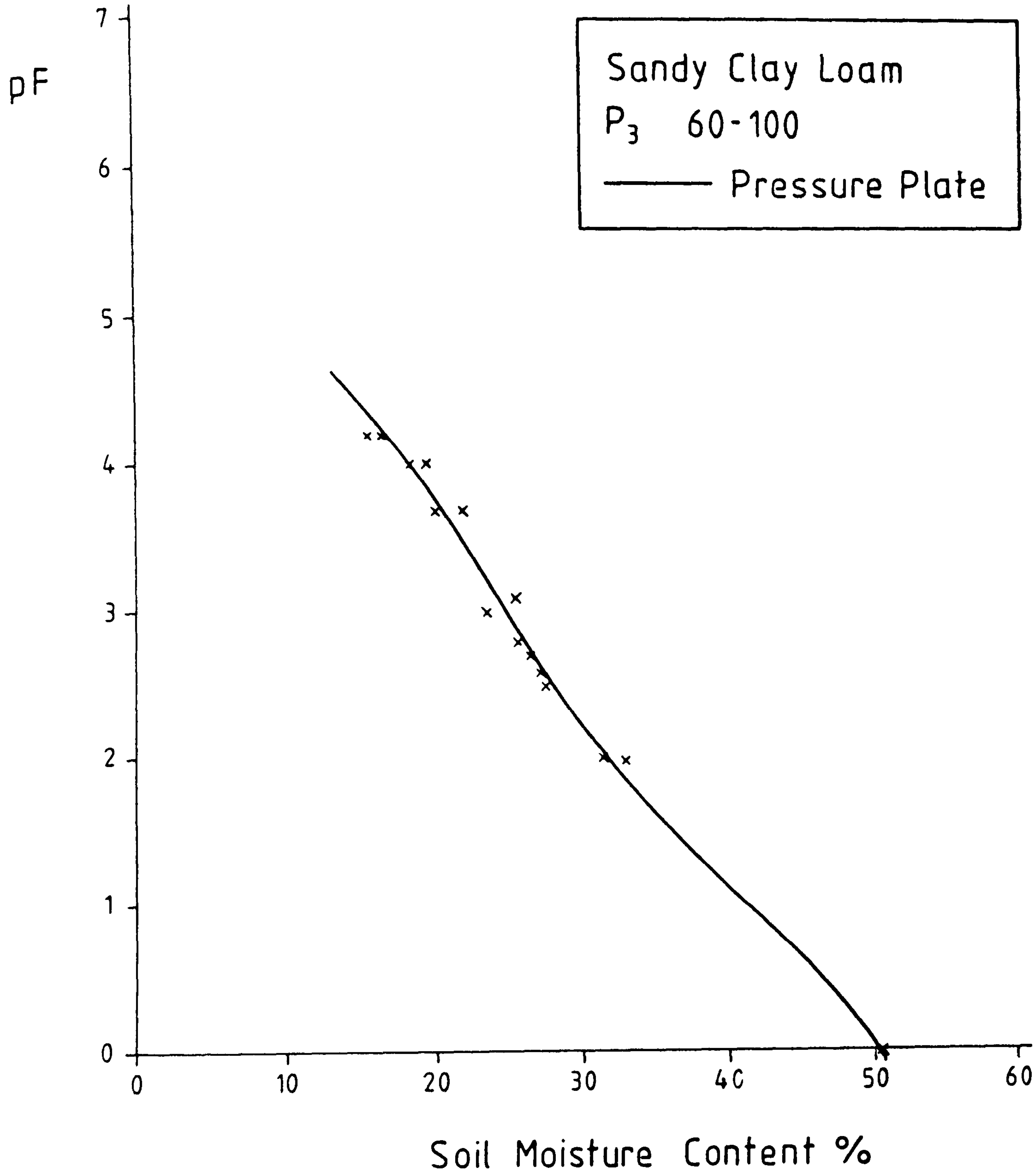

pF
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
Soil Moisture Content %
Sandy Clay Loam
P_3 60-100
Pressure Plate

Figure 3·12

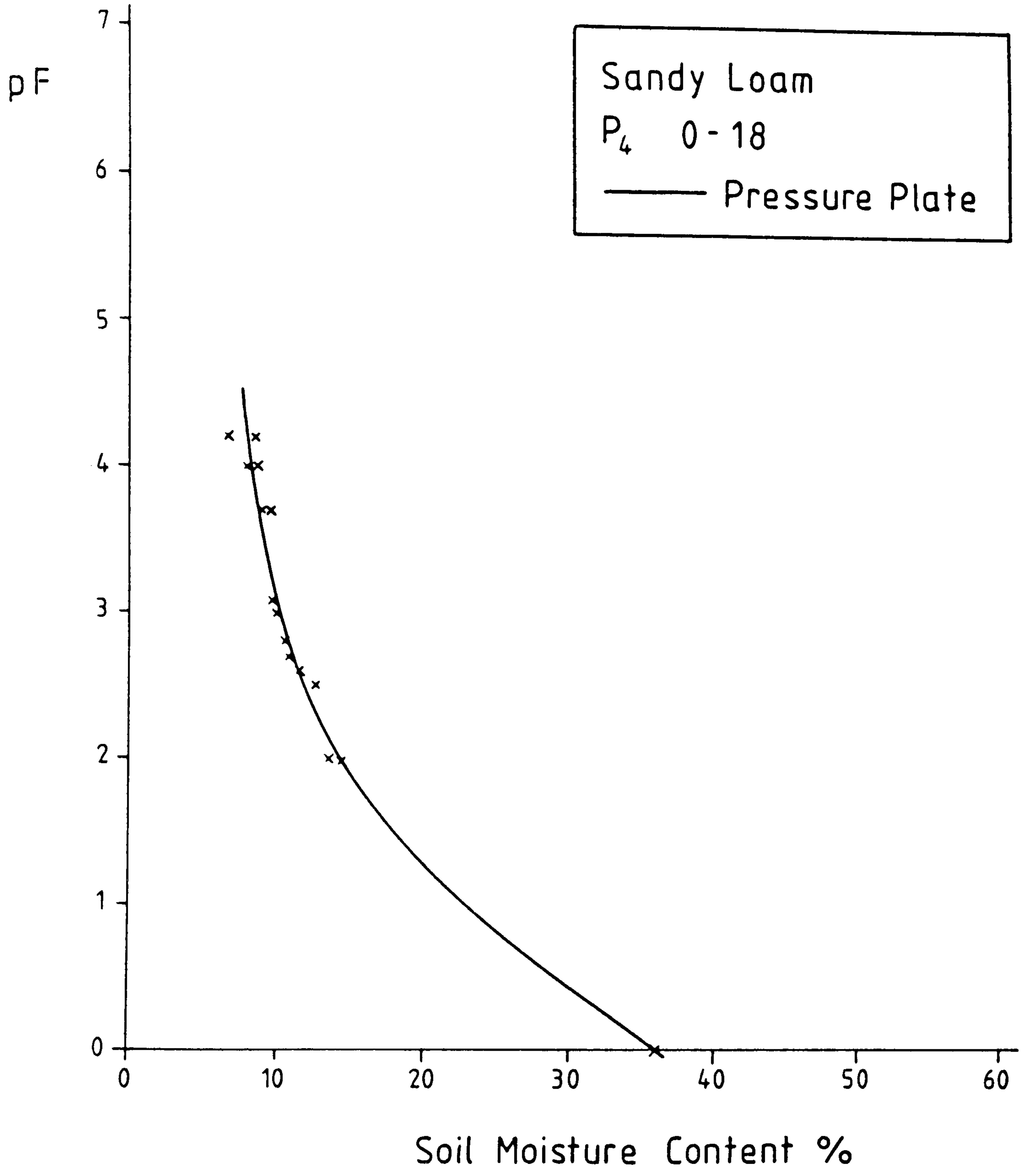

pF
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
Soil Moisture Content %
Sandy Loam
P_4 0 - 18
Pressure Plate

Figure 3·13

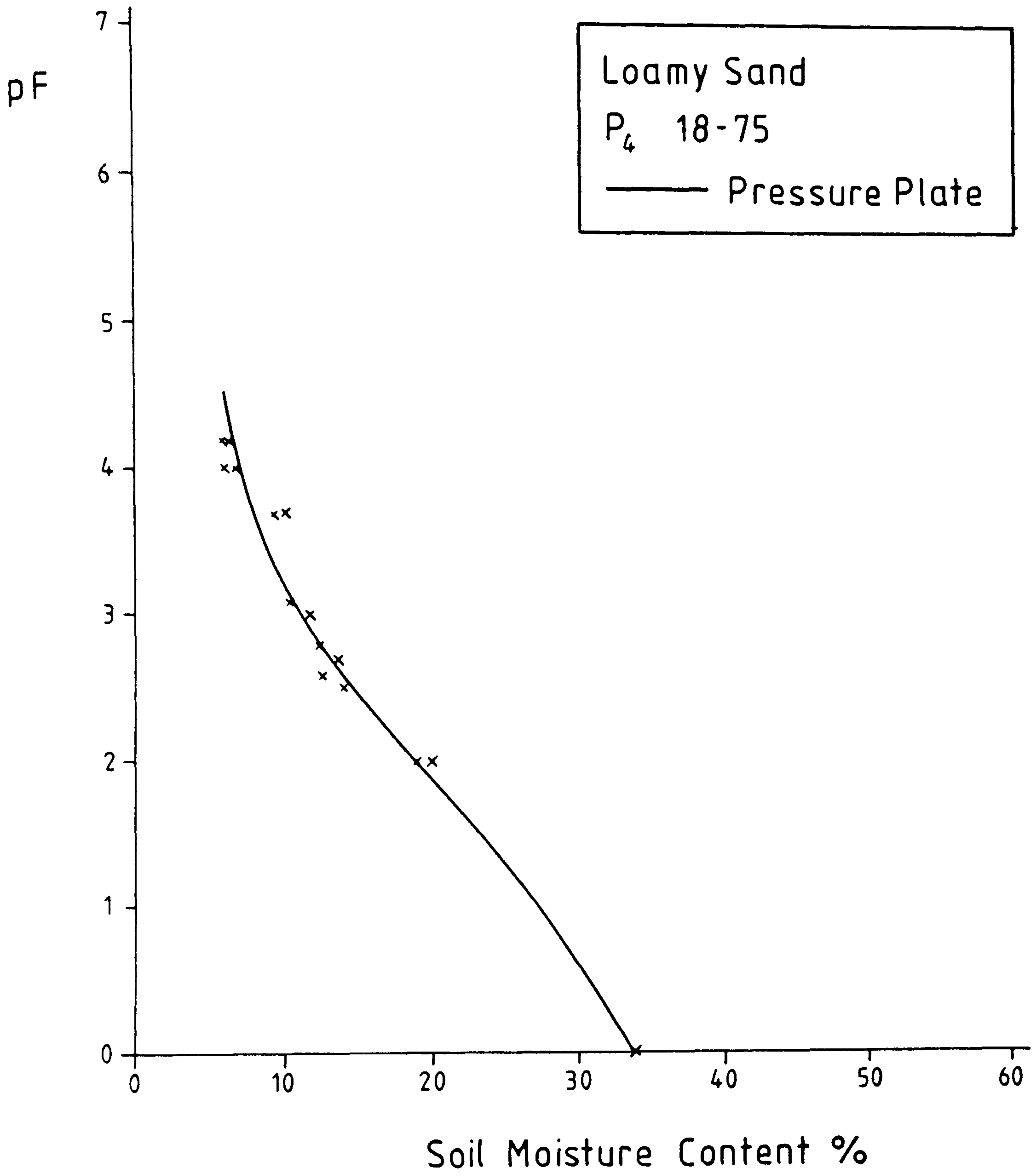

pF
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
Soil Moisture Content %
Loamy Sand
P4 18-75
Pressure Plate

Figure 3·14

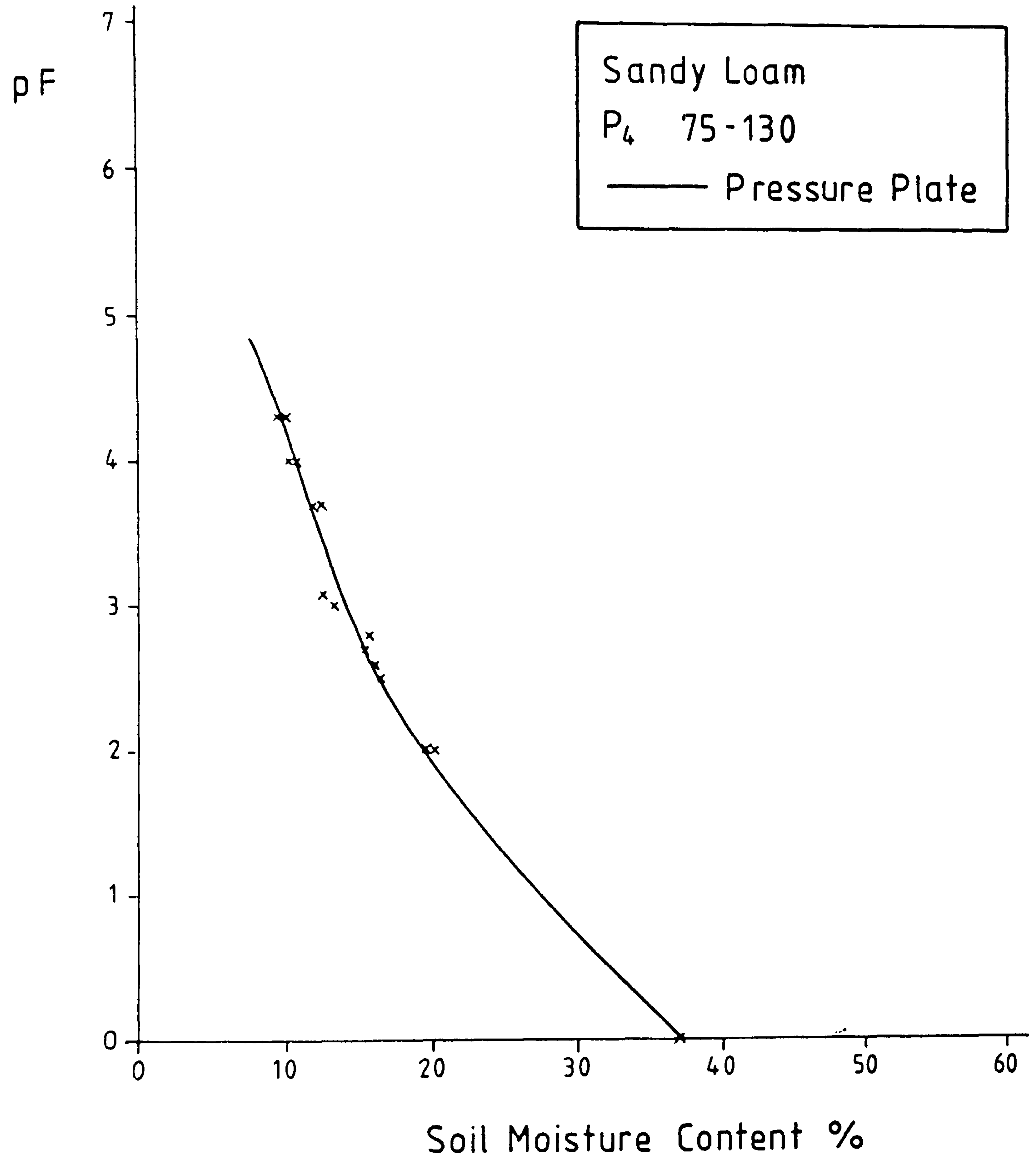

pF
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
Soil Moisture Content %
Sandy Loam
P_4 75-130
—— Pressure Plate

Figure 3·15

differences did occur they are shown on the figures.

3.2.2 Filter Paper Method

This was first proposed in the 1930's by Gardner (Ref. 3.9) and has been used by several more recent workers (Refs. 3.10, 3.11, 3.12). However, until this research, the method was unknown in Saudi Arabia.

Essentially the filter paper method consists of nothing more than placing the soil sample (at some particular moisture content) in direct contact with a filter paper, which then gradually takes up moisture from the soil until an equilibrium state is achieved. If the moisture content/suction relationship for that particular type of filter paper is known, and if the paper is oven dried before the experiment and weighed after moisture equilibrium is attained, then for each trial a suction/moisture content relationship is found. Repeating the experiment for various moisture contents of the soil sample results in an entire moisture content/suction curve for the soil.

The filter papers used in this work were of the Whatman No. 42 type utilised by earlier workers (Refs. 3.10, 3.11, 3.12), and its moisture content/suction calibration curve (Fig. 3.16) was found to compare very well to those produced

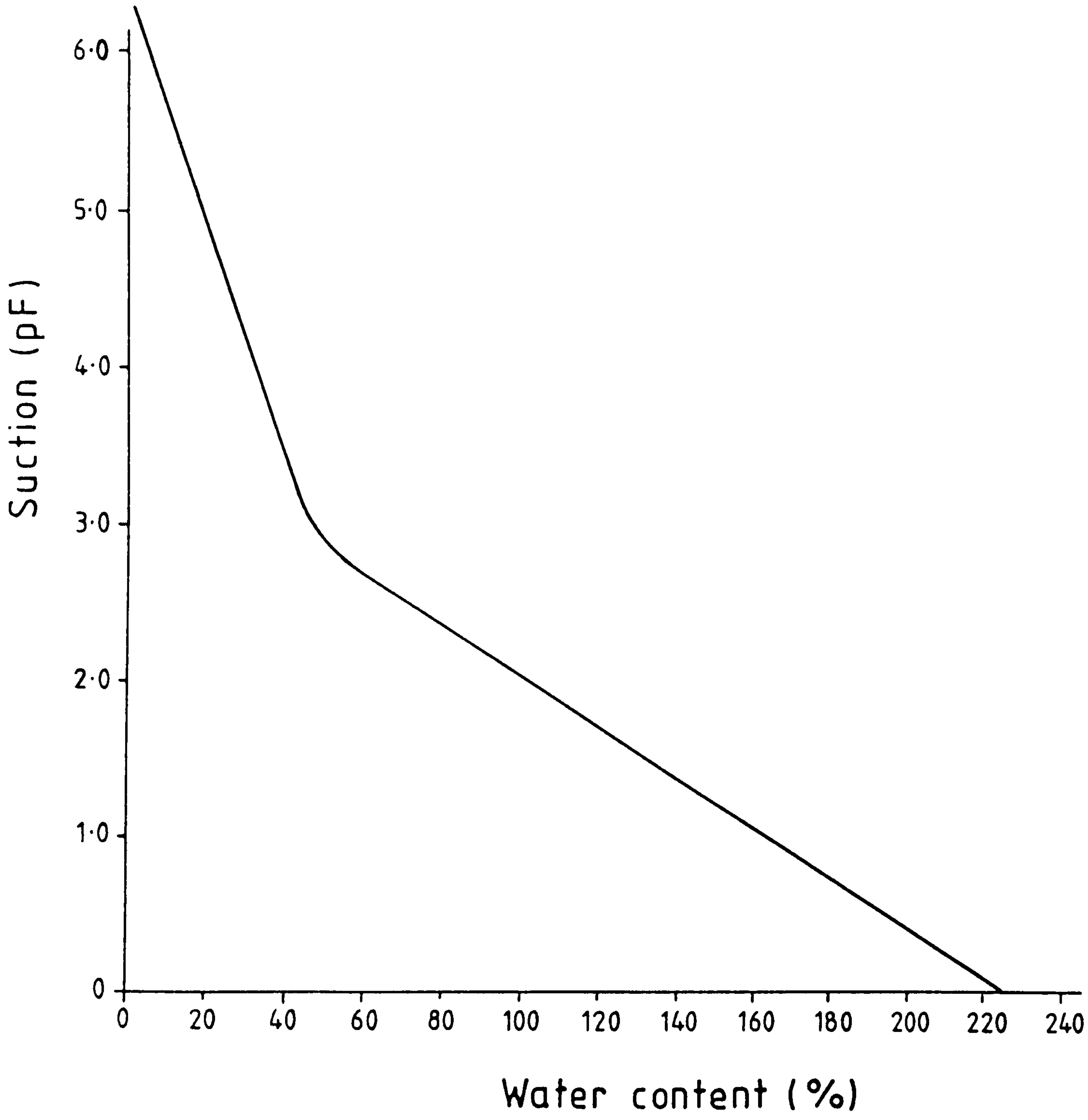


Figure 3·16 CALIBRATION CURVE FOR WHATMAN No 42 FILTER PAPER

(After Fawcett R.G. and Collis G.N. 1967) by the previous workers.

The apparatus needed for the work consisted of a set of weighing tins. Each tin was half filled with the soil sample (packed at its field density value) at some chosen moisture content, a filter paper (dried in a micro-wave oven and then weighed precisely) was placed over the soil, and the tins then completely filled with more soil (at the same density and moisture values). After a week, the sample was dismantled, the paper weighed and its increase in moisture content calculated. From the calibration curve, the suction/moisture content of that soil sample was obtained. With enough soil samples (14 to 19 proved adequate) at different moisture contents, it was possible to produce well defined moisture content/suction curves over as wide a pF range as was wanted. (Figs. 3.17 to 3.26).

To ensure that repeatability of results was being achieved, 3 replicates of each sample were tested. In practice no variation of moisture contents greater than 2% were found, thus indicating that the method does give good repeatability.

Overall the filter paper method proved simple to carry out. The same need for accurate weighing, as had been necessary with the pressure plate tests, was essential, as also was careful marking of each sample tins, but no other problems

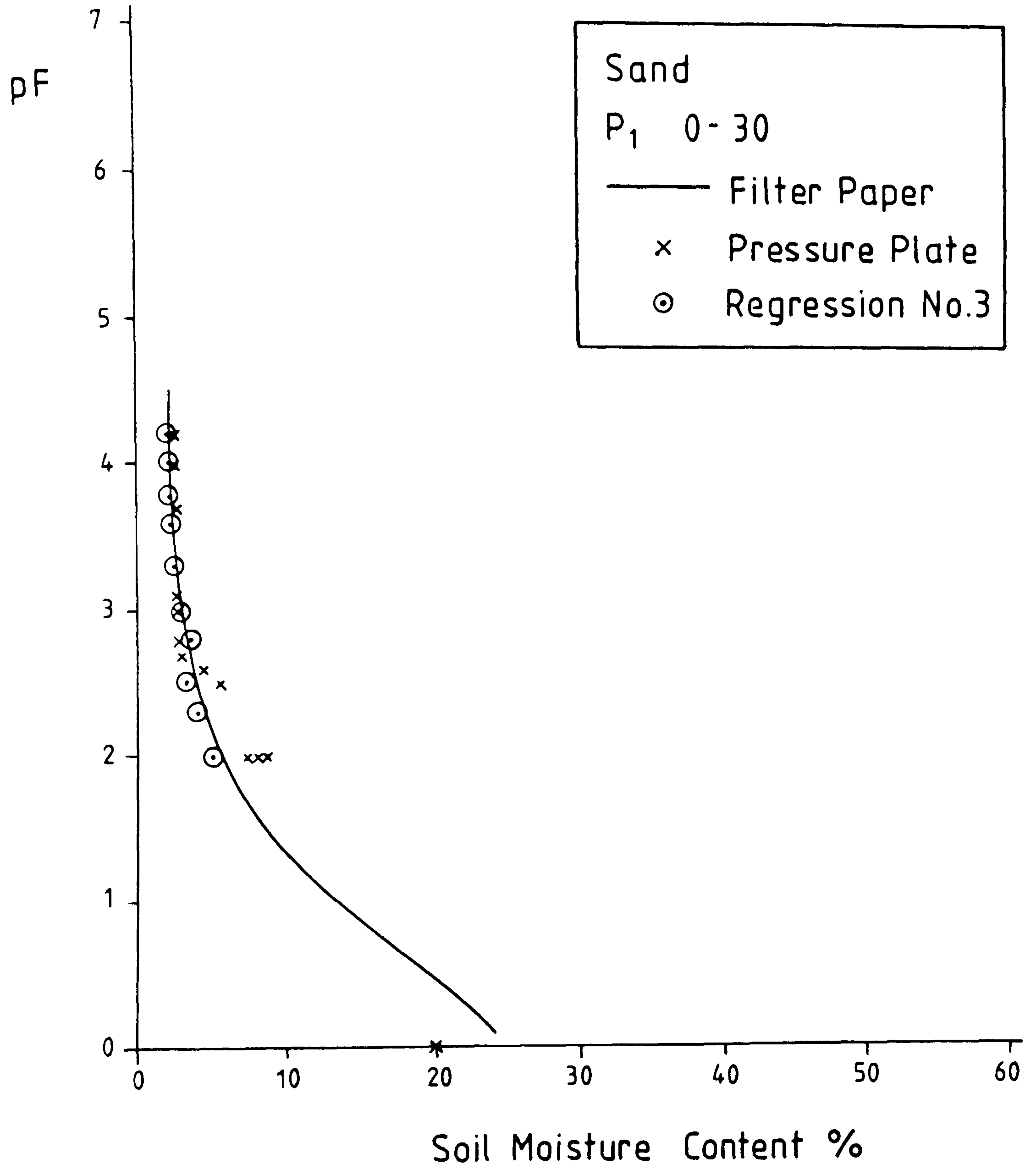

pF
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
Soil Moisture Content %
Sand
P1 0-30
Filter Paper
× Pressure Plate
⊙ Regression No.3

Figure 3·17

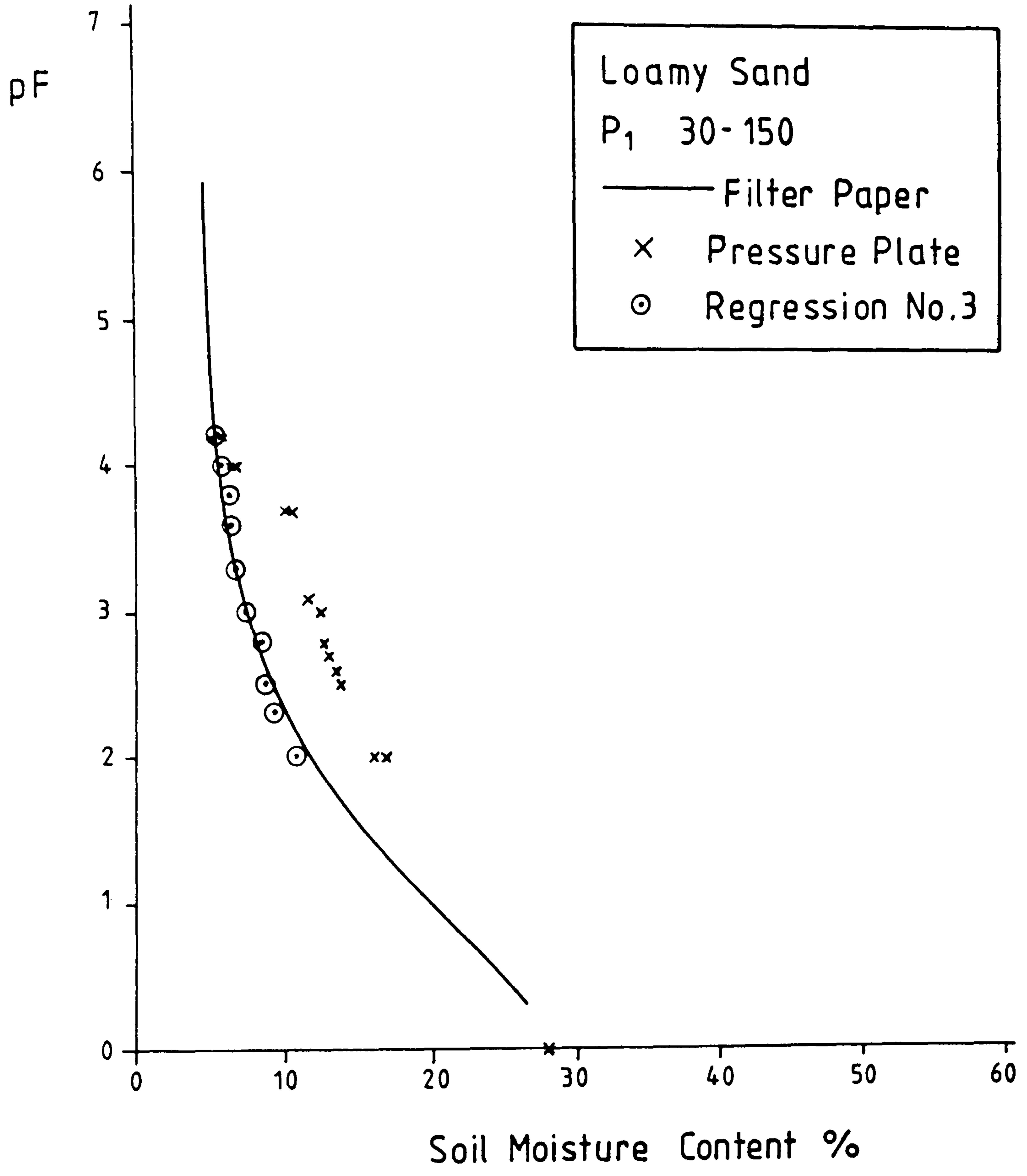

pF
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
Soil Moisture Content %
Loamy Sand
P_1 30-150
Filter Paper
× Pressure Plate
⊙ Regression No.3

Figure 3·18

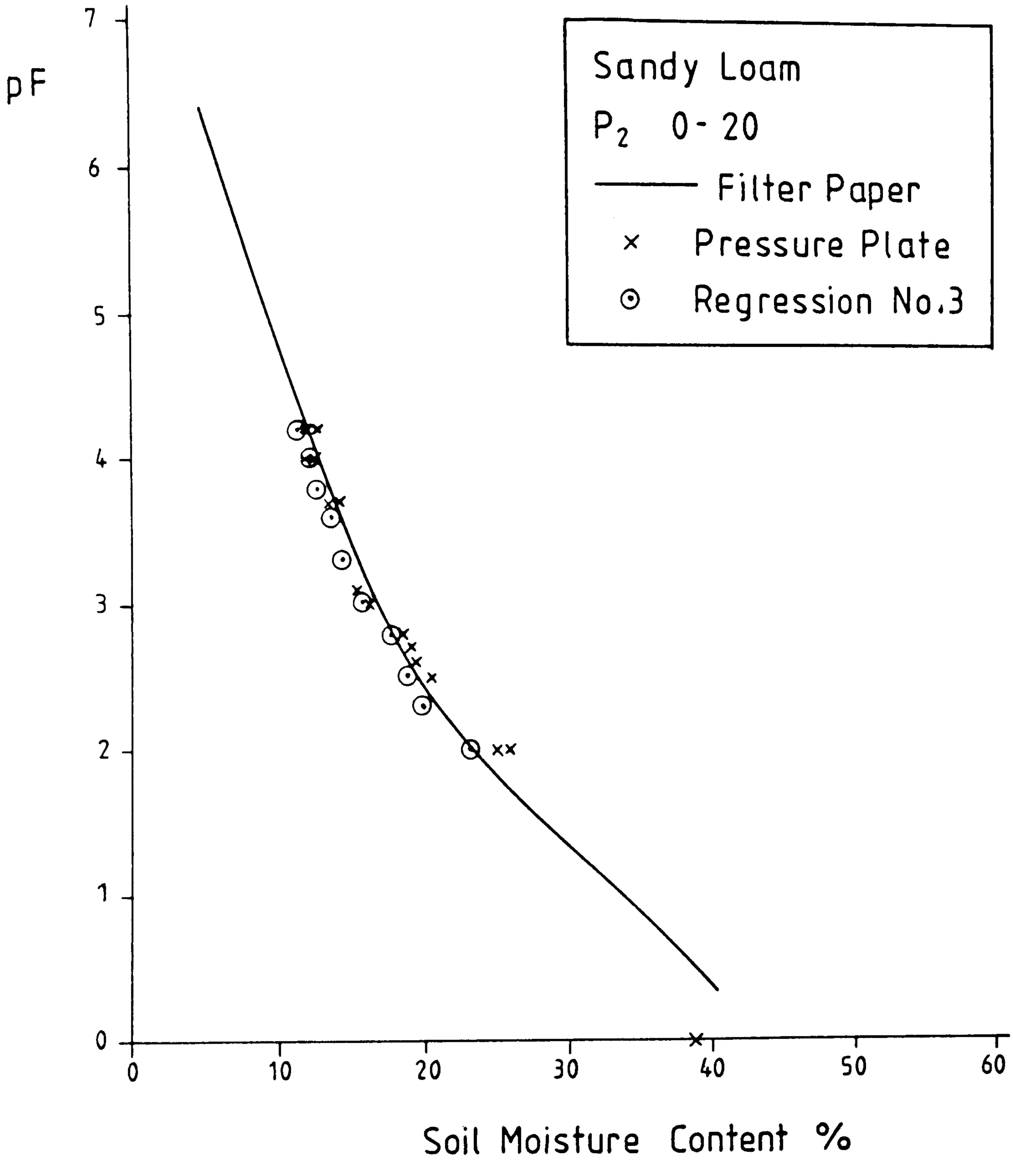

pF
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
Soil Moisture Content %
Sandy Loam
P_2 0- 20
Filter Paper
× Pressure Plate
⊙ Regression No.3

Figure 3·19

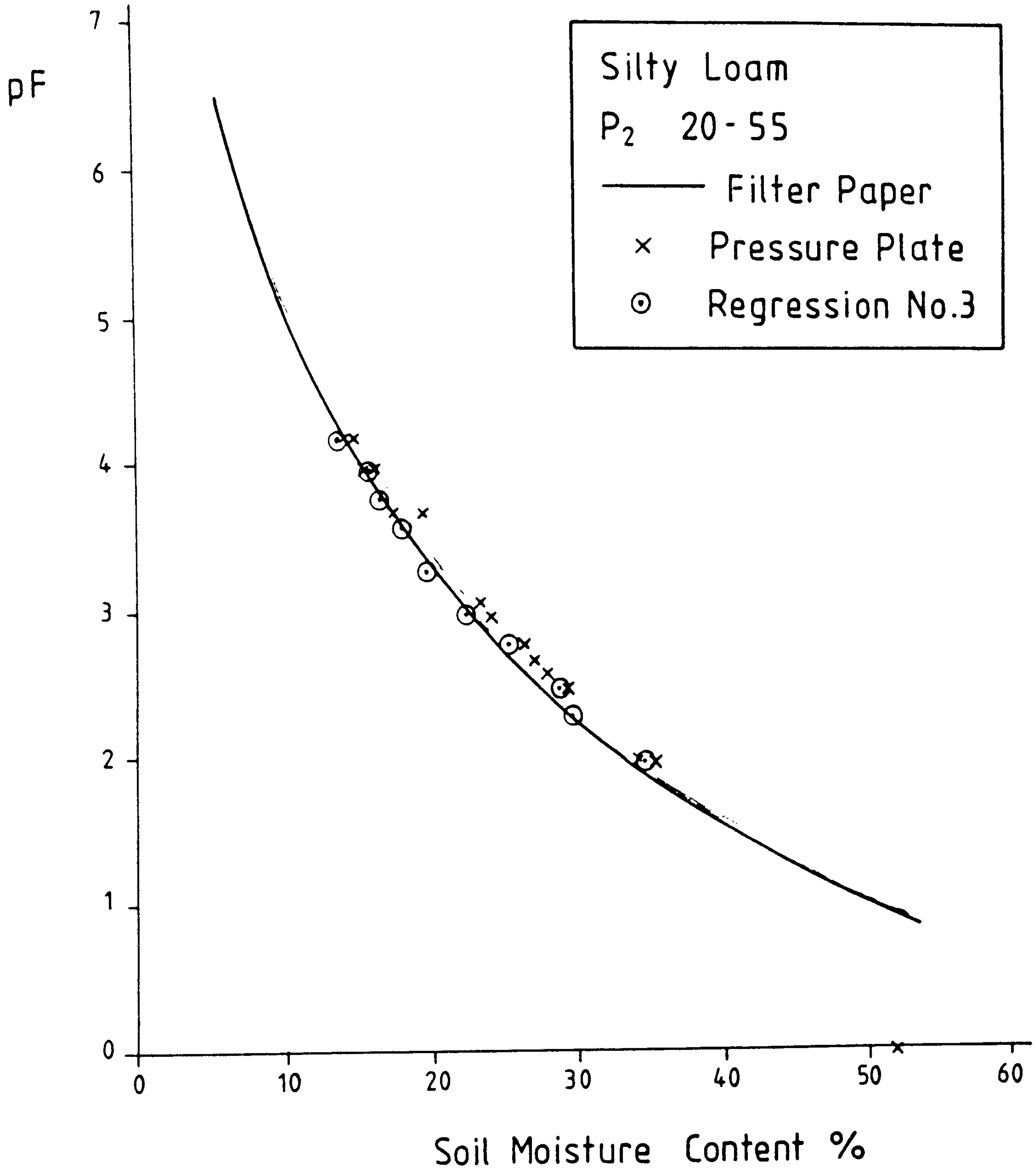

pF
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
Soil Moisture Content %
Silty Loam
P_2 20 - 55
Filter Paper
× Pressure Plate
⊙ Regression No.3

Figure 3·20

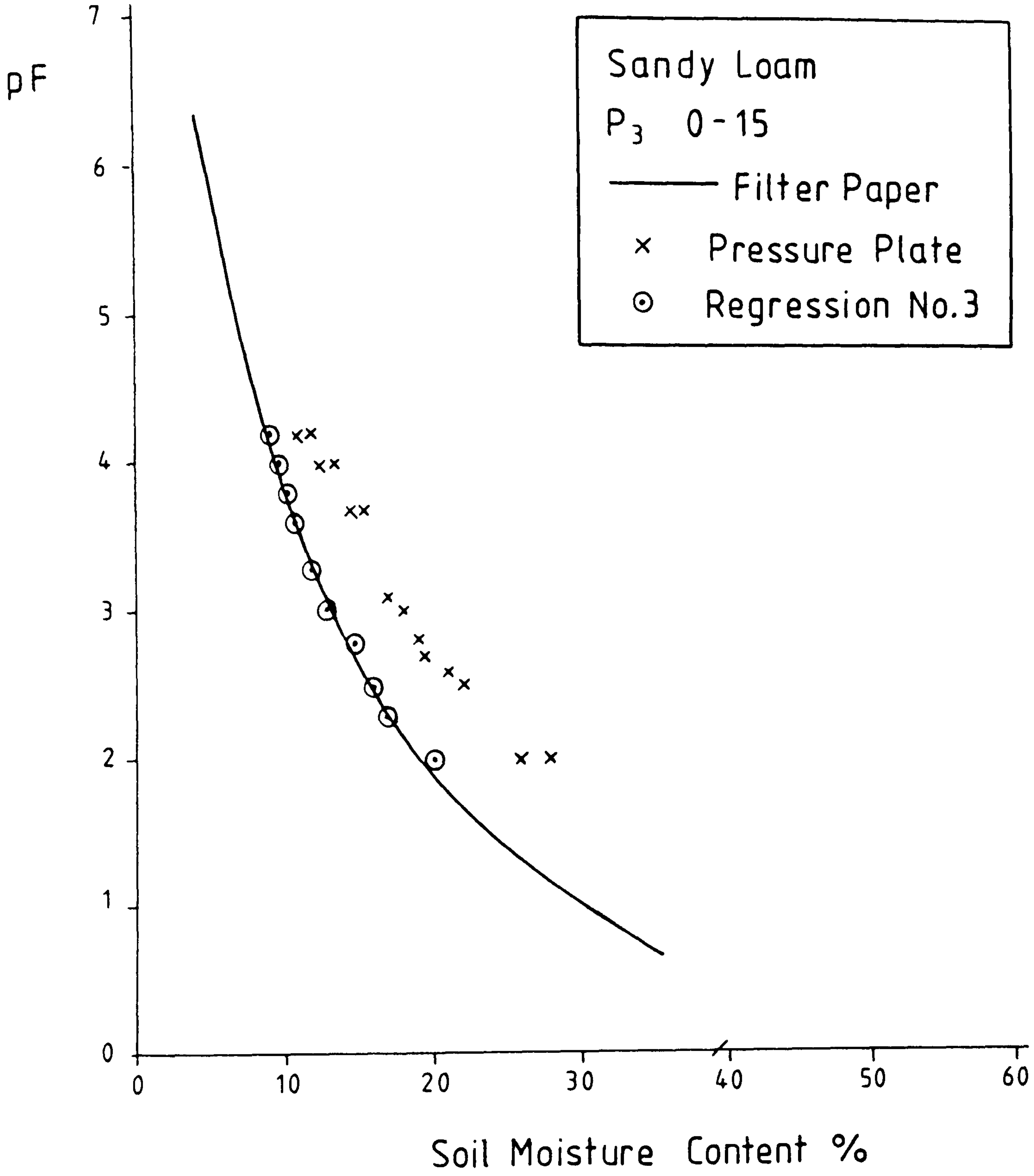

pF
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
Soil Moisture Content %
Sandy Loam
P_3 0-15
Filter Paper
× Pressure Plate
⊙ Regression No.3

Figure 3·21

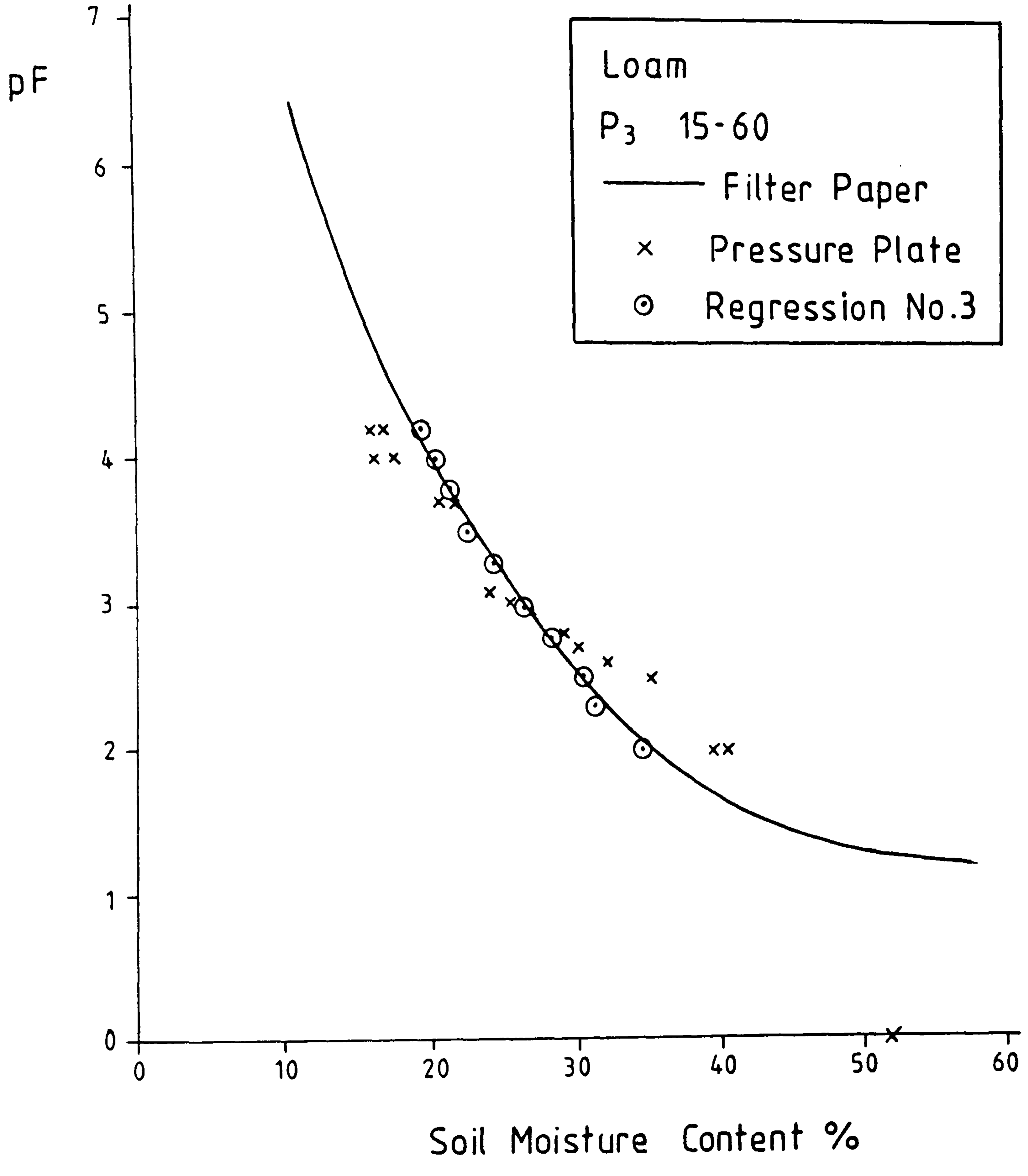

pF
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
Soil Moisture Content %
Loam
P3 15-60
Filter Paper
× Pressure Plate
⊙ Regression No.3

Figure 3·22

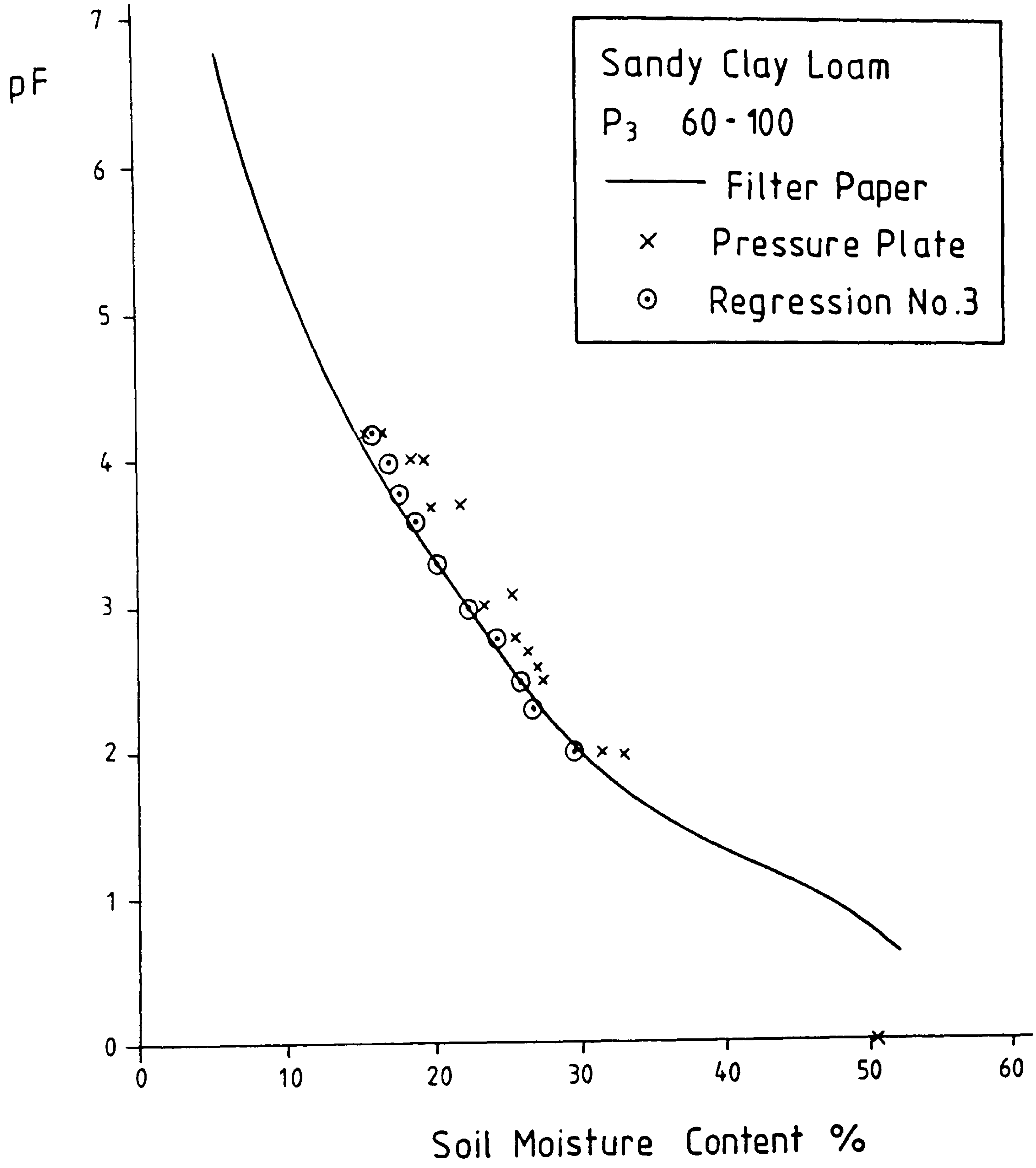

Sandy Clay Loam
P_3 60 - 100
Filter Paper
× Pressure Plate
⊙ Regression No.3
pF
0
1
2
3
4
5
6
7
0
10
20
30
40
50
60
Soil Moisture Content %

Figure 3·23

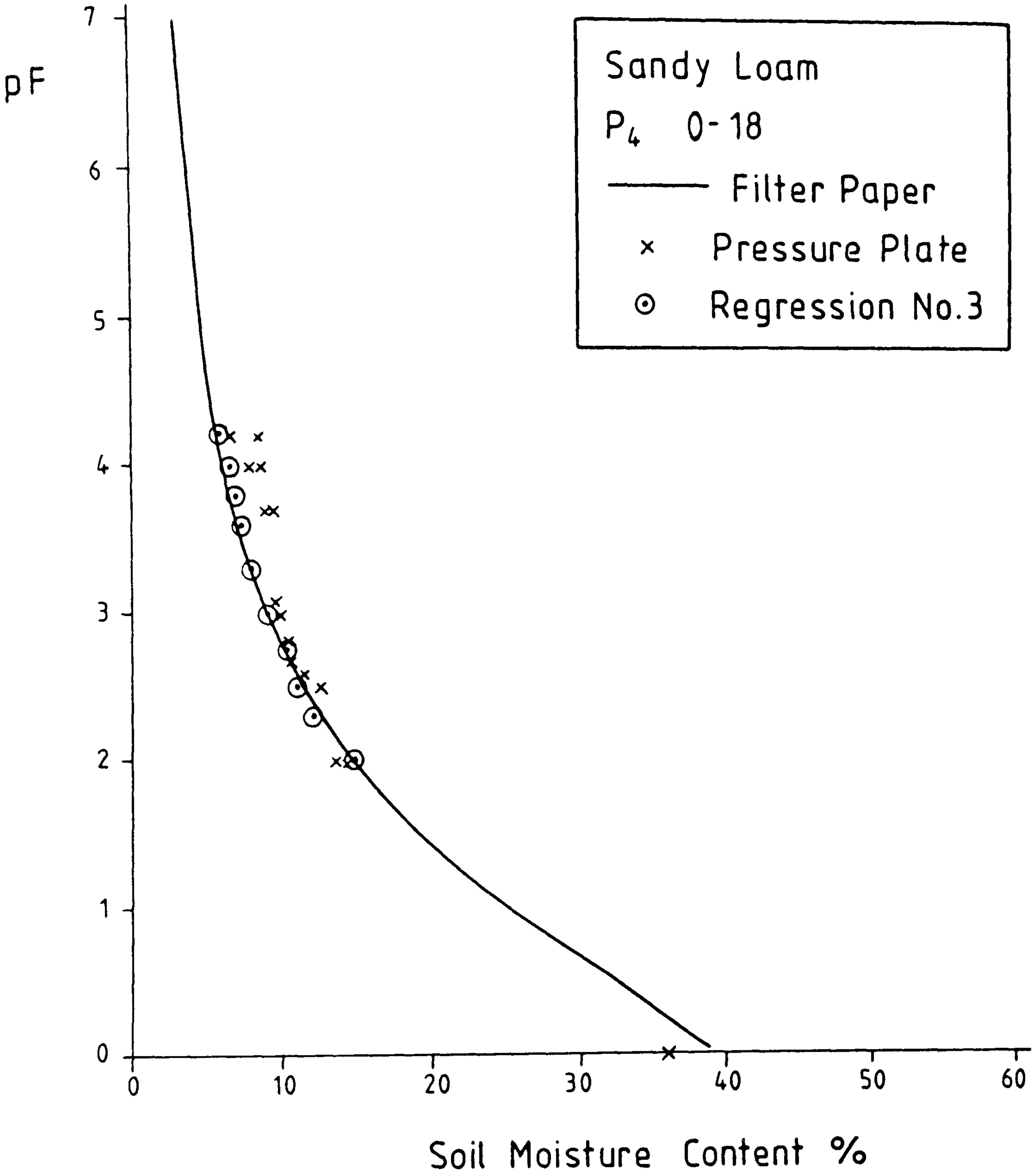

pF
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
Soil Moisture Content %
Sandy Loam
P4 0-18
Filter Paper
× Pressure Plate
⊙ Regression No.3

Figure 3·24

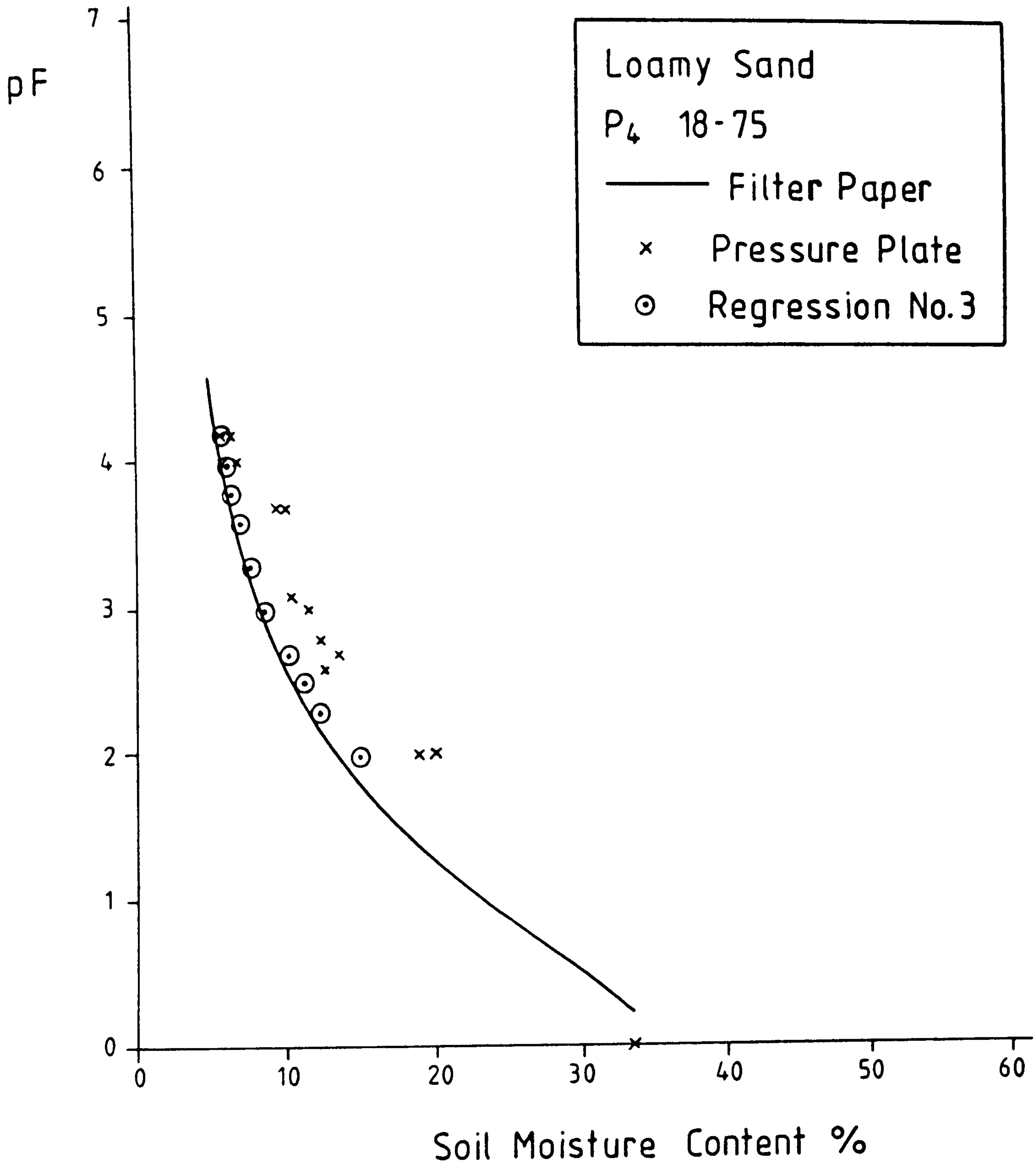

pF
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
Soil Moisture Content %
Loamy Sand
P₄ 18-75
—— Filter Paper
× Pressure Plate
⊙ Regression No. 3

Figure 3·25

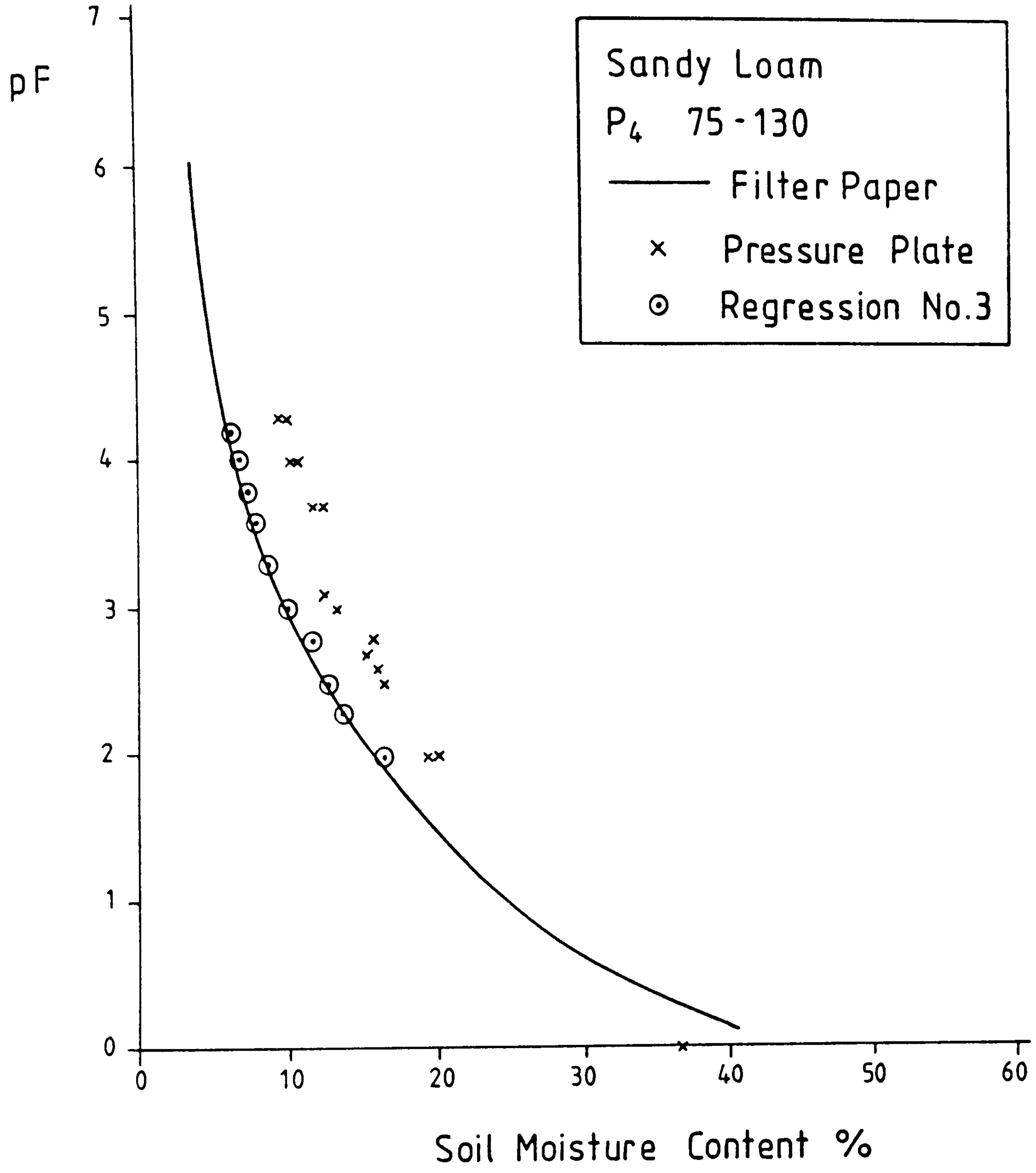

pF
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
Soil Moisture Content %
Sandy Loam
P4 75 - 130
Filter Paper
Pressure Plate
Regression No.3

Figure 3·26

were found. The total time to produce one soil's water content/suction curve was a little longer than that for the pressure plate method (20 days in contrast to the earlier recorded 15 days).

The only precaution, not covered in the above account, and necessary in practice, was that the test filter paper had to be sandwiched between two others to prevent soil particles adhering to the test paper and distorting the weighing results.

Although the filter paper and pressure plate methods proved little different in terms of difficulty and time, a comparison of the results (See Figs. 3.17 to 3.26) gained shows marked differences, with the pressure plate generally indicating a higher suction level at any specific soil moisture content.

3.2.3 Computer Assisted Analysis

The differences in the pressure plate and filter paper results obviously posed a problem, and made the use of some other independent method essential if the discrepancy was to be understood.

Estimating soil water retention from a soil's physical properties has been the focus of attention since 1959, when Lund was able to relate the moisture content at the 15 bar suction level to the amount and type of clay in a soil sample (Ref. 3.13).

Many other workers (e.g. Refs. 3.14, 3.15, 3.16 and 3.17 and 3.21) have attempted to widen Lund's approach to encompass the fuller textural, structural and organic variations between soil types, and recently Rawls and Brakensiek (Ref. 3.18) have claimed a solution to the problem.

Rawls and Brakensiek's regression analysis was based on a very large statistical population of samples from 2,543 soil horizons, which include almost the complete range of soil types, and the research aimed to produce soil moisture retention curves with only a limited input of specific data. The work allows three predictions of the necessary curves based on

(a) inputting only the particle size distribution plus the percentage organic content and the measured field value of the soil's bulk density (regression line 1).

(b) inputting the data listed above plus the measured moisture content at the 15 bar suction level (regression line 2).

and

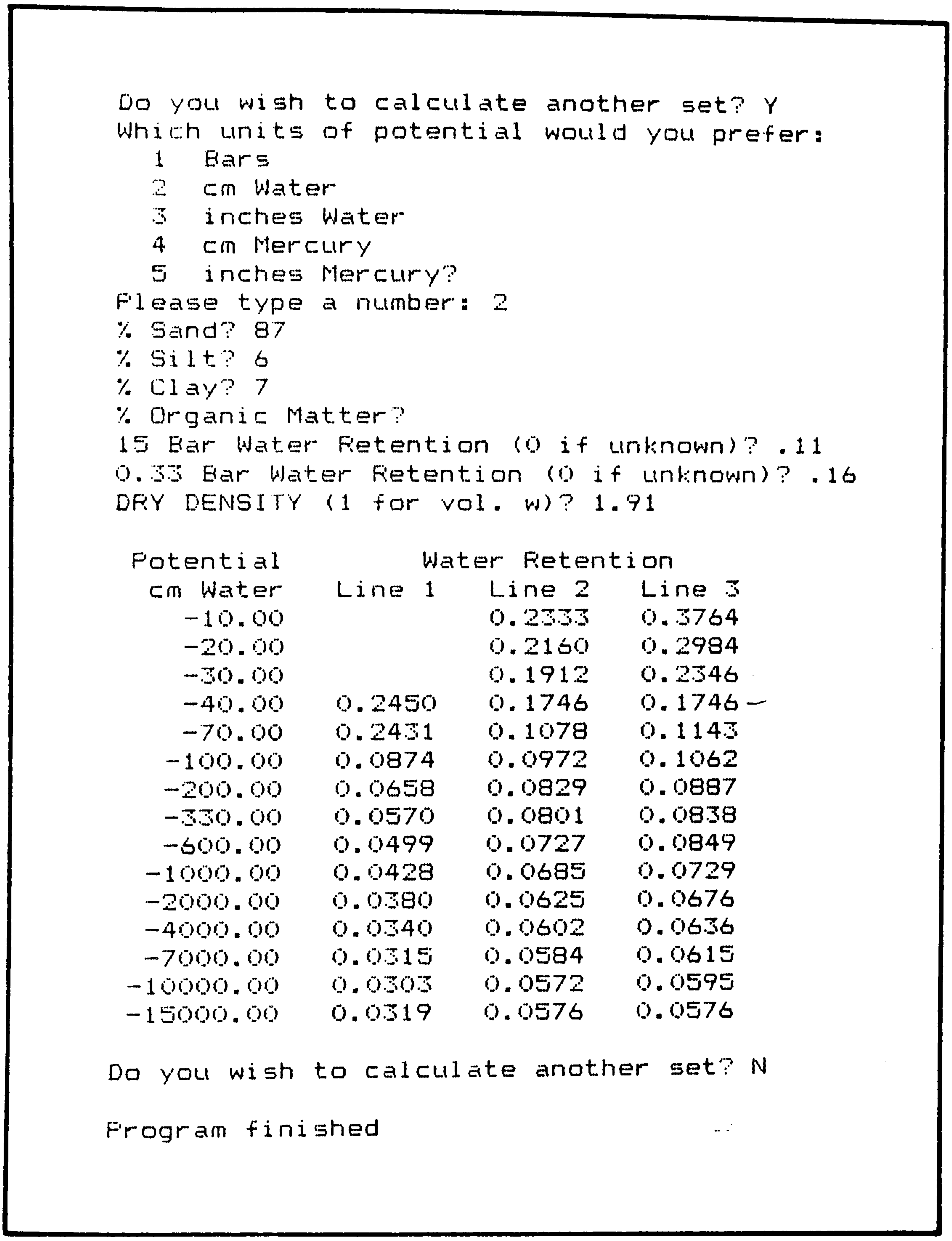
(c) inputting the data listed in (a) plus the measured moisture content at the 0.33 and 15 bar suction levels (regression line 3).

Thus three possible predictions could be obtained for each of the 10 tested Al-Hasa soils.

Apart from the possible value of the Rawls and Brakensiek method in resolving the differences between the pressure plate and filter paper results, a wider interest in the method has to be stated. Measuring a soil's water retention properties is both expensive and time-consuming even in the developed countries. In Al-Hasa an additional problem is the lack of trained manpower able to conduct such work. Thus any method which reduces the work load and costs and still produces accurate data would be a significant benefit to the work of the H.I.D.A. organisation.

The Rawls and Brakensiek regression analyses are in fact easily programmed for use on a micro computer (Ref. 3.19) and it proved simple to produce print-outs of each of the three regression lines (Fig. 3.27).

In the range from a pF of 2 up to a pF of 4.2 (the range of practical interest for agricultural use), the third regression line gave results which correspond extremely well with those of the filter paper work. (See Figs. 3.17 to



```
Do you wish to calculate another set? Y
Which units of potential would you prefer:
   1  Bars
   2  cm Water
   3  inches Water
   4  cm Mercury
   5  inches Mercury?
Please type a number: 2
% Sand? 87
% Silt? 6
% Clay? 7
% Organic Matter?
15 Bar Water Retention (0 if unknown)? .11
0.33 Bar Water Retention (0 if unknown)? .16
DRY DENSITY (1 for vol. w)? 1.91

 Potential          Water Retention
  cm Water    Line 1     Line 2     Line 3
    -10.00               0.2333     0.3764
    -20.00               0.2160     0.2984
    -30.00               0.1912     0.2346
    -40.00    0.2450     0.1746     0.1746
    -70.00    0.2431     0.1078     0.1143
   -100.00    0.0874     0.0972     0.1062
   -200.00    0.0658     0.0829     0.0887
   -330.00    0.0570     0.0801     0.0838
   -600.00    0.0499     0.0727     0.0849
  -1000.00    0.0428     0.0685     0.0729
  -2000.00    0.0380     0.0625     0.0676
  -4000.00    0.0340     0.0602     0.0636
  -7000.00    0.0315     0.0584     0.0615
 -10000.00    0.0303     0.0572     0.0595
 -15000.00    0.0319     0.0576     0.0576

Do you wish to calculate another set? N

Program finished
```

Figure 3·27 TYPICAL COMPUTER OUTPUT

from Rawls and Brakensiek

3.26). In contrast the pressure plate data, in this range, differs markedly from the computer aided results.

The second and first regression lines proved unfortunately to be much less compatible to the filter paper results (Fig. 3.27) with the errors that are listed in Table 3.2.

3.2.4 Summary of Laboratory Based Methods

The somewhat surprising conclusion of this work is that the widely utilised pressure plate appears to be less accurate than is usually believed.

The filter paper method is cheaper to carry out (since equipment costs are less), just as easy to perform, and gives results which compare very well to the Rawls and Brakensiek predictions. Thus is appears that the filter paper method should be adopted as the standard practice in Al-Hasa.

This conclusion may seem presumptuous on the basis of tests on a mere 10 different soil samples, but other workers have challenged the validity of the pressure plate. Most obvious of these were Chahal and Yong (Ref. 3.20) who noted that no one had ever carried out experimental work to check the underlying assumption of the pressure plate method, i.e. -

TABLE 3.2

Comparison of Rawls & Brakensiek Results with those derived by Filter Paper Experiments

(P_1 0 - 30)

Moisture Content					Errors %		
Suction Value pF	Filter Paper Results	Rawls & Brakensiek					
		Regression No. 1	Regression No. 2	Regression No. 3	Regression No. 1	Regression No. 2	Regression No. 3
					Field Capacity		
2.00	5.10	7.46	7.71	4.88	-46.30	-51.20	4.30
2.30	4.40	5.09	5.69	3.38	-15.70	-29.31	23.20
2.50	3.40	4.15	5.16	2.76	-22.05	-51.80	18.80
2.80	3.20	3.41	4.22	3.50	- 6.60	-31.90	- 9.40
3.00	2.80	2.62	3.68	2.53	6.42	-31.43	9.64
3.30	2.60	2.15	2.96	2.40	17.30	-13.84	7.70
3.60	2.50	1.82	2.71	2.33	27.20	- 8.40	6.80
3.80	2.40	1.64	2.55	2.34	31.70	- 6.25	2.50
4.00	2.40	1.54	2.42	2.31	35.83	- 0.83	3.75
4.20	2.40	1.71	2.38	2.38	28.75	0.83	0.83
					Wilting Point		

(P_1 30 -150)

Moisture Content					Errors %		
Suction Value pF	Filter Paper Results	Rawls & Brakensiek					
		Regression No. 1	Regression No. 2	Regression No. 3	Regression No. 1	Regression No. 2	Regression No. 3
					Field Capacity		
2.00	11.40	8.74	9.72	10.62	23.33	14.73	6.84
2.30	9.70	6.58	8.29	8.87	32.16	14.53	8.60
2.50	9.20	5.70	8.01	8.83	38.04	12.93	8.91
2.80	8.00	4.99	7.27	8.49	37.62	9.12	-6.12
3.00	7.50	4.28	6.85	7.29	42.93	2.80	2.80
3.30	7.00	3.80	6.25	6.76	45.71	10.71	3.42
3.60	6.50	3.40	6.02	6.36	47.70	7.38	2.15
3.80	6.20	3.15	5.84	6.15	49.20	5.80	0.80
4.00	6.00	3.03	5.72	5.95	49.50	4.70	0.83
4.20	5.70	3.19	5.76	5.76	44.03	- 1.05	-1.05
					Wilting Point		

(P$_2$ 0 - 20)

Moisture Content					Error %		
Suction Value pF	Filter Paper Results	Rawls & Brakensiek			Regression No. 1	Regression No. 2	Regression No. 3
		Regression No. 1	Regression No. 2	Regression No. 3			
					Field Capacity		
2.00	22.20	17.06	20.97	23.15	23.15	5.50	-4.30
2.30	20.00	12.55	18.28	19.85	37.25	8.60	0.75
2.50	18.90	10.36	17.21	18.90	45.18	8.94	0.00
2.80	17.10	8.39	15.65	17.73	50.93	8.50	-3.70
3.00	16.00	6.60	14.62	15.59	58.80	8.62	2.60
3.30	14.20	5.31	13.35	14.16	62.60	6.00	0.28
3.60	13.00	4.18	12.50	13.04	67.85	3.85	-3.10
3.80	12.00	3.47	11.86	12.38	71.10	1.20	-3.20
4.00	10.10	3.11	11.53	11.82	69.20	-14.16	-17.02
4.20	9.80	2.12	11.10	11.10	78.40	-13.30	-13.30
					Wilting Point		

(P_2 20 - 55)

Moisture Content					Errors %		
Suction Value pF	Filter Paper Results	Rawls & Brakensiek					
		Regression No. 1	Regression No. 2	Regression No. 3	Regression No. 1	Regression No. 2	Regression No. 3
2.00	34.50	19.57	24.68	34.85	43.30	28.50	-1.01
2.30	30.00	14.50	21.92	29.56	51.70	26.93	1.50
2.50	26.80	11.97	20.79	28.50	55.33	22.42	-6.34
2.80	25.20	9.69	19.12	25.25	61.54	24.12	-0.20
3.00	23.00	7.90	17.98	22.13	65.65	21.82	3.78
3.30	20.00	6.33	16.60	19.60	68.35	17.00	2.00
3.60	18.00	4.94	15.62	17.61	72.60	13.20	2.20
3.80	16.20	4.06	14.86	16.39	74.93	8.33	-1.20
4.00	15.30	3.62	14.48	15.44	76.30	5.35	-0.91
4.20	14.00	2.25	13.99	13.99	83.92	0.07	0.07

(P_3 0 - 15)

Moisture Content					Errors %		
Suction Value pF	Filter Paper Results	Rawls & Brakensiek			Regression No. 1	Regression No. 2	Regression No. 3
		Regression No. 1	Regression No. 2	Regression No. 3			
2.00	18.60	16.24	19.16	20.02	12.70	-3.01	-7.63
2.30	17.00	12.03	16.31	16.87	29.23	4.11	1.30
2.50	14.50	9.99	15.15	15.90	31.10	-4.50	-9.70
2.80	14.40	8.16	13.57	14.89	43.33	5.80	-3.40
3.00	13.80	6.66	12.52	12.90	51.73	9.30	6.50
3.30	12.30	5.42	11.25	11.65	55.93	8.53	5.30
3.60	11.10	4.33	10.42	10.68	60.99	6.12	3.78
3.80	10.20	3.63	9.80	10.11	64.41	3.92	0.88
4.00	9.60	3.29	9.47	9.63	65.72	1.35	-0.31
4.20	9.00	2.35	9.00	9.00	73.90	0.00	0.00

(P_3 15 - 60)

Moisture Content					Errors %		
Suction Paper pF	Filter Paper Results	Rawls & Brakensiek			Regression No. 1	Regression No. 2	Regression No. 3
		Regression No. 1	Regression No. 2	Regression No. 3			
2.00	35.00	20.37	27.15	34.64	41.80	22.42	1.02
2.30	32.10	15.56	25.49	31.25	51.52	20.60	2.64
2.50	30.50	13.12	24.91	30.50	56.98	18.32	0.00
2.80	28.30	10.92	23.67	28.68	61.41	16.40	-1.34
3.00	26.50	9.06	22.79	26.15	65.81	14.00	1.32
3.30	24.50	7.55	21.67	24.13	69.18	11.55	1.51
3.60	22.50	6.17	20.82	22.46	72.57	7.50	0.18
3.80	21.35	5.27	20.10	21.46	71.94	5.90	-0.51
4.00	20.01	4.83	19.76	20.57	75.86	1.24	-2.80
4.20	19.30	3.57	19.50	19.50	81.50	-1.03	-1.03

(P$_3$ 60 - 100)

Moisture Content					Errors %		
Suction Value pF	Filter Paper Result	Rawls & Brakensiek					
		Regression No. 1	Regression No. 2	Regression No. 3	Regression No. 1	Regression No. 2	Regression No. 3
2.00	30.11	20.22	21.73	29.69	32.84	27.83	1.40
2.30	28.00	17.88	20.50	26.59	36.14	26.80	5.03
2.50	26.50	16.68	20.25	26.00	37.05	23.60	1.90
2.80	23.90	15.69	19.32	24.48	34.40	19.16	-2.42
3.00	22.50	14.51	18.70	22.21	35.51	16.90	1.30
3.30	20.50	13.69	17.86	20.46	33.20	12.90	0.19
3.60	19.00	12.82	17.29	19.02	32.52	9.00	-0.10
3.80	18.00	12.41	16.78	18.17	32.60	6.80	-0.94
4.00	17.50	11.81	16.55	17.42	32.51	5.42	0.45
4.20	16.00	12.08	16.49	16.49	24.50	-3.06	-3.06

(P_4 0 ÷ 18)

Moisture Content					Errors %		
Suction Value pF	Filter Paper Results	Rawls & Brakensiek					
		Regression No. 1	Regression No. 2	Regression No. 3	Regression No. 1	Regression No. 2	Regression No. 3
2.00	13.00	12.66	12.80	14.34	2.61	1.53	-10.30
2.30	12.00	10.15	10.69	11.72	15.41	10.91	2.30
2.50	11.00	9.07	10.10	11.00	17.54	8.18	0.00
2.80	10.30	8.21	9.01	10.66	20.30	12.52	-3.50
3.00	9.50	7.40	8.36	9.01	22.10	5.20	5.15
3.30	8.00	6.75	7.48	8.17	15.62	6.50	-2.12
3.60	7.40	6.18	7.08	7.53	16.50	4.32	-1.80
3.80	7.20	5.78	6.78	7.18	19.72	5.83	0.30
4.00	6.50	5.59	6.59	6.87	14.00	-1.40	-4.30
4.20	6.00	5.80	6.50	6.50	3.33	-8.30	-8.30

(P_4 18 - 75)

Moisture Content					Errors %		
Suction Value pF	Filter Paper Results	Rawls & Brakensiek			Regression No. 1	Regression No. 2	Regression No. 3
		Regression No. 1	Regression No. 2	Regression No. 3			
2.00	14.50	11.07	12.47	15.27	23.70	14.00	-5.31
2.30	12.50	8.01	10.28	12.25	35.92	17.76	2.00
2.50	12.00	6.69	9.66	11.50	44.25	19.50	4.20
2.80	10.30	5.60	8.54	10.80	45.63	17.08	-4.85
3.00	9.00	4.64	7.88	9.00	48.44	12.44	0.00
3.30	8.00	3.90	6.99	8.00	51.25	12.62	0.00
3.60	7.40	3.29	6.59	7.26	55.54	10.94	1.89
3.80	6.80	2.92	6.29	6.83	57.05	7.50	-0.44
4.00	6.41	2.74	6.10	6.48	57.25	4.83	-1.09
4.20	6.00	2.63	6.00	6.00	56.20	0.00	0.00

(P_4 75 - 130)

Moisture Content					Errors %		
Suction Value pF	Filter Paper Results	Rawls & Brakensiek			Regression No. 1	Regression No. 2	Regression No. 3
		Regression No. 1	Regression No. 2	Regression No. 3			
2.00	17.00	12.01	12.44	16.87	29.40	26.82	0.76
2.30	14.30	9.55	10.47	13.70	33.21	26.78	4.20
2.50	13.20	8.48	9.93	13.00	36.30	23.61	1.53
2.80	11.50	7.62	8.90	11.93	33.73	22.60	-3.73
3.00	10.50	6.67	8.28	10.07	36.50	21.14	4.09
3.30	8.70	6.06	7.45	8.91	30.34	14.36	-2.41
3.60	8.50	5.53	7.06	8.03	34.94	16.94	5.52
3.80	7.50	5.17	6.77	7.51	31.06	9.73	-0.13
4.00	7.19	4.99	6.59	7.10	30.60	8.34	1.25
4.20	6.70	5.18	6.50	6.50	22.70	2.98	2.98

that the water retained in a soil is under a tension exactly equal to the positive pressure under which it equilibriated in the pressure plate apparatus. Chahal and Yong realised that if nucleation of air bubbles and water vapour occurred in the pores of the soil sample that was being tested in the pressure plate, then the soil would actually have a lower tension than the positive gas pressure under which it had come to equilibrium.

By use of a remarkably simple cell that allowed direct suction measurement (via a mercury manometer) as well as the usual connection to the pressure plate pressure gauge (Fig. 3.28), Chahal and Yong proved that their supposition was correct and that the pressure plate apparatus invariably over estimates the suction that the soil sample actually experiences (Fig. 3.29). The reason for this situation were not explained theoretically since it would be extremely difficult to measure the volumes of air/gas trapped between soil grains and the rate at which these increased or decreased.

However, this work - which appears to have gone almost unnoticed amongst the practitioners who have to carry out soil moisture evaluations - does clearly confirm the conflict between the filter paper and pressure plate results

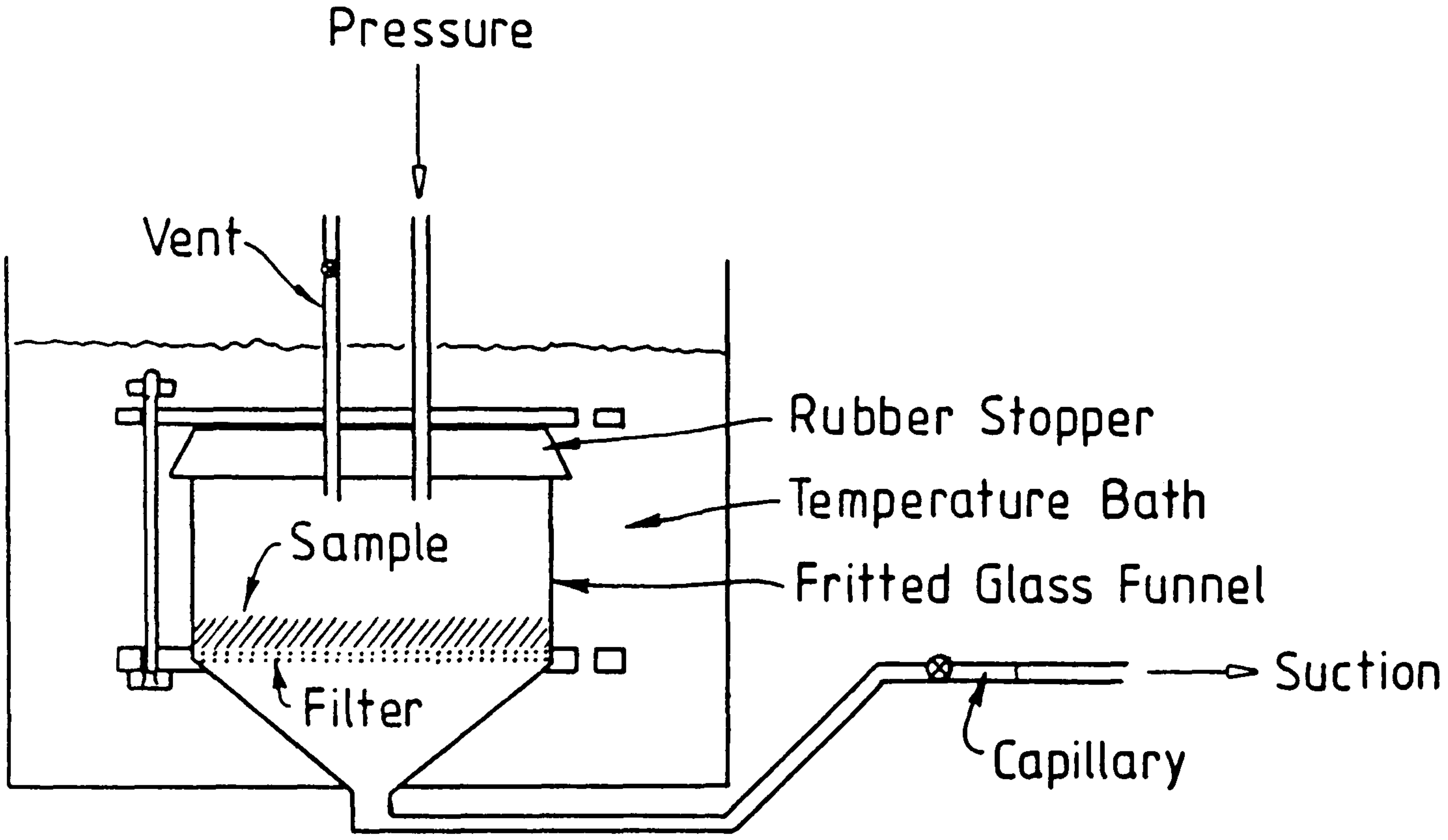


Figure 3·28 SCHEMATIC DIAGRAM OF THE EXPERIMENTAL CELL

after Chahal and Yong 1964

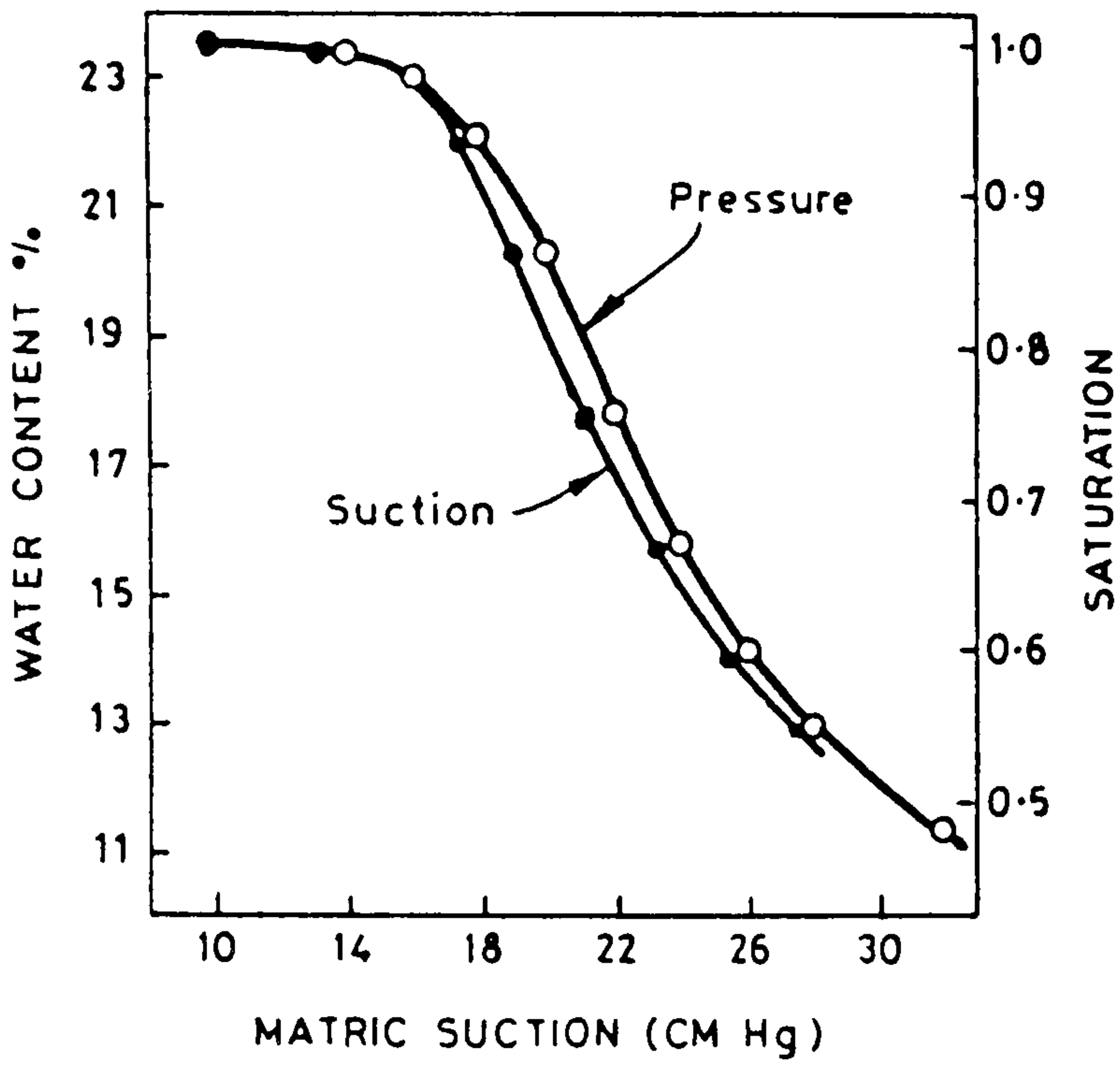


Figure 3·29 (a)

SOIL WATER CHARACTERISTIC CURVES FOR INITIALLY SATURATED COARSE SILT

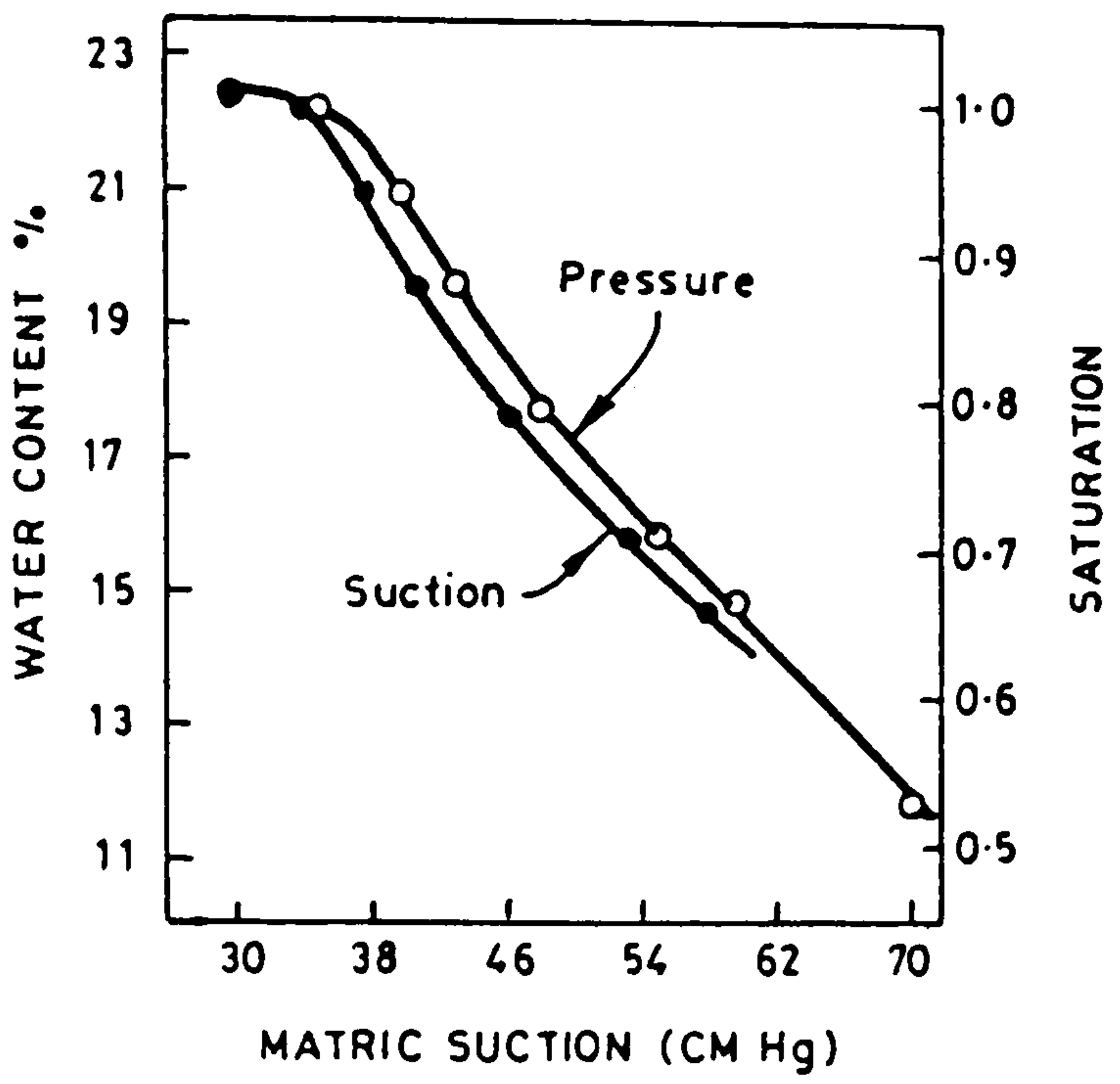


Figure 3·29 (b)

SOIL WATER CHARACTERISTIC CURVES FOR INITIALLY SATURATED FINE SILT

after Chahal and Yong 1964

noted here and strengthens the argument that for accurate control of irrigation water usage pressure plate testing of soil samples should not be the standard practice.

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CHAPTER FOUR

The Fieldwork Investigations

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The Fieldwork Investigations

4.1 Introduction

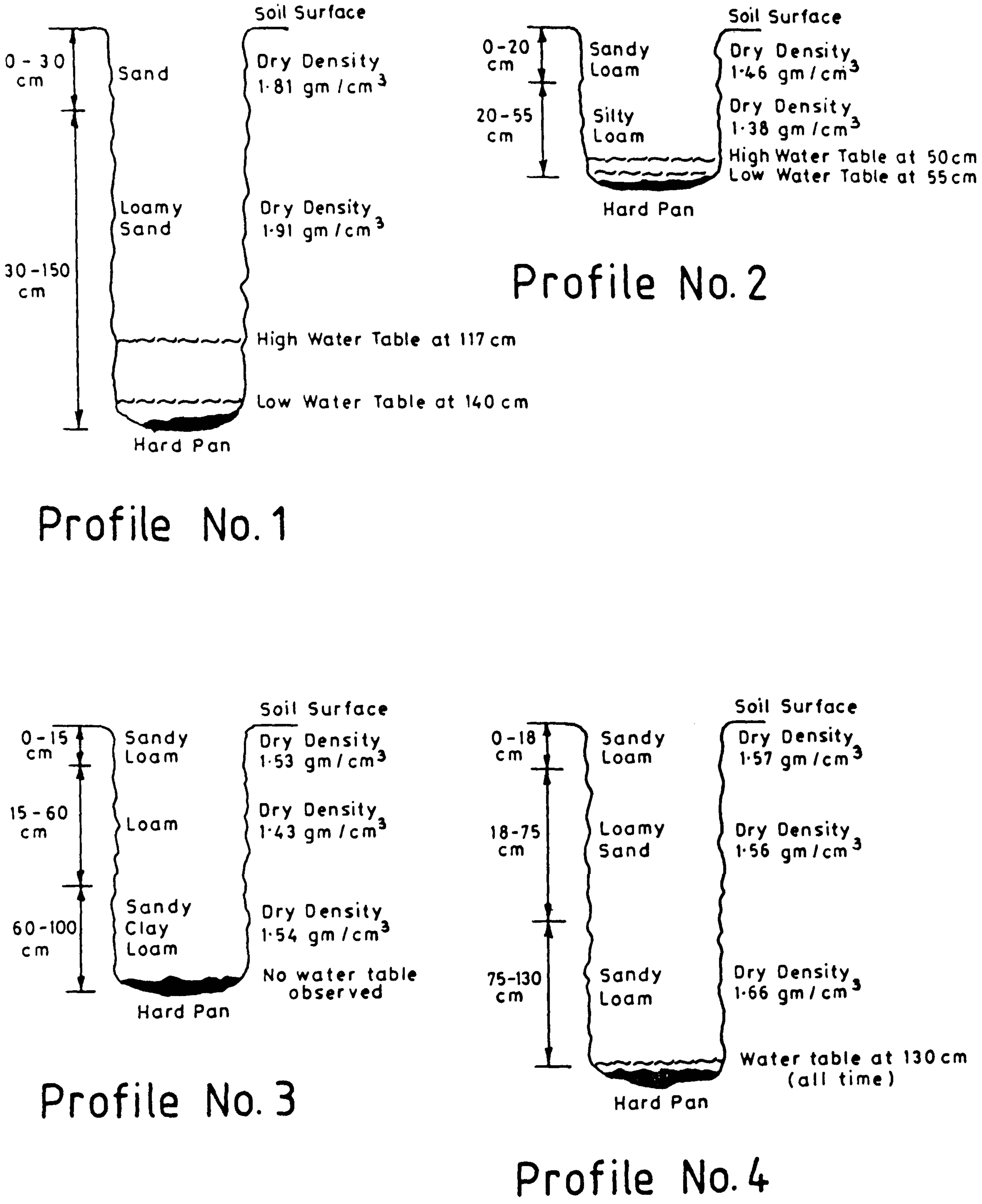
The laboratory and computer studies noted in Chapter 3 established a method of accurately defining the suction/water content relationships as the Al-Hasa soil types dry out.

Whilst this is useful, it is only a part of the data needed to allow the individual farmers to control their irrigation water usage. The missing element is - of course - some cheap and simple device that will accurately indicate the actual soil moisture condition in the irrigated fields.

Thus a field work study was essential to test various possible measuring devices.

4.2 The Soil Profiles

Four soil profiles were excavated, down to the hard pan layer, using a mechanical digger. These profiles (Fig. 4.1)



Profile No. 1

Profile No. 2

Profile No. 3

Profile No. 4

Figure 4·1

were selected:-

(a) to encompass the range of soil types known to typify the oasis of its surrounding area

and

(b) to include land that was being subjected to quite different irrigation and cultivation regimes.

This last criteria meant that the soil moisture contents would be quite different in the various profiles, and so a wider range of data would be available against which the accuracy of the various soil moisture and soil suction measuring devices could be tested.

The locations of the soil profile sites are indicated on Fig. 3.4.

Profile No. 1 is in an area devoted to palm tree cultivation and is under constant drip feed irrigation, with small and metered additions of water to the surface layers occurring throughout each day. This profile includes 30 cm of blown and loose sand (bulk density 1.81 gm/cm^3) over 120 cm of loamy sand (bulk density 1.91 gm/cm^3). The local perched water table exists at 150 cm below ground surface because of the existence of the hard pan layer and the ineffectiveness of the local drainage works.

Profile No. 2 is in an area given over to sun flower cultivation, where the hard pan occurs at the shallow depth of 55 cm. Sandy loam (20 cm thick) overlies 35 cm of silty loam, and the local water table is very high (at between 50 and 55 cm depths). This profile was subjected to daily surface irrigation throughout the period of the field study.

Profile No. 3 was located in one of the saline ("sabkah") areas that lie uncultivated throughout the oasis area. No irrigation at all took place on this and the soils were thus especially dry. No water table occurred in the profile, and crystalline spots of gypsum were visible in the sandy clay loam at the base of the profile.

Profile No. 4 lies in an area given over to winter wheat cultivation and irrigated on the central pivot system.

The profiles were excavated in October 1986, and once the pits were dug each profile was measured and recorded.

Samples were then taken for physical and chemical analysis (Tables 4.1 and 4.2). All analyses were carried out to the recommendations of the United States agricultural standards.

In addition to the samples (Ref. 4.1) removed for immediate analysis, other large samples were taken for the laboratory based soil suction/soil moisture investigations, and for laboratory evaluations of the tensiometers, gypsum blocks,

TABLE 4.1

Particle Size

St. No.	Field No.	Very Coarse Sand %	Coarse Sand %	Medium Sand %	Fine Sand %	Very Fine Sand %	Total Sand %	Clay %	Silt %	Texture
1	P1 0 - 30	1.30	14.70	24.70	24.70	8.40	93.00	1.00	5.00	Sand
2	P1 30 - 150	1.60	15.30	31.60	28.90	9.60	87.00	7.00	7.00	Loamy Sand
3	P2 0 - 20	3.70	5.10	18.00	20.50	7.51	54.80	1.00	39.60	Sandy Loam
4	P2 20 - 55	4.00	5.50	16.40	15.60	6.90	48.40	1.10	49.80	Silty Loam
5	P3 0 - 15	2.50	3.70	13.90	21.30	14.50	56.00	1.70	39.60	Sandy Loam
6	P3 15 - 60	0.10	1.00	4.80	20.40	18.30	44.40	4.60	48.40	Loam
7	P3 60 - 100	0.40	1.00	14.10	28.30	13.60	57.50	32.10	8.50	Sandy Clay Loam
8	P4 0 - 18	1.60	16.00	43.10	14.50	5.40	80.50	12.50	6.90	Sandy Loam
9	P4 18 - 75	1.60	25.70	48.40	5.20	1.50	82.30	2.70	14.70	Loamy Sand
10	P4 75 - 130	0.40	7.00	53.10	17.30	2.60	80.00	12.20	7.30	Sandy Loam

TABLE 4.2

Chemical Analysis

Sample	pH	E.C. Millimhos	Meq/L								
			Co_3	HCO_3	cL	SO_4	Ca	Mg	Na	K	Saturation %
P1 0 - 30	8.10	11.30	-	8.00	100.00	9.90	42.00	12.00	60.90	3.00	20.00
P1 30 - 150	7.80	33.50	-	8.00	340.00	12.50	60.00	55.00	239.20	6.30	29.20
P2 0 - 20	7.80	18.70	-	10.00	185.00	-	70.00	38.00	79.00	4.80	40.00
P2 20 - 55	8.40	5.80	-	8.00	40.00	10.50	28.00	6.00	24.10	0.40	54.00
P3 0 - 15	7.40	140.00	-	8.00	2045.00	-	277.50	222.50	1348.40	14.30	40.00
P3 15 - 60	8.00	45.00	-	12.00	480.00	6.10	85.00	42.50	364.30	6.30	64.00
P3 60 - 100	7.80	44.00	-	7.00	470.00	23.20	70.00	55.00	369.70	[illegible].60	63.20
P4 0 - 18	7.40	80.00	-	15.00	1200.00	-	255.00	155.00	587.20	8.40	25.60
P4 18 - 75	7.70	42.40	-	6.00	415.00	42.40	55.50	49.50	353.40	4.80	30.80
P4 75 - 130	7.90	44.60	-	6.00	470.00	36.70	80.00	25.00	402.30	5.40	36.40

soil moisture cells and psychrometers that would later be installed to monitor conditions in each of the profiles.

Once all the necessary samples had been taken, a slotted plastic pipe was installed in each of the four pits and the pits then backfilled. The plastic pipe then acted as a groundwater monitoring point for the remainder of the field study period (October 1986 to May 1987).

With the groundwater monitoring point installed, the access tube for neutron probe measurements was emplaced. This was done by drilling an auger hole in the undisturbed soil adjacent to each profile pit down to the hard pan and installing an aluminium tube that exactly fitted the auger hole dimensions.

The final task was to install tensiometers, gypsum blocks, soil moisture cells and psychrometers at various depths in the undisturbed soils around each of the profile pits (Table 4.3). In each such installation, a hole was augered to allow the instrument access and the hole then backfilled with the soil removed by the auger. Care was taken to compact the backfilled holes to bulk densities similar to those in the profiles.

A total of 33 tensiometers, 16 gypsum blocks, 16 soil moisture cells and 4 psychrometers were used in the field

TABLE 4.3

Profiles No. & depths cm	Bulk density Dry density gm/cm^3	Texture	Installed Tensiometer Numbers	Installed Gypsum blocks Numbers	Soil Moisture Cell Numbers	Psychrometer Numbers
P1 0 - 30	1.81	Sand	5	2	2	1
50	1.91	Loamy Sand	1	-	-	-
75	1.91	Loamy Sand	2	1	1	-
90	1.91	Loamy Sand	1	1	1	-
P2 0 - 20	1.46	Sandy Loam	5	2	2	1
50	1.38	Silty Loam	3	2	2	-
P3 0 - 15	1.53	Sandy Loam	4	1	1	1
50	1.43	Loam	2	1	1	-
75	1.54	Sandy Clay Loam	1	1	1	-
90	1.54	Sandy Clay Loam	1	1	1	-
P4 0 - 18	1.57	Sandy Loam	4	1	1	1
50	1.56	Loamy Sand	2	1	1	-
75	1.66	Sandy Loam	1	1	1	-
90	1.66	Sandy Loam	1	1	1	-
TOTAL			33	16	16	4

studies, with the majority of these installed in the top 50cm of the profiles to ensure that the part of the soil profiles most subject to soil moisture changes were adequately monitored.

4.3 The Neutron Probe

The obvious intention of the field studies was to measure soil suction and to relate this to the soil moisture state at the measuring instrument. Whilst this can be done by the combination of tensiometers and gypsum/soil moisture blocks, it is sensible to ensure that some additional method is included to allow accurate measurement of the soil moisture contents of the soils. For this reason, use was made of the Troxler Type 3222 neutron moisture meter. (Fig. 4.2).

Neutron probes have been widely used (Refs. 4.2, 4.3) in such field studies, since they are rapid and easy to handle. The theory behind their use rests on the property of fast neutrons to lose energy as they collide with the nuclei of surrounding atoms and to lose more kinetic energy in collisions with low atomic weight atoms, such as hydrogen. As hydrogen in soils is largely associated with the water held between soil grains, a relationship can be established with soil moisture content and the number of slow neutrons being reflected back to the probe's detector unit. Van

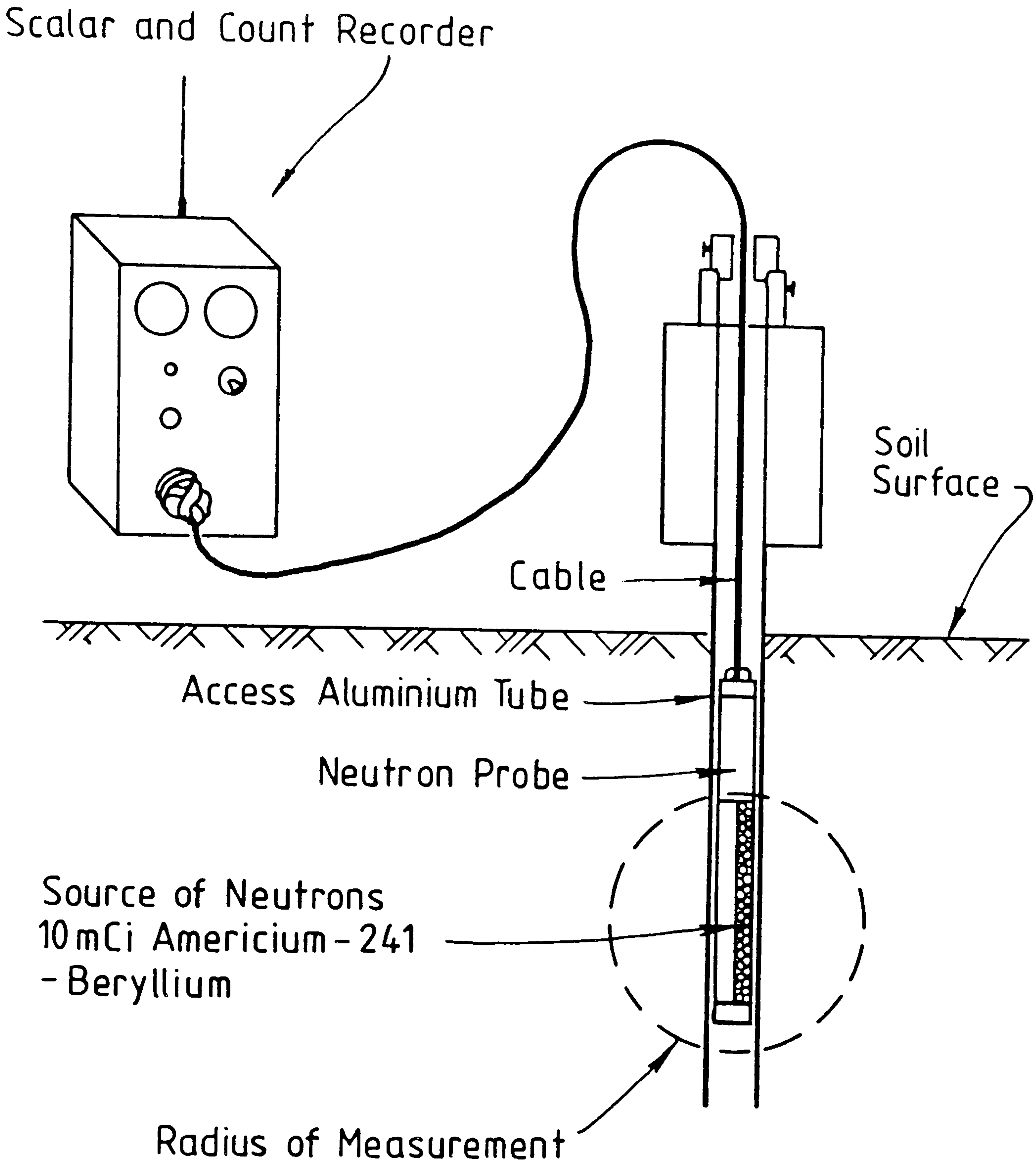


Figure 4·2 SCHEMATIC DIAGRAM OF THE NEUTRON MOISTURE PROBE USED FOR MEASURING MOISTURE CONTENT OF SOIL

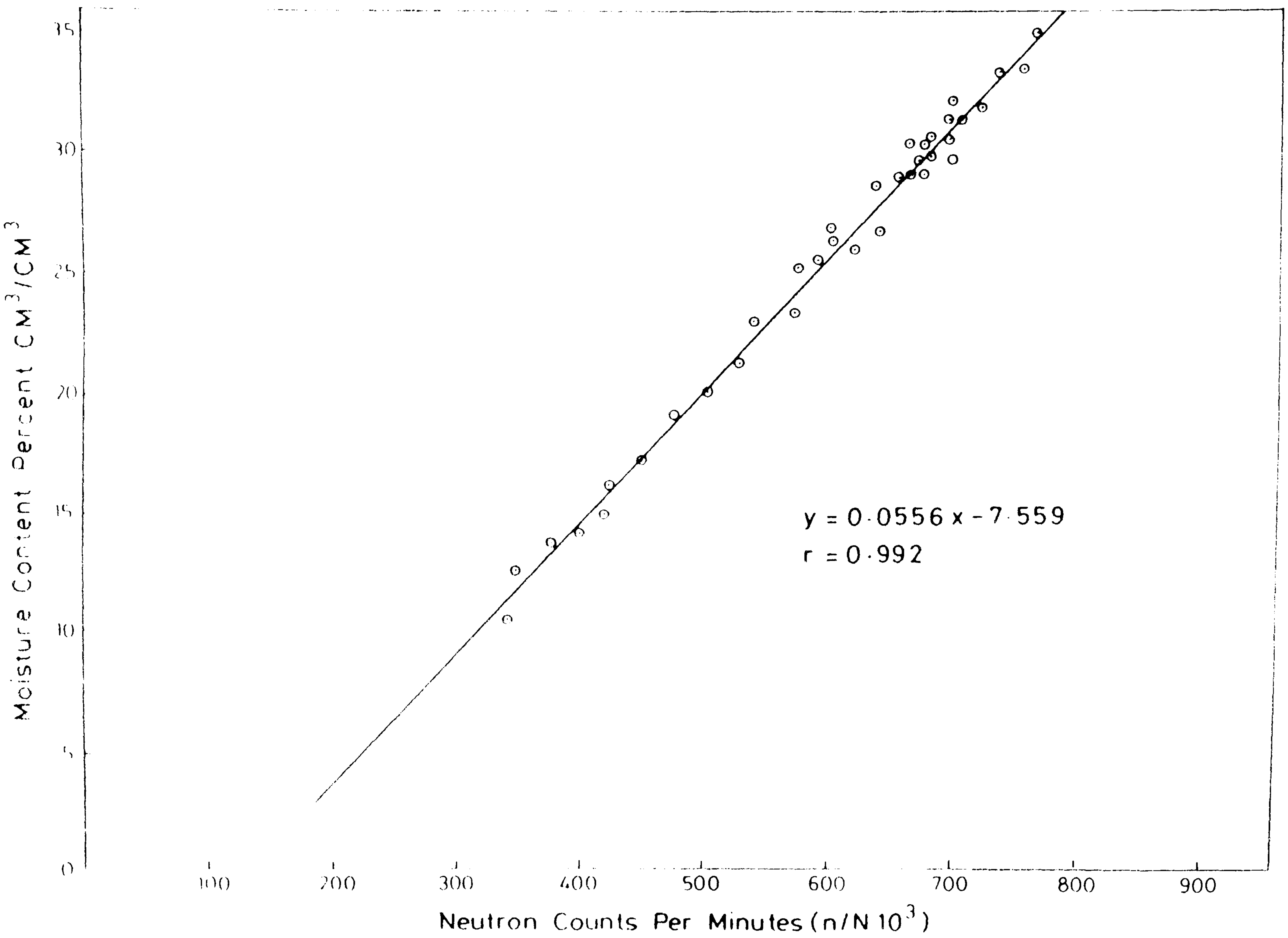


Figure 4·3 Field calibration

Bauel (Refs. 4.4, 4.5) and other workers found it possible to calibrate neutron probe results (in neutron counts per minute) against the moisture values obtained by gravimetric analysis of soil samples from around the probe.

Manufacturers do provide a general calibration curve with each neutron moisture probe, but this may not be accurate in particular soils (where hydrogen sources other than those in the soil water might exist). Thus it is good practice to calibrate a neutron probe for the soil profile in which it is to be used.

This was done by driving the neutron probe's access tube into the undisturbed soil, and it was found that this could easiest be done if the soil were wetted first and then an auger hole a fraction smaller than the access tube's external dimensions were drilled. In this way, a vertical hole and one without air pockets around the aluminium access tube could be achieved.

Calibration then consisted of no more than lowering the probe head down the tube, obtaining neutron counts at each chosen depth and then taking soil samples (adjacent to the tube) at the same chosen depth for a soil moisture analysis. To ensure that all the soil moisture data (from the laboratory and the field studies) was plotted and compared on the same basis, the gravimetric values of moisture content from each soil sample were then converted to volumetric values and the calibration curve obtained (Fig. 4.3). For comparison, the general calibration curve provided by the instrument manufacturers is also shown (Fig. 4.4) and the differences between the two lines are obviously significant.

Neutron probe work was carried out each week on the 4 profile sites from October 1986 to May 1987, and on three separate occasions, the calibration of the probe was rechecked in each profile to check that accurate results were still being obtained. The results of these three recalibrations are given in Table 4.4, and it is noticeable that the errors between the neutron probe predictions of soil moisture content and the actual laboratory values exceed a 2% level only on one occasion. Thus it was assumed that the neutron probe gave acceptably accurate soil moisture predictions against which the tensiometer results could be plotted to see if field derived soil moisture/soil suction curves equivalent to those obtained by the filter paper method could be achieved.

4.4 Field Activities

Daily readings of all tensiometers, gypsum blocks, soil moisture cells and psychrometers were taken along with

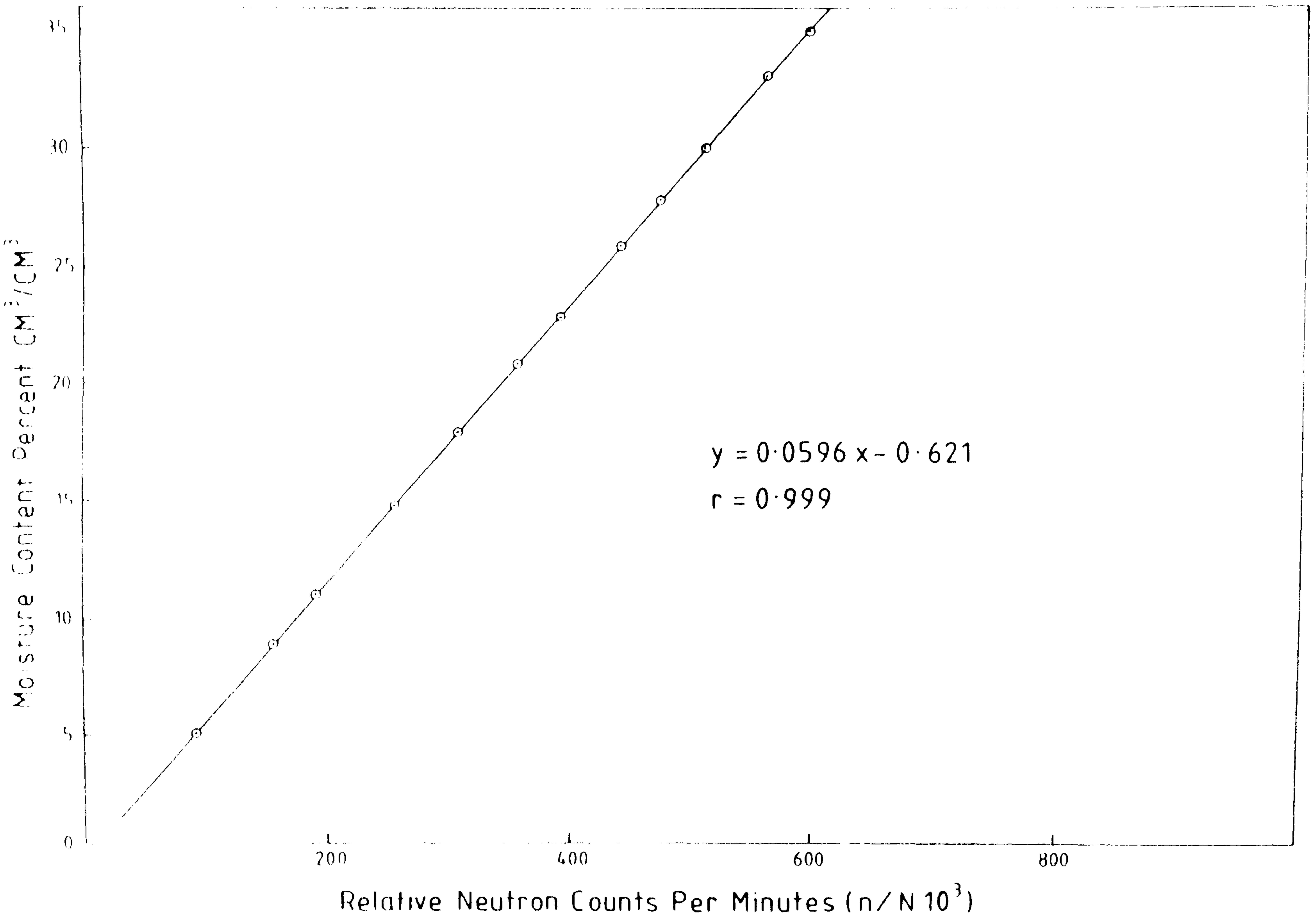


Figure 4·4 Manufacturers calibration

TABLE 4.4

% Moisture Measured	% Moisture Predicted	% Error
8.42	8.14	-3.32
11.60	11.39	+1.81
12.50	12.46	-0.32
13.83	13.53	+2.17
16.35	16.48	+0.79
17.20	17.46	+1.49
18.00	18.26	+1.42
22.90	22.74	+0.70
25.60	25.25	-1.37
27.80	27.79	-0.036
29.00	29.14	+0.48
31.30	31.64	-1.07

groundwater level readings.

If any instrument appeared not to be functioning properly, this was noted, and if the condition persisted, the instrument was withdrawn and replaced with one in known working order. In fact, this proved necessary only in the case of two tensiometers in profile No. 3, where the heavier clay loam at the base of the profile compacted around the instrument tips and broke them.

No interference from the public occurred, largely because access to the King Faisal University Farm is restricted to authorised personnel. This situation does not - of course - apply on the oasis, where a larger population exists and was the reason why no instrumented profiles were installed in the oasis itself.

Climatic data was collected daily by the King Faisal University Farm staff and was available for this work as required.

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CHAPTER FIVE

Tensiometers

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Tensiometers

5.1 Introduction

Tensiometers were the first practical method of measuring soil moisture variations in field conditions, and arose from Buckingham's (Ref. 5.1) pioneer studies of the relationship between moisture content, in a particular soil, and the amount of soil suction* that it could develop.

Prior to Buckingham's work, only the laboratory based method of gravimetrically determining the moisture levels in a sample of a soil had been available. Not only was this a slow and inconvenient process, but it also posed the difficulty that a particular amount of soil moisture could mean very different conditions in different soils. Thus having 15% of moisture in a sand implies large amounts of water easily accessible for plant growth, whilst the same moisture state in a heavy clay marks the onset of plant wilting, since the moisture cannot easily be taken up.

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* (For definitions see Appendix 1)

Buckingham's proof that soil moisture and soil suction are related explained this effect, and also opened the way to measuring soil moisture levels in field conditions, provided that some mechanism to measure soil suction levels could be devised.

Various later workers (Refs. 5.2, 5.3 and 5.4) soon proposed suction measuring devices, which consisted of water filled columns with a porous tip at one end in contact with the soil, and a method of reading suctions in the water filled column at the other. As water was pulled through the porous tip by the drying soil, this left a partial vacuum in the water filled container and so activated the suction measuring system.

These early devices contained all the elements we now recognise as essential for a tensiometer's function (Fig. 5.1), and proved capable of measuring suctions (and so soil moisture contents) from the fully saturated soil state (a zero suction value) to about 900 cm of equivalent water suction head. Readings above about 900 cm of suction cannot be obtained by tensiometers, since the water column at a suction equal to one negative atmosphere develops vapour bubbles, which block and break up the water column between the porous tip and the suction measuring system. This upper measuring limit is a direct function of a basic property of

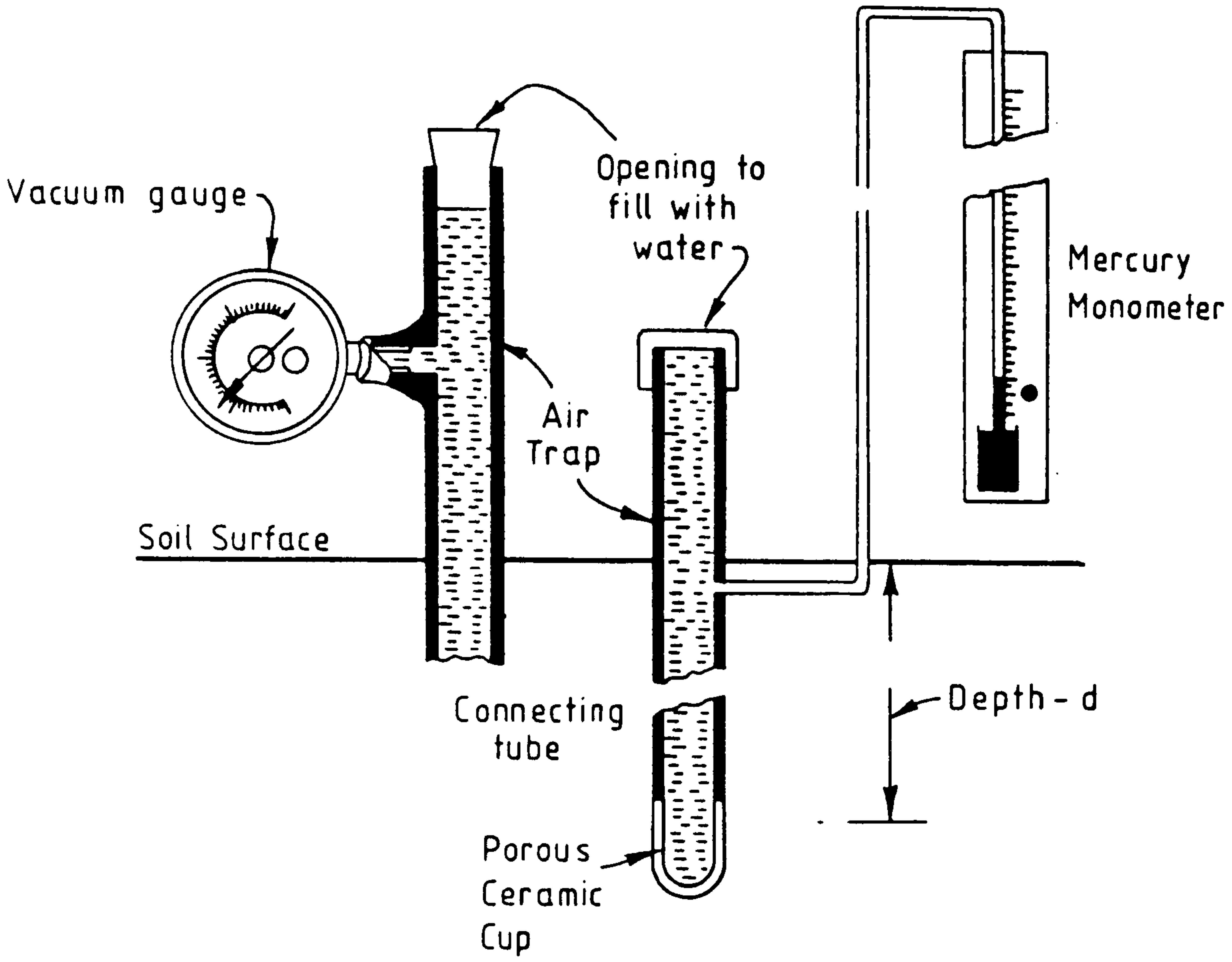


Figure 5·1 Schematic illustration of the essential parts of a Tensiometer

(After S J Richards 1965)

water and is generally termed "cavitation". Since cavitation onset is affected by atmospheric pressure levels, the vapour pressure of water, altitude, and temperature, the effect can occur at suctions as low as 815.8 cm of water, or as high as 917.8 cm of water.

Tensiometers soon spread out of scientific laboratories and were taken up by commercial farmers and irrigation users, where today they are still widespread. In scientific work, tensiometers gradually declined in importance as later devices appeared that have either longer measuring ranges or the ability to produce results as electronic signals that can be stored in data loggers or used to activate computer controllers. (Ref. 5.5).

Although it is true that tensiometers can only have a limited measuring range, it happens (see Chapter 3) that this is the range of interest in Al-Hasa conditions. The criticism that tensiometers have to be manually serviced is no limitation in a society where manual labour is far more abundant than is the ability to service and maintain more complex devices, and the cheapness of tensiometers (£10 or less per unit) does offer the advantage that every farmer can be given a supply from even a moderate irrigation control budget.

Thus, it was decided that a critical evaluation of tensiometers in the Al-Hasa conditions could well be worth while.

5.2 Comparison of Tensiometer Types

Prior to any field trials, it seemed sensible to examine the various tensiometer types that exist to see which have advantages for the Al-Hasa situation.

Apart from minor geometrical variations and shape changes, the more important variations lie in

(a) the methods employed to measure the partial vacuum in the water column core of the tensiometer

and

(b) the type and size of porous tip placed in contact with the soil whose moisture state is to be monitored.

5.2(a) Variations in Methods of Measuring Tensiometers Suction Levels

Simple vacuum gauges of the Bourdon type (Fig. 5.2) are the

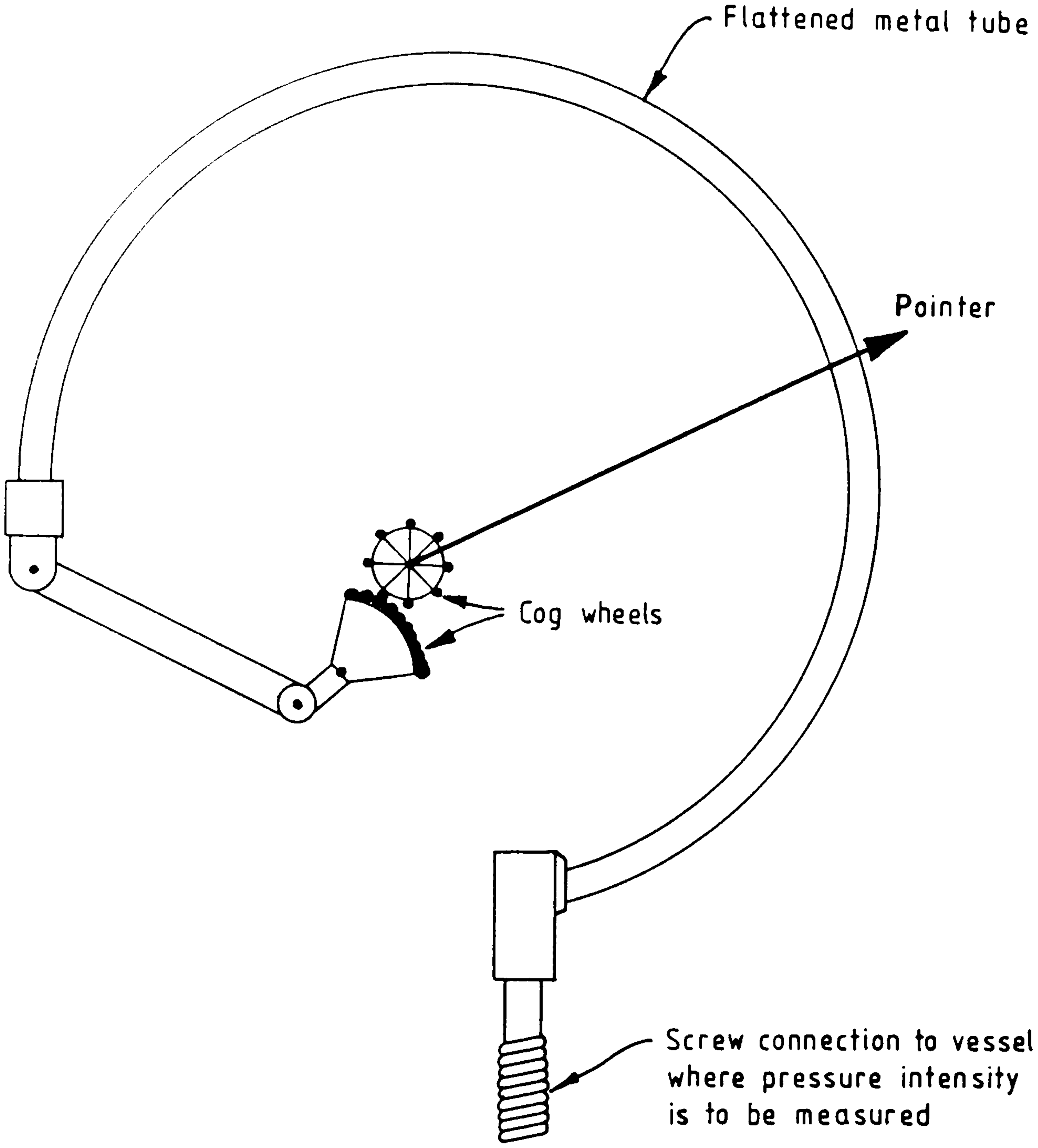
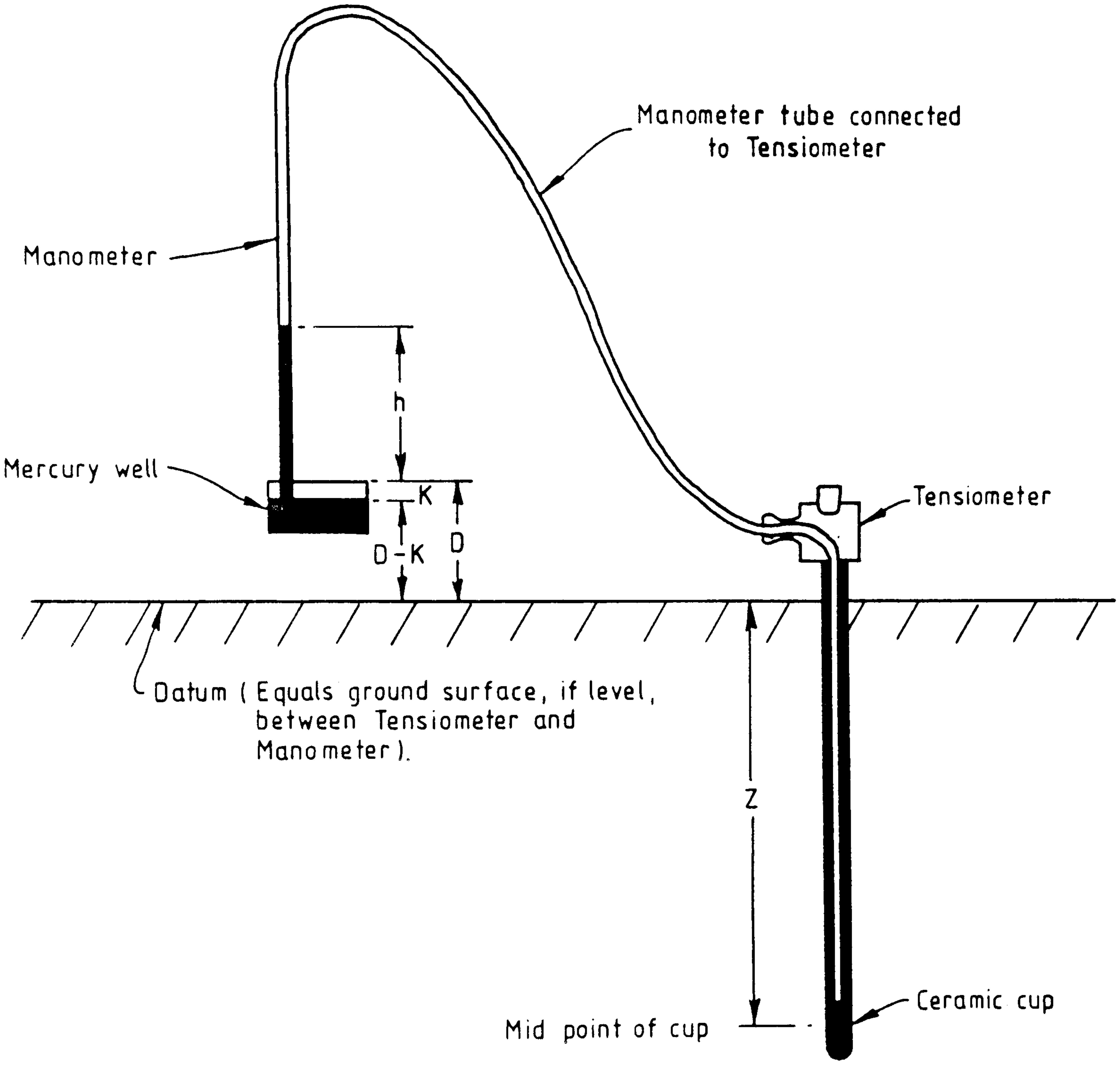


Figure 5·2 Internal parts of a Bourdon (dial) gauge commonest suction measuring devices, but these exist in a variety of forms and costs. The cheapest (retailing at about £3.00 per unit) have non-air tight steel cases and the working parts are thus potentially susceptible to rust and other damage. More expensive sealed gauges of the type usually employed on commercially available tensiometers cost about £10.00 each, and the most expensive type (£30.00 or more) has an internal filling of glycerine to lubricate the working parts and prevent external climatic damage.

Additionally, mercury filled manometers have been widely used in scientific studies (Fig. 5.3), and recently electronic suction transducers have grown in popularity as they produce results that may be stored electronically.

The implications of the published literature are that vacuum gauges are less accurate than are mercury manometers, and that electronic transducers have superceded all earlier suction measuring systems.

To evaluate this, a variety of suction measuring systems was built on to exactly the same tensiometer bodies to determine which had a reasonable measuring accuracy and whether this accuracy would be degraded with length of exposure to the Al-Hasa soil and climatic conditions. Thus 10 different tensiometers (Table 5.1) were tested.



$$\text{Suction} = [Z + (D-K)] - [12{\cdot}6\,(h+K)]$$

Figure 5·3

TABLE 5.1

Details of the Tensiometers Tested

Tensiometers	Suction Measuring Device	Comments
Nos. 1 & 2	Simple Bourdon gauge without air tight seal	Cheapest Boudon gauge available
Nos. 3 & 4	Bourdon gauge with rubber seal over gauge body	Type used in American commercial tensiometers
Nos. 5 & 6	Glycerine filled Bourdon gauge	Most expensive Bourdon gauge available
Nos. 7 & 8	Mercury U-tube manometer	Constructed in-house
Nos. 9 & 10	Electronic suction transducer	

Prior to any experimental use in soils, each had its suction measuring device checked and recalibrated. In the case of the Bourdon gauges (Nos. 1 to 6) this was done with the mercury manometer board shown on Plate 3.1. The transducer gauges were checked by a mercury filled hanging pot system.

After the suction systems were checked, each tensiometer was checked as a unit to ensure that all joints were vacuum tight and that no leakages had developed. The apparatus specially developed for this purpose is shown on Plate 5.1.

To test the tensiometers in soils called for some method of producing a known suction on the soil samples, against which the accuracy of the various tensiometers could be compared. After consideration of various options, the sand box method, developed by Van der Harts and Stackman (Ref. 5.6) and used by several other workers (Refs. 5.7, 5.8 and 5.9) was selected, since this had the very real advantages of simplicity, and of the imposed suction being easily and directly measured.

The sand box that was used was built in a ceramic sink (17cm high, 32 cm wide and 42 cm long), in the bottom of which a slotted u-PVC drainage pipe system was laid. Above the pipes was placed a 1 cm thick sand drainage layer (particles from 600 to 2,000um), and above that was a layer of 7 cm of coarse silt (particles from 20 to 60um). Prior to emplacing

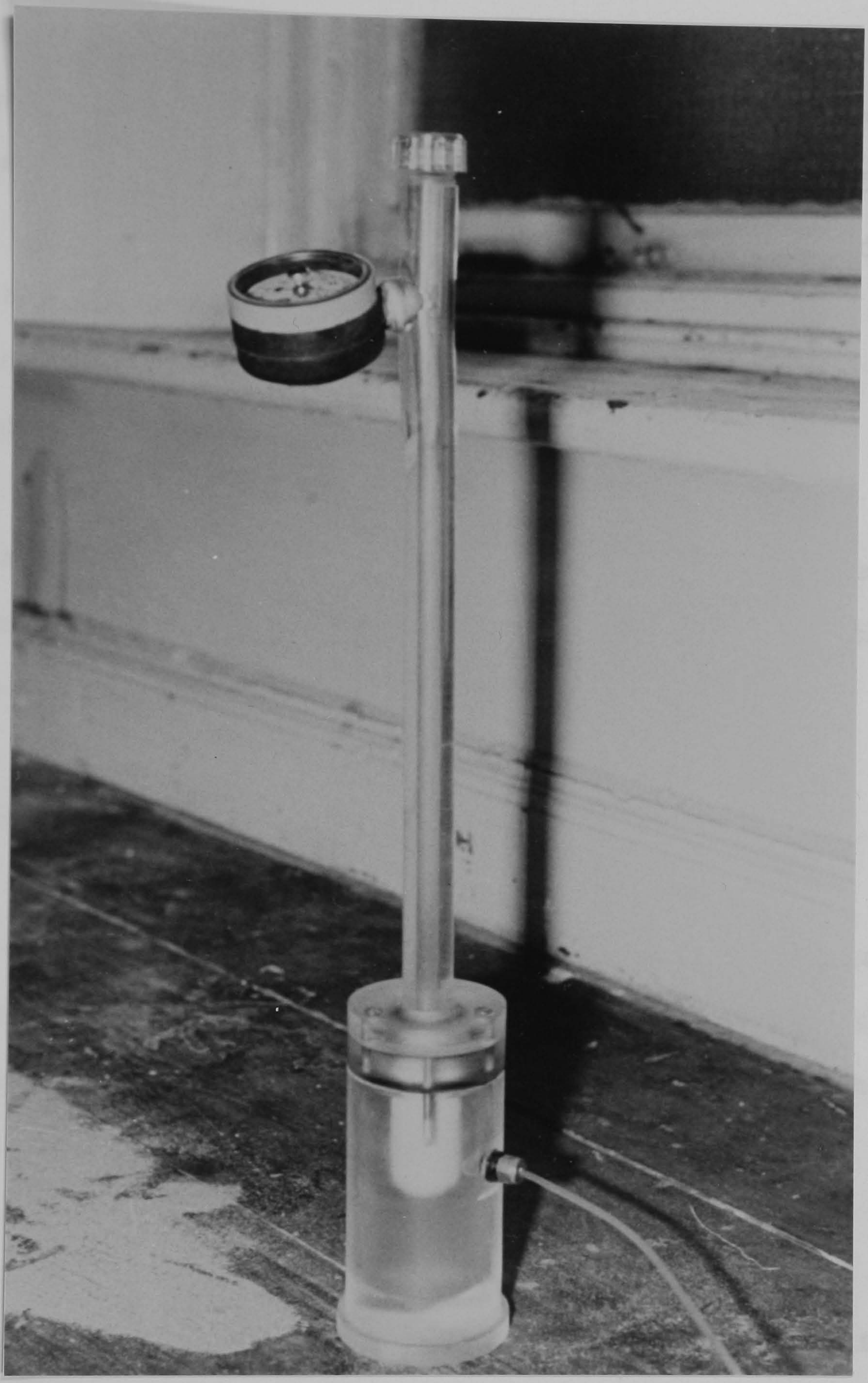


Plate 5.1 Apparatus for Checking Tensiometers as Complete Units

the sand and silt layers, the walls of the sink had been plastered with a kaolin/water paste, and this was carried over the top of the silt layer to give a (hopefully) air tight seal to prevent atmospheric air being pulled into the sand box (along the interface of the sink walls and the filling materials) when it was being operated in below atmospheric conditions.

The sand and silt layers had, of course, been de-aired by progressive flooding from the sink base before the kaolin top seal was trowelled on.

A cross-section of the sand box is shown in Fig. 5.4.

When the sand box was completed, u-PVC rings (each 10 cm high and 8 cm in diameter) were placed onto the kaolin top seal and packed with two soils (see Table 5.2) that typify the extremes of the Al-Hasa soil types. The soils (at field capacity moisture levels) were packed to the same densities as occur in the field, and each ring proved large enough to allow up to 5 tensiometers to be installed in the soil. (Plate 5.2).

In practice, the sand box proved to be a little disappointing in that suctions of only 500 cm of water head were achieved instead of the desired 850 to 900 cm levels. Despite this, the device did give accurate repeatable

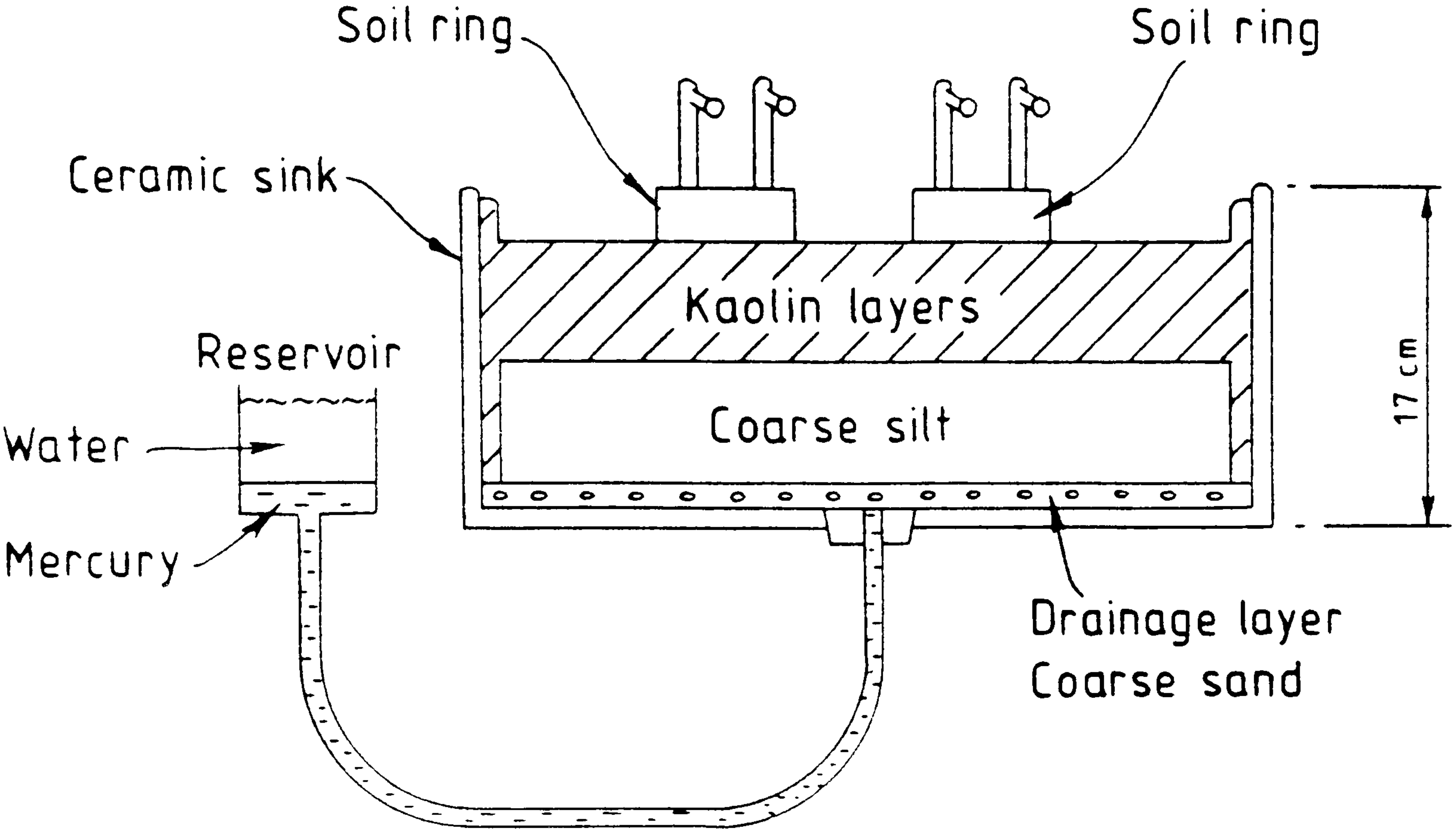


Figure 5·4 Sand box details

TABLE 5.2

Particle Size Distribution of the Soils Used in the Sand Box Experiment Compared to the Surface Layers of the Soils in the Al-Hasa profile pits

Soil Type	% Sand	% Silt	% Clay	% Organic
Sand Box Soils				
Blown dune sand	99.90	0.05	0.03	0.00
Sandy clay	61.00	23.00	16.00	5.90
Al-Hasa Profiles				
Surface dune sand (Profile No. 1)	93.00	5.00	1.00	1.00
Sandy Loam (Profile No. 2)	55.00	39.60	1.00	4.40
Sandy Loam	56.00	39.60	1.70	2.50

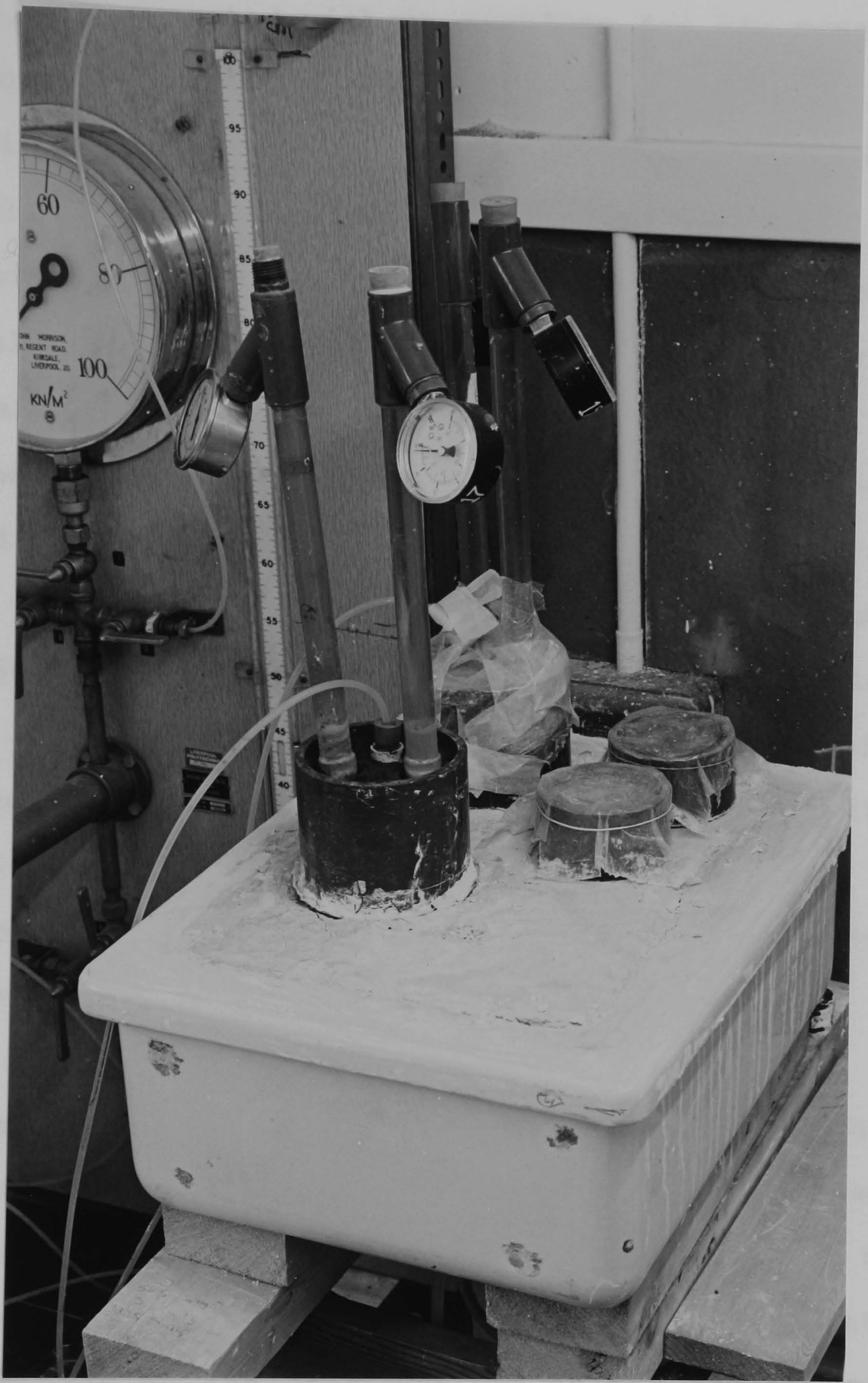


Plate 5.2   Tensiometers Under Test on Sand Box

results, and operated without problems for six months. The operational method was to initially expose the sand box to a very slight positive head by levelling the water reservoir a few millimeters above the top of the kaolin seal. Then the reservoir was lowered to a particular level and held there until all the tensiometers developed equilibrium readings. In general this took 96 hours to achieve, since drainage from the soil samples through the underlying extremely fine grained kaolin seal proved to be very slow indeed. (Ref. 5.10). By progressively repeating this process, suctions of up to 500 cm of water head were achieved before minute air bubbles (drawn from the atmosphere past the kaolin seal) appeared in the tube leading to the water reservoir. When such air appeared, the experiment was terminated and the sand box progressively reflooded over a one week period to flush out air locks.

Considerable effort was made to improve the atmospheric seal in the sand box and so allow higher suctions to be achieved, but without success, as other workers (Ref. 5.8) had also experienced. Ultimately the alternations of negative and positive head on the sand box led to the kaolin seal layer becoming detached from the drainage silt layer (Plate 5.3) and the experimental rig was abandoned.

The results of the sand box experiments are shown in Figs. 5.5 to 5.14 and may be summarised as follows:-

Plate 5.3 Separation of Kaolin Seal from the Sand Box Materials due to Alternating Negative and Positive Heads

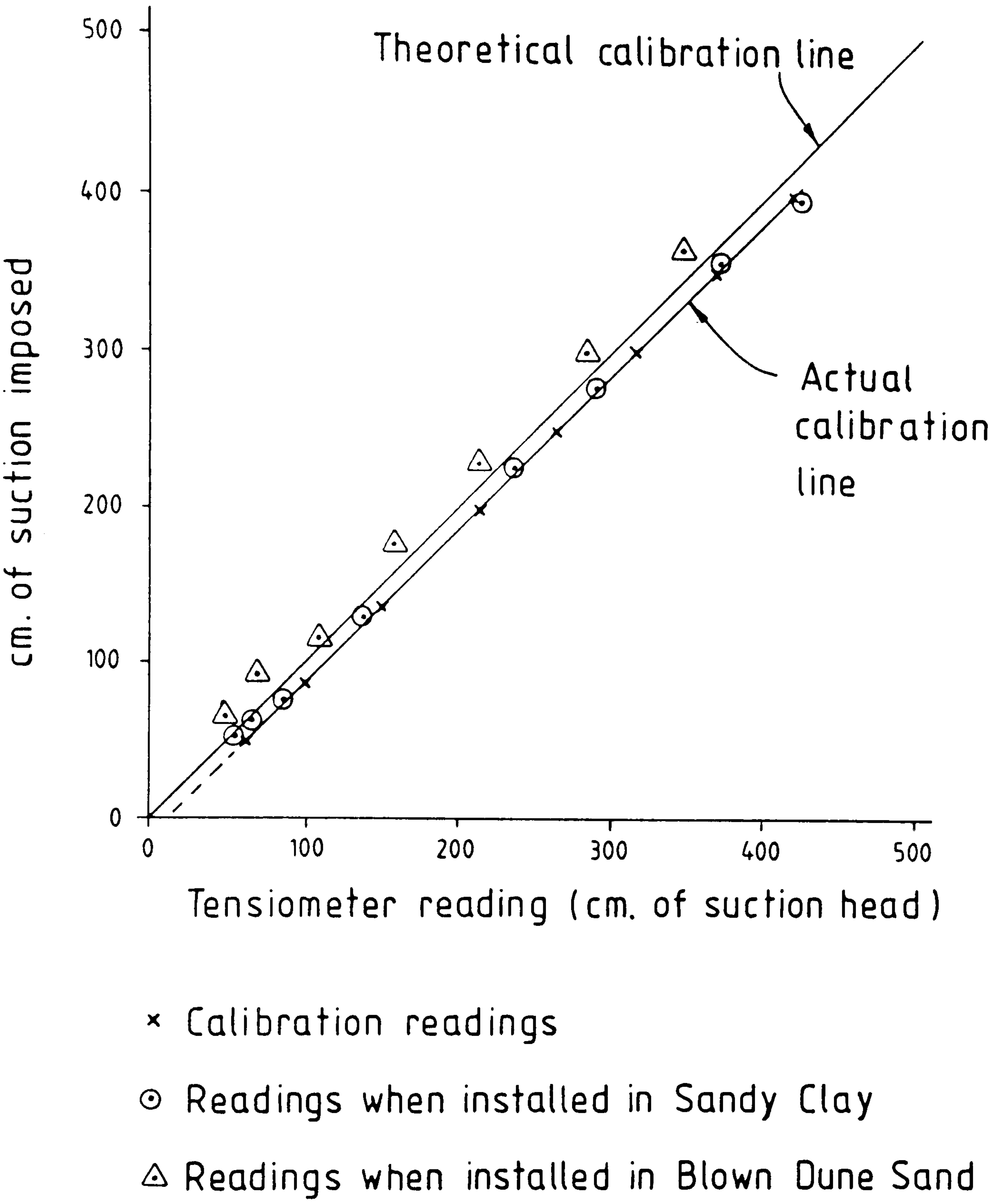


Figure 5·5 Accuracy of Tensiometer No. 1

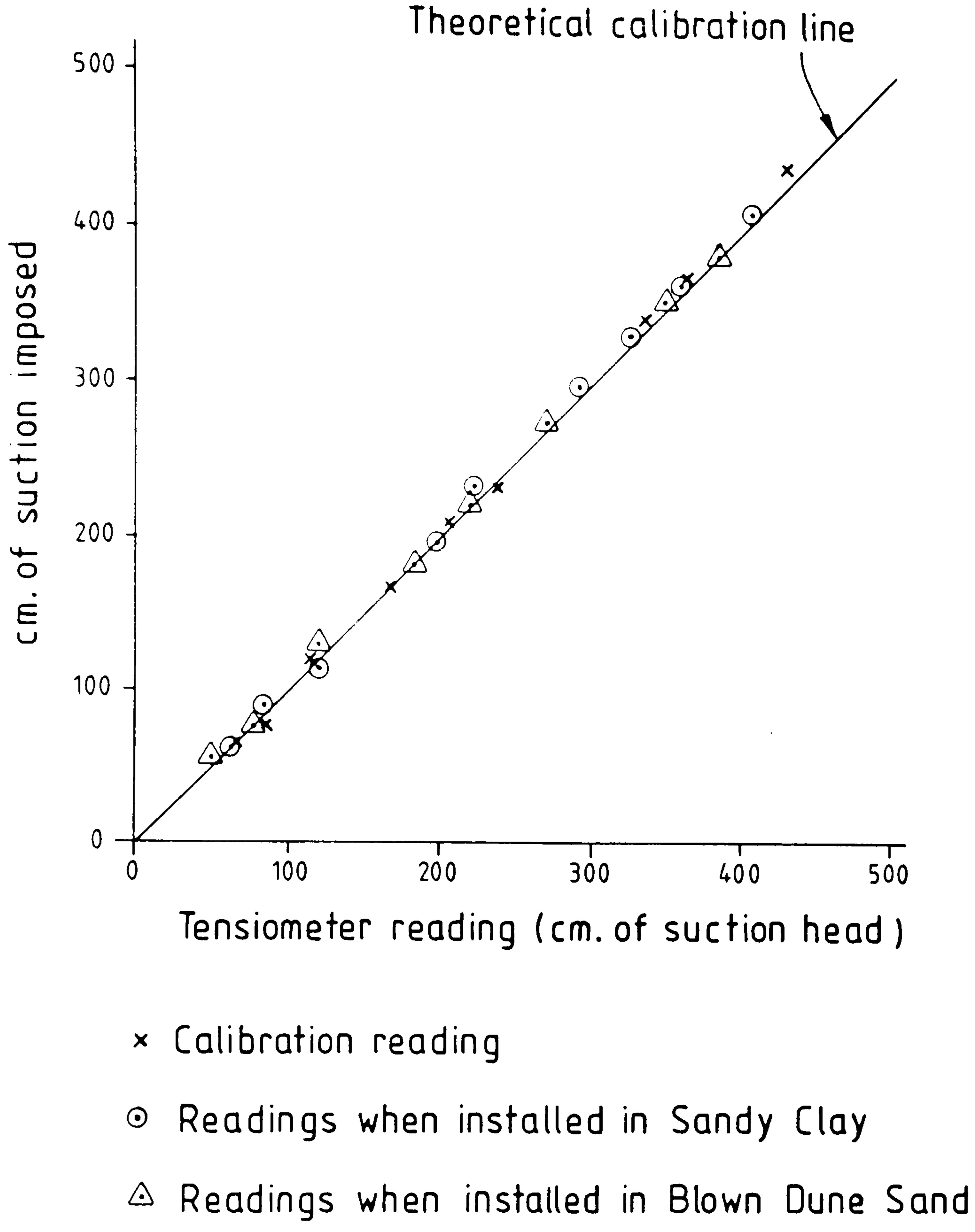


Figure 5·6 Accuracy of Tensiometer No. 2

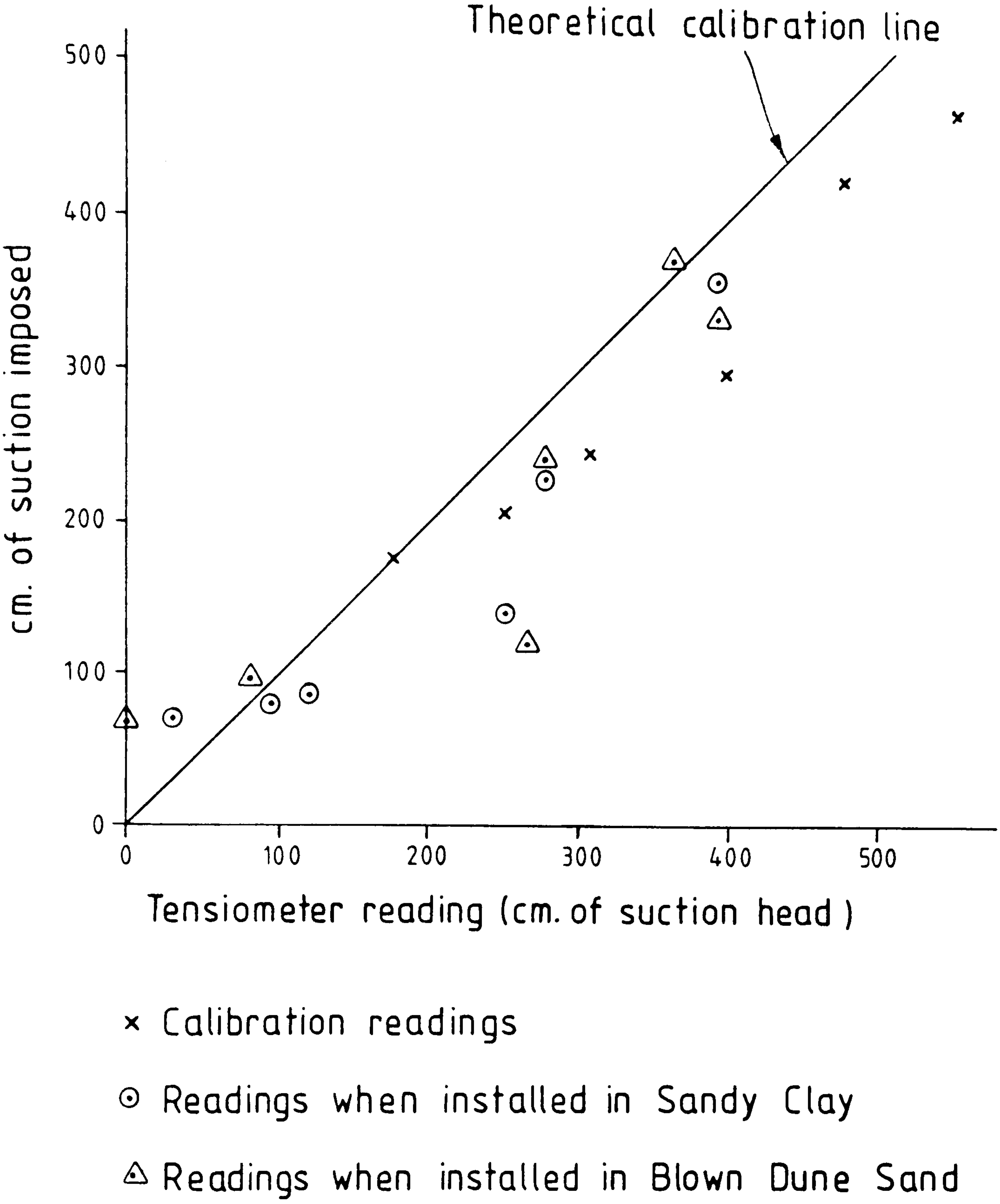


Figure 5·7 Accuracy of Tensiometer No. 3

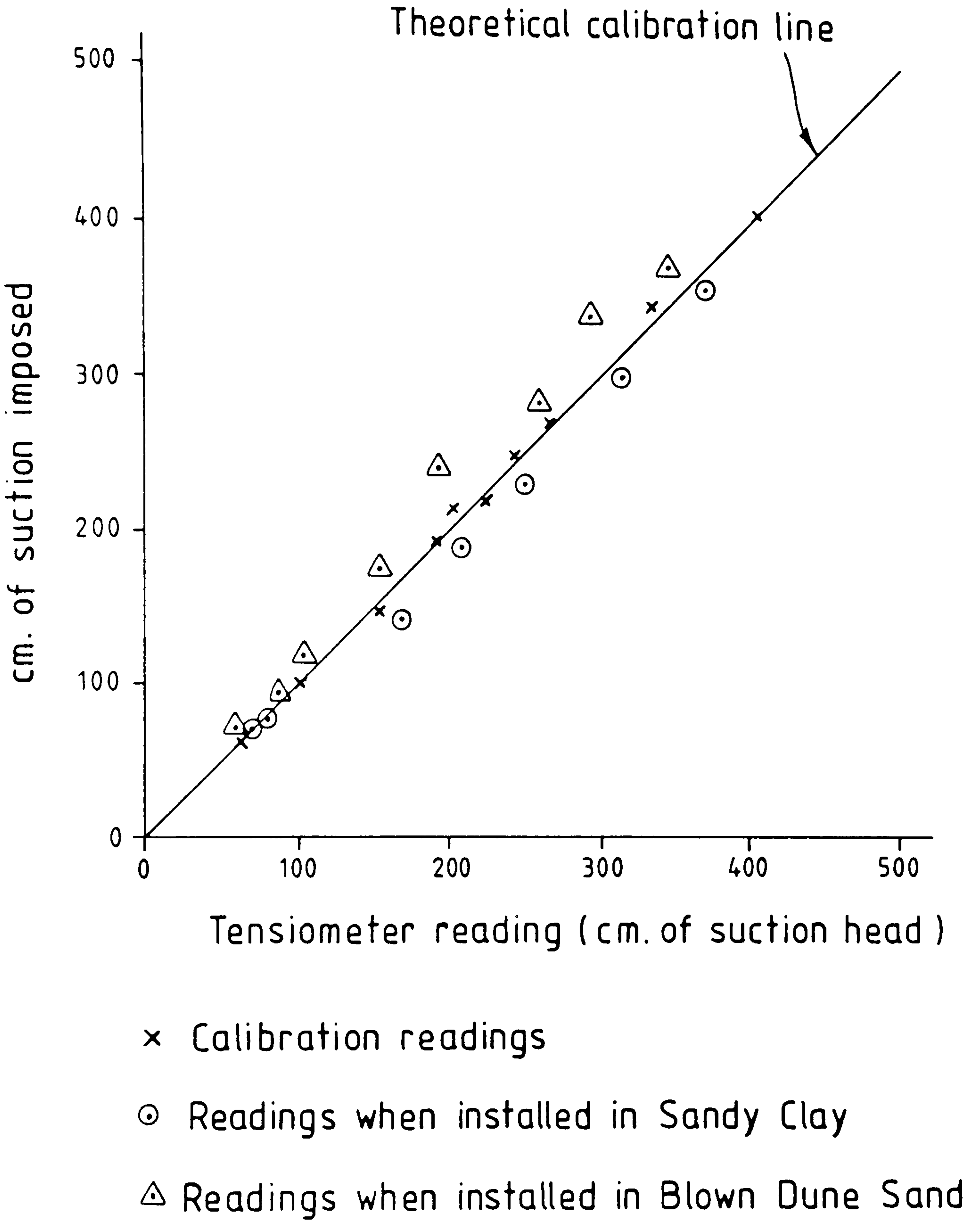


Figure 5·8 Accuracy of Tensiometer No. 4

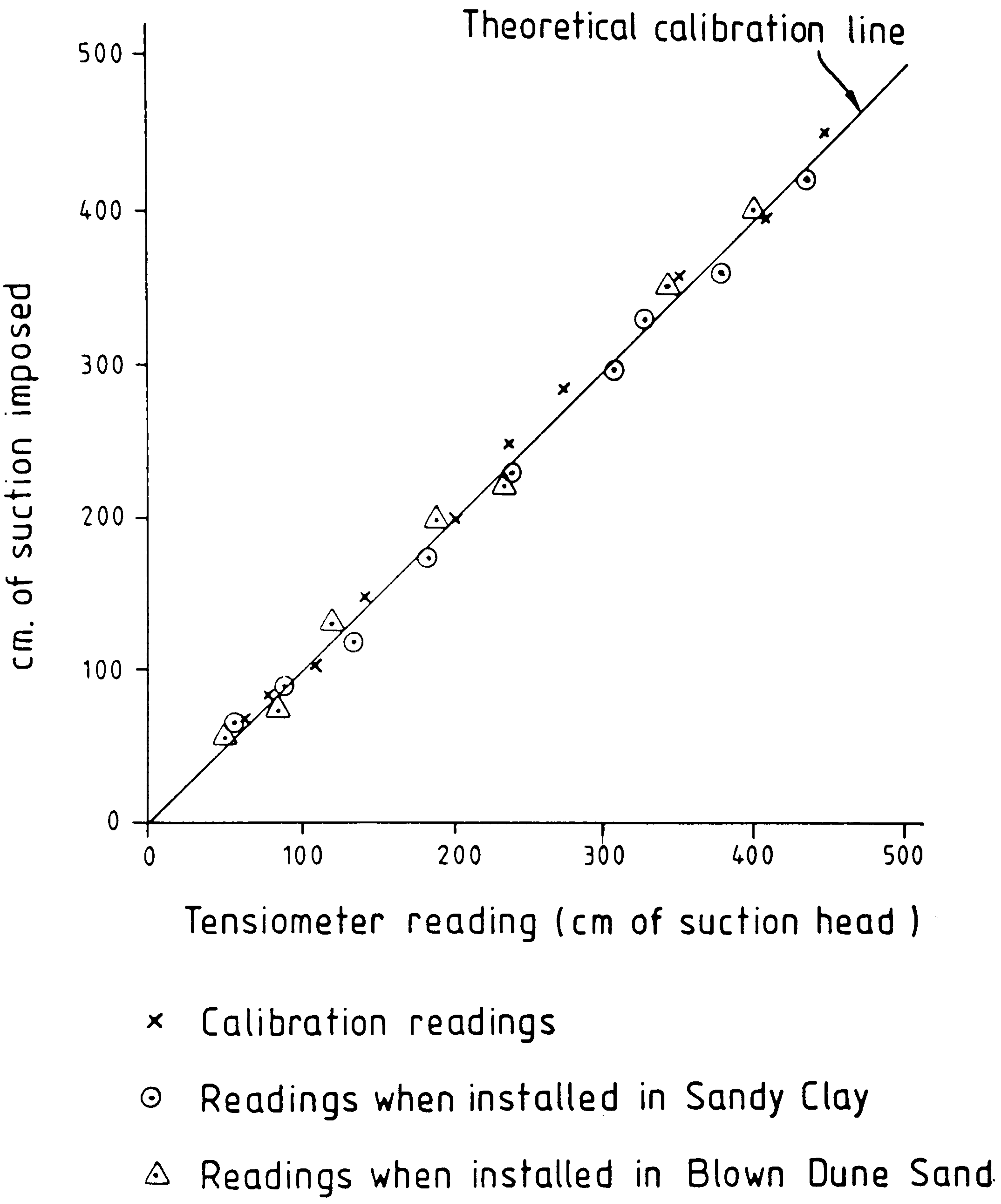


Figure 5·9 Accuracy of tensiometer No. 5

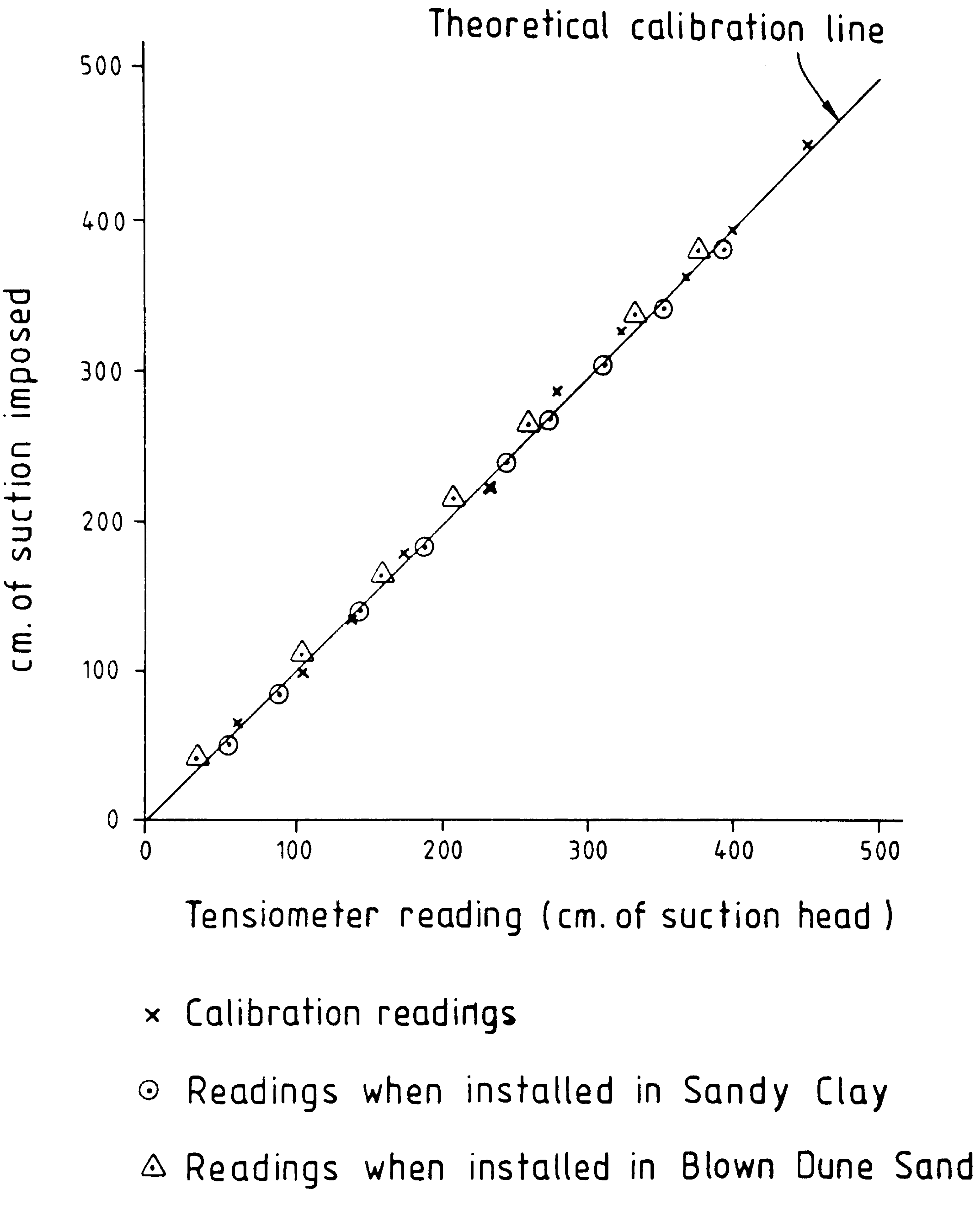
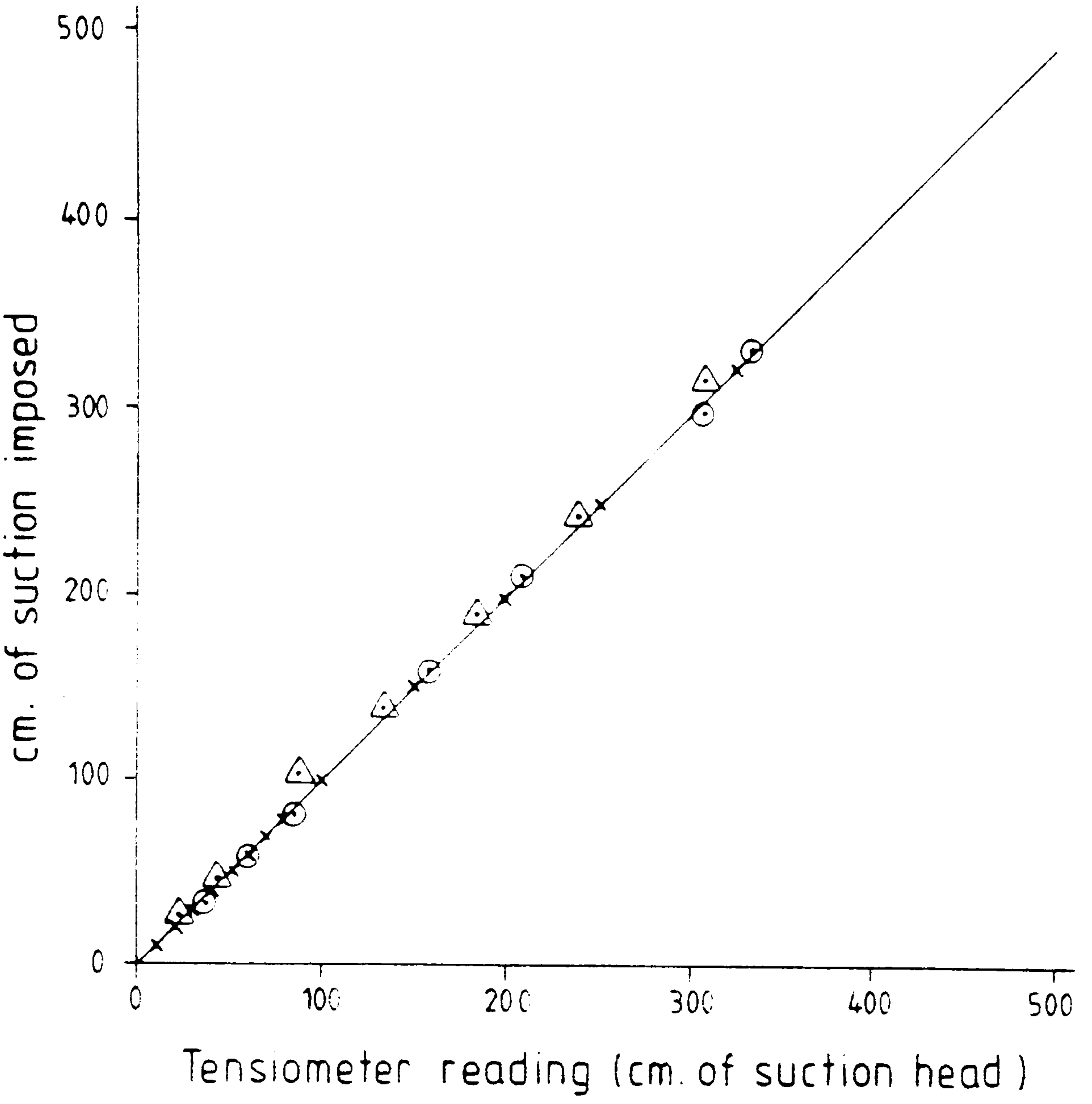


Figure 5·10 Accuracy of Tensiometer No. 6



× Calibration reading

⊙ Readings when installed in Sandy Clay

△ Readings when installed in Blown Dune Sand

Figure 5·11 Accuracy of Tensiometer No.7

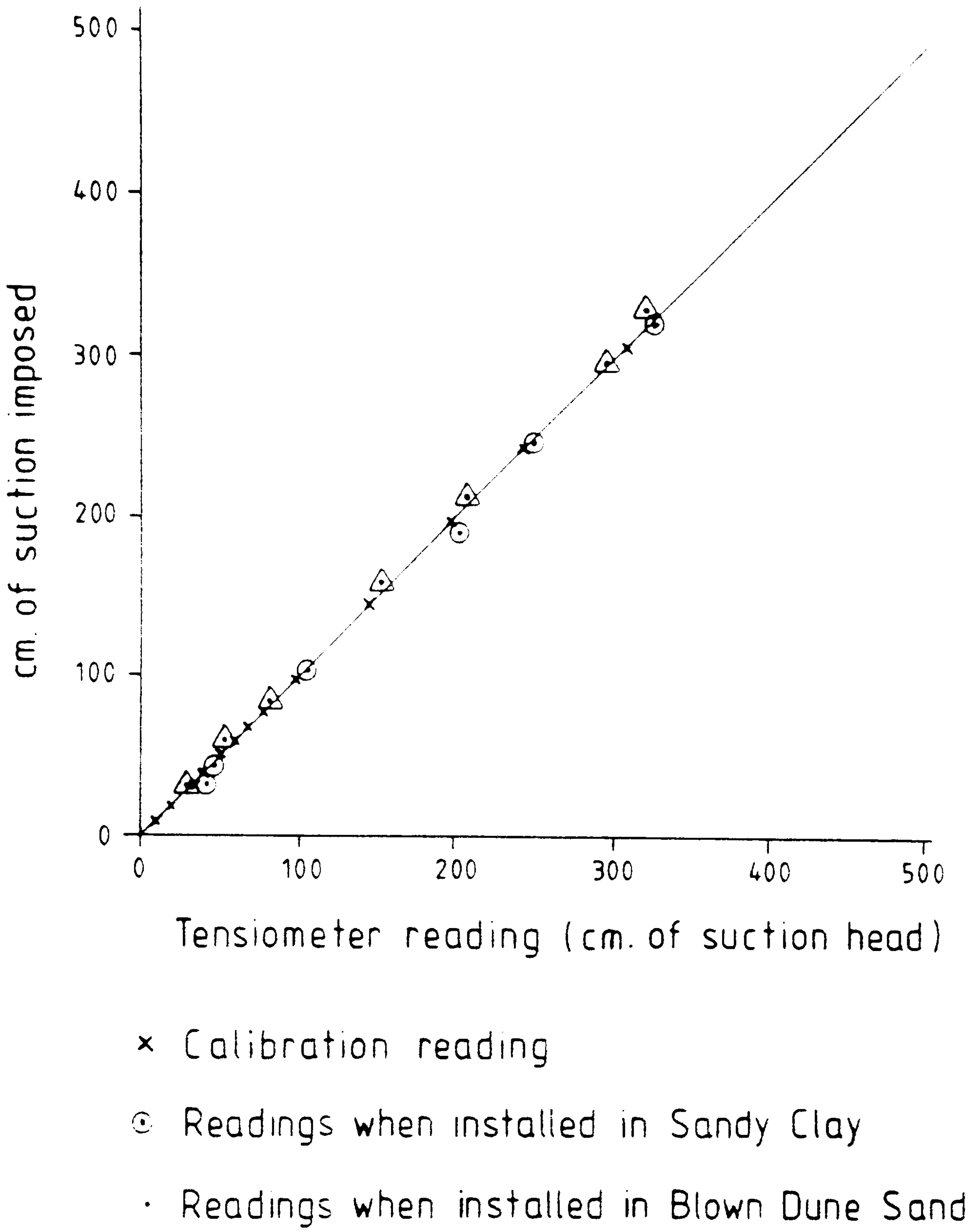


Figure 5·12 Accuracy of Tensiometer No. 8

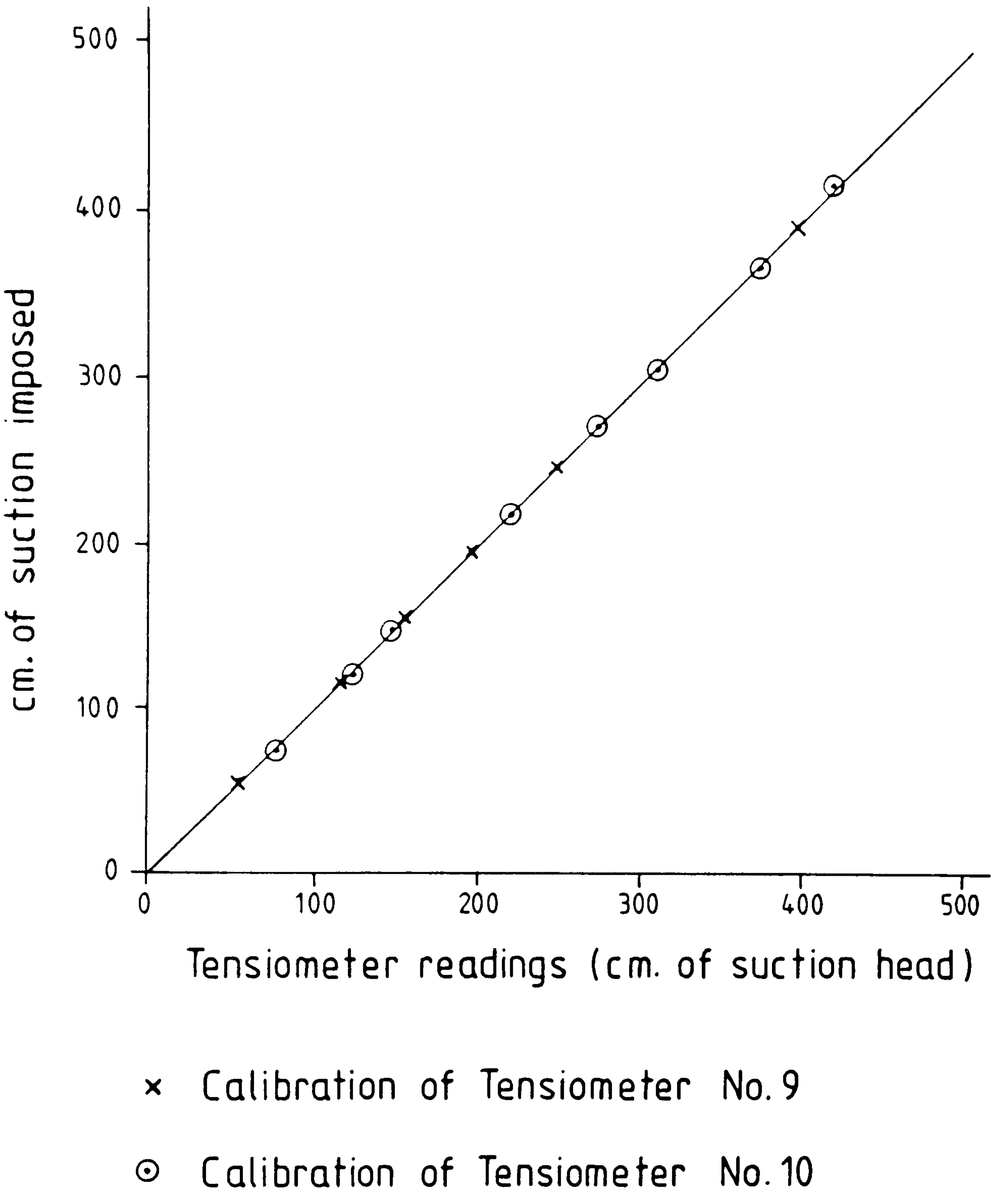


Figure 5·13 Calibration of Tensiometers Nos 9 & 10

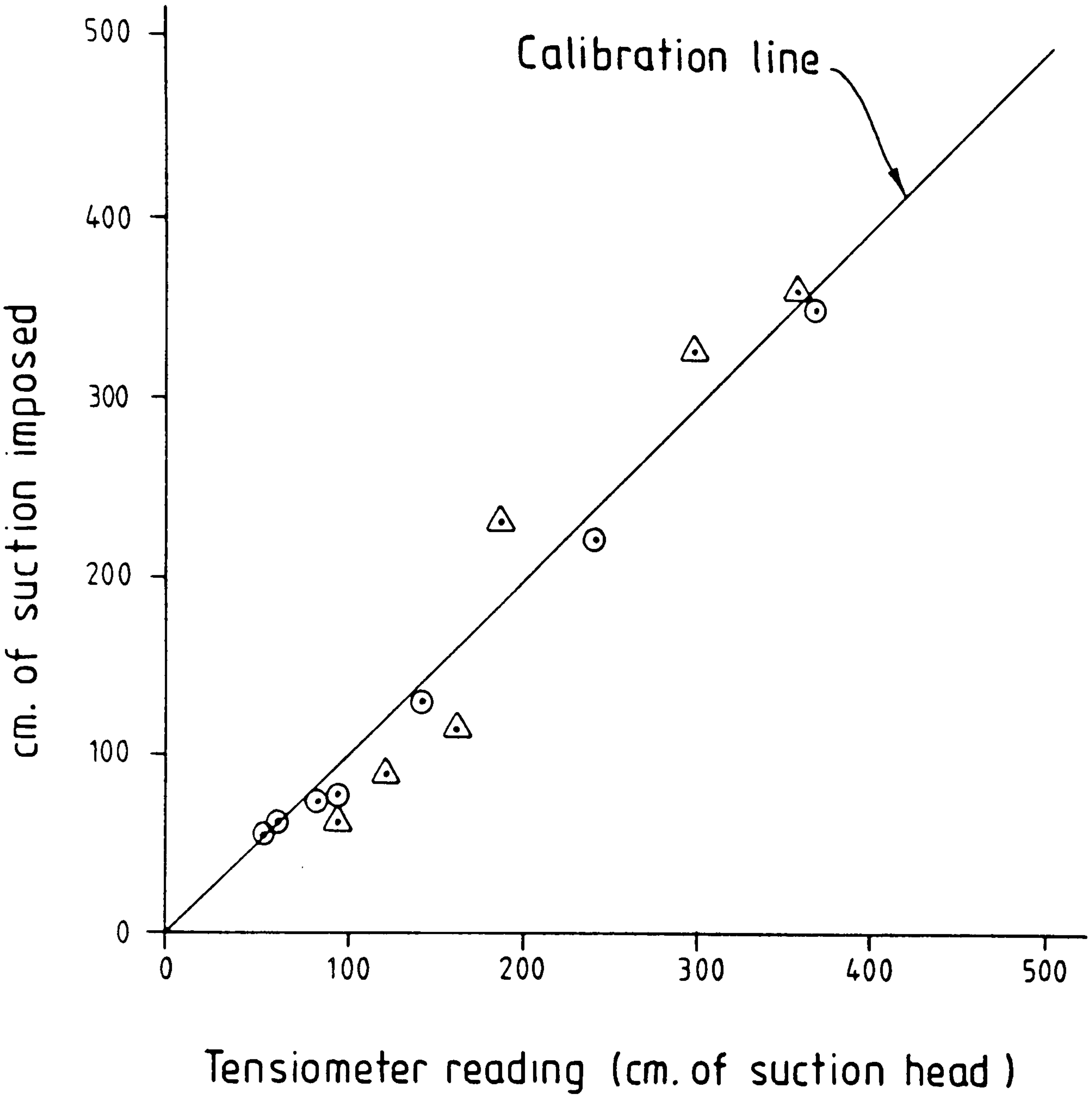


Figure 5·14 Initial testing of tensiometer No. 9

(a) the cheapest Bourdon gauges (see Fig. 5.6) could produce remarkably accurate results; where errors did occur these seem to be due to factory mis-zeroing of the gauges (Fig. 5.5)

(b) the rubber cased gauges used in commercial tensiometers could be extremely inaccurate (Fig. 5.7) or - at best - of mediocre accuracy (Fig. 5.8)

(c) mercury manometers were as accurate as expected and were able to read very low suctions much more accurately (to ±1%) than could any Bourdon gauge. This is of course unsurprising, since the internal friction of a gauge's working parts can only be overcome once enough force is exerted, thus errors at very low suctions (of 100 cm or less) are to be expected

(d) the pressure transducers (Plate 5.4) were precisely accurate in calibration, (Fig. 5.13), but gave grossly inaccurate results in the sand box trials. Further work revealed that this was due to the transducers being temperature sensitive, (see Table 5.3) and reacting to daily temperature variations in the laboratory. Obviously this would not be a positive attribute in the Al-Hasa conditions, and -

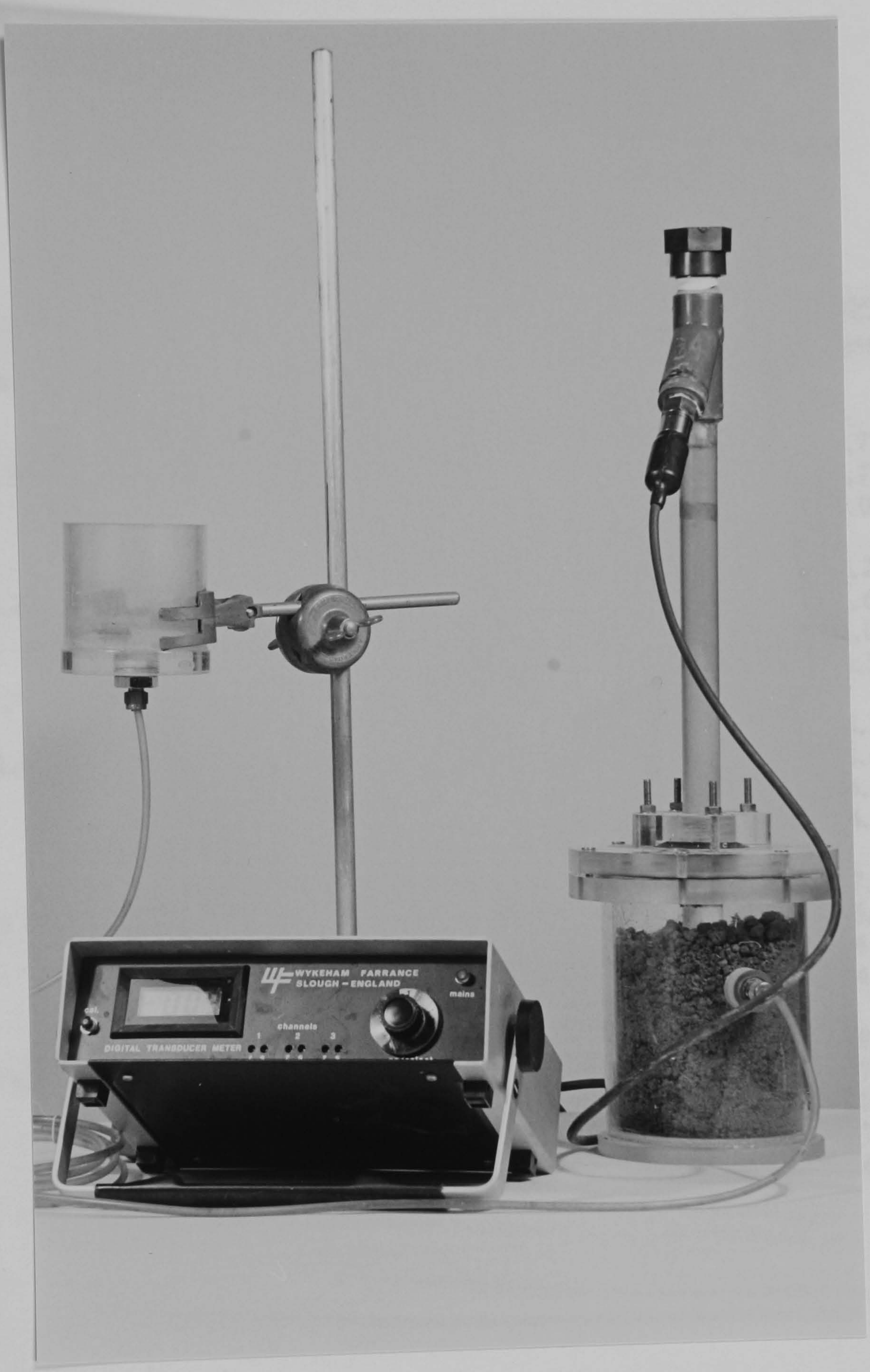


Plate 5.4 Pressure Transducer

TABLE 5.3

Monitoring Tensiometer No. 9's Response to Air Temperatures

Imposed Suction (cm)	Tensiometer Reading (cm)	Air Temperature (O°C)
56.31	51.82	15.7
	55.27	14.7
	56.99	14.0
64.25	54.92	17.2
	62.18	15.6
	65.29	15.0
	72.54	14.5
132.30	134.72	16.1
	137.83	15.4
	144.05	14.8
	145.08	14.6
225.92	239.39	17.0
	241.46	16.1
	245.26	14.6
	252.86	14.0
373.08	351.31	18.1
	354.42	17.7
	355.80	17.1
	367.89	17.0
	393.80	16.8

though avoidable by some sort of temperature shielding - would introduce additional unacceptable complexity.

Whilst no statistic conclusions are possible (because of the small population of each type tested and because the total population of each type from which the two tested examples were taken varied considerably), it does appear that cheap Boudon gauges can be acceptably accurate provided that each is thoroughly calibrated prior to field use. The low unit costs of these cheap gauges is such that repair and maintenance is quite sub-economic and so the gauges have to be seen as disposable items of limited life.

The more expensive gauges appear to offer no real advantages to off-set their initially higher costs, and the mercury manometer system is far too delicate for field use. The transducer systems - as mentioned above - are initially very expensive (when the transducer and the read-out unit costs are considered) and too sensitive to temperature variations.

Thus these initial results favour the adoption of the cheapest Bourdon gauges in Al-Hasa tensiometers.

5.2(b) Anticipated Life of the Cheap Bourdon Gauges

As part of another worker's (Ref 5.11) research 35 of the cheap gauges had been installed on tensiometers in the hot ($29^{o}C$ to $8^{o}C$ over winter and early summer of 1986) and humid conditions of a tunnel house experiment, that lasted for 10 months. The gauges were checked and calibrated prior to being placed in the tunnel house, and then their continued accuracy was deliberately ignored until the end of the experiment. When the work ended, the gauges were recalibrated, and 22 were found to give readings that were 10% or more inaccurate. These errors were most apparent in the lower suction ranges and typically caused gauges to under read the imposed suction value. Stripping of the gauges (Plate 5.5) showed visible corrosion due to the hot humid conditions.

Whilst this initial investigation cast real doubt on the practicality of using cheap gauges without an air-tight seal in Al-Hasa, it had been noticeable that the tunnel house atmosphere was extremely humid (due to the necessary watering of crop experiments) and this is not the case in Al-Hasa. Thus it was decided to risk using 33 of the cheap gauges in the 8 month Al-Hasa field trials (Chapter 4). These gauges - on recalibration after the trials ended - in fact proved to be invariably accurate. No inaccuracies above ±5% were found, and in 90% of the gauges the measured errors did not exceed ±3%. When stripped down, all the gauges did show that atmospheric dust had entered their working parts and that some surface scratching had occurred,

Plate 5.5 Corrosion of Gauge Working Parts

but no rusting or corrosion was visible.

The conclusion from this, is that the cheap gauges can last for a single growing season in Al-Hasa and remain acceptably accurate. Since the gauges are seen as disposable stock, to be disposed of once inaccurate, and since annual recalibration would have to take place if irrigation usage is to be accurately controlled, a usable life of one growing season does seem acceptable and the use of the cheap Bourdon gauges is recommended.

5.2(c) Tensiometer Tip Characteristics

Obviously the tip of a tensiometer is a crucial element of the device. It has to allow water to pass through at an acceptably high rate (i.e. a high water conductance, to give a sensitive response to any change in moisture state of the surrounding soils) and has to prevent atmospheric air entering the sub-atmospheric core of the tensiometer.

Commercially, tensiometer tips are manufactured by relatively few companies, and most guarantee their tips, as able to prevent air entry up to a suction of minus one atmosphere. Since it is unlikely that any local manufacture of tips could ever occur at Al-Hasa, where the raw materials do not exist, it was decided to make use of the commercially available varieties and (since these all have similar conductance rates of about 8ml/minute, for each atmosphere change in suction) to consider whether or not the dimensions of the porous tip made any real difference to the accuracy and sensitivity of a tensiometer.

Tensiometer tips are available in a wide range of sizes and geometrical shapes, but the commonest are cylindrical and are either of the "normal" type (8.89 cm long, 1.60 cm internal diameter), or of the "micro" variety (2.3 cm long, 0.675 cm internal diameter). Both these types were evaluated.

In the sand box, where only the "normal" tips were used, no real response times to changes to imposed suction could be determined, since the moisture movement from the soil samples was controlled by the very low hydraulic conductivity of the kaolin seal material. To overcome this limitation, another special soil cell (Fig. 5.15) was built and filled with the two test soils at their field capacity moisture levels and field density values. This gave suction/soil moisture curves of the type shown in Fig. 5.16 and response times (to imposed suction changes) of between 0.50 minutes (at 50 cm suction) to 6.00 minutes (at 447 cm suctions). These response times are obviously as good as could be wanted, though they do - of course - relate to only the small soil sample that the test cell could contain and

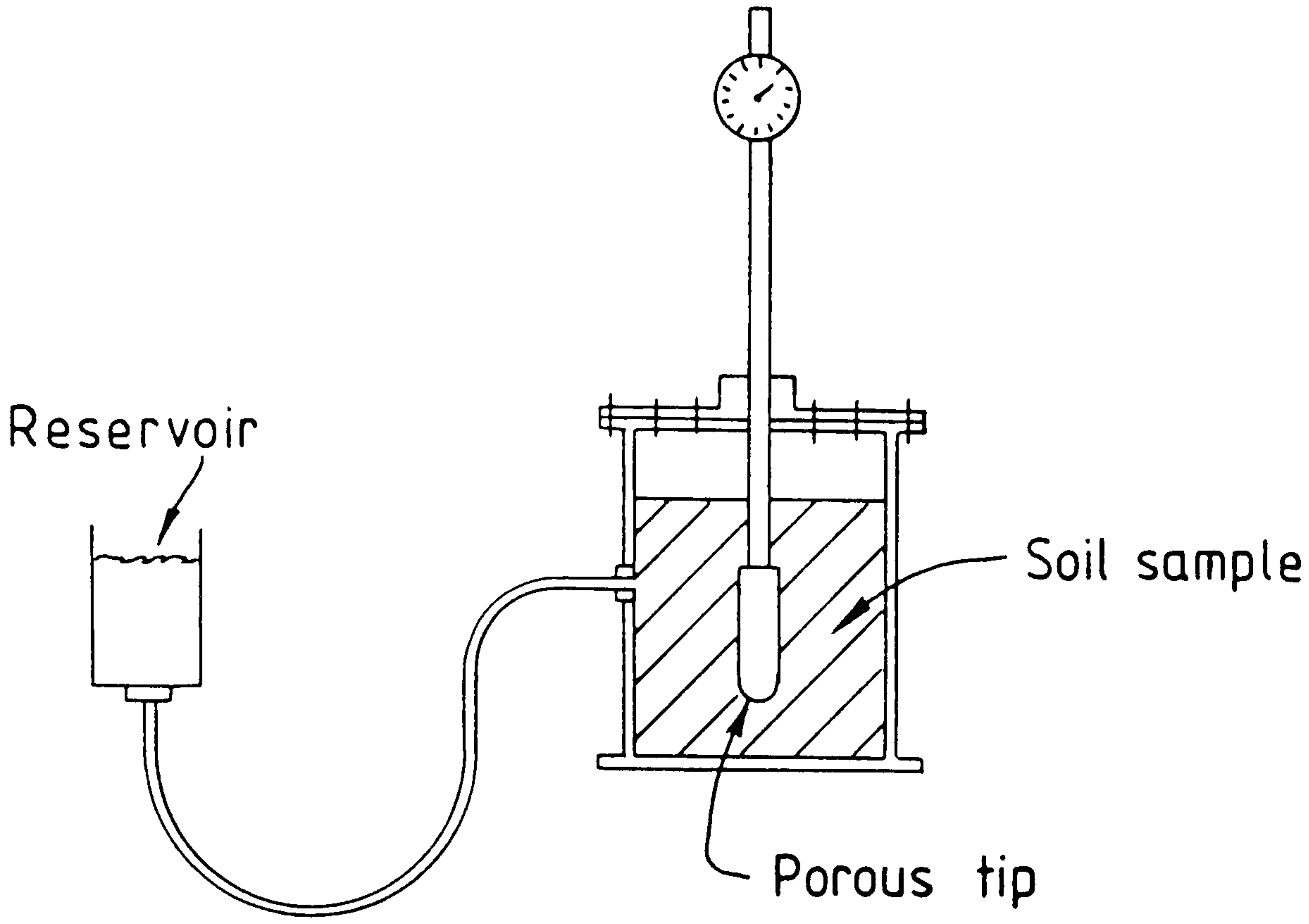


Figure 5·15 Time response equipment for Tensiometers

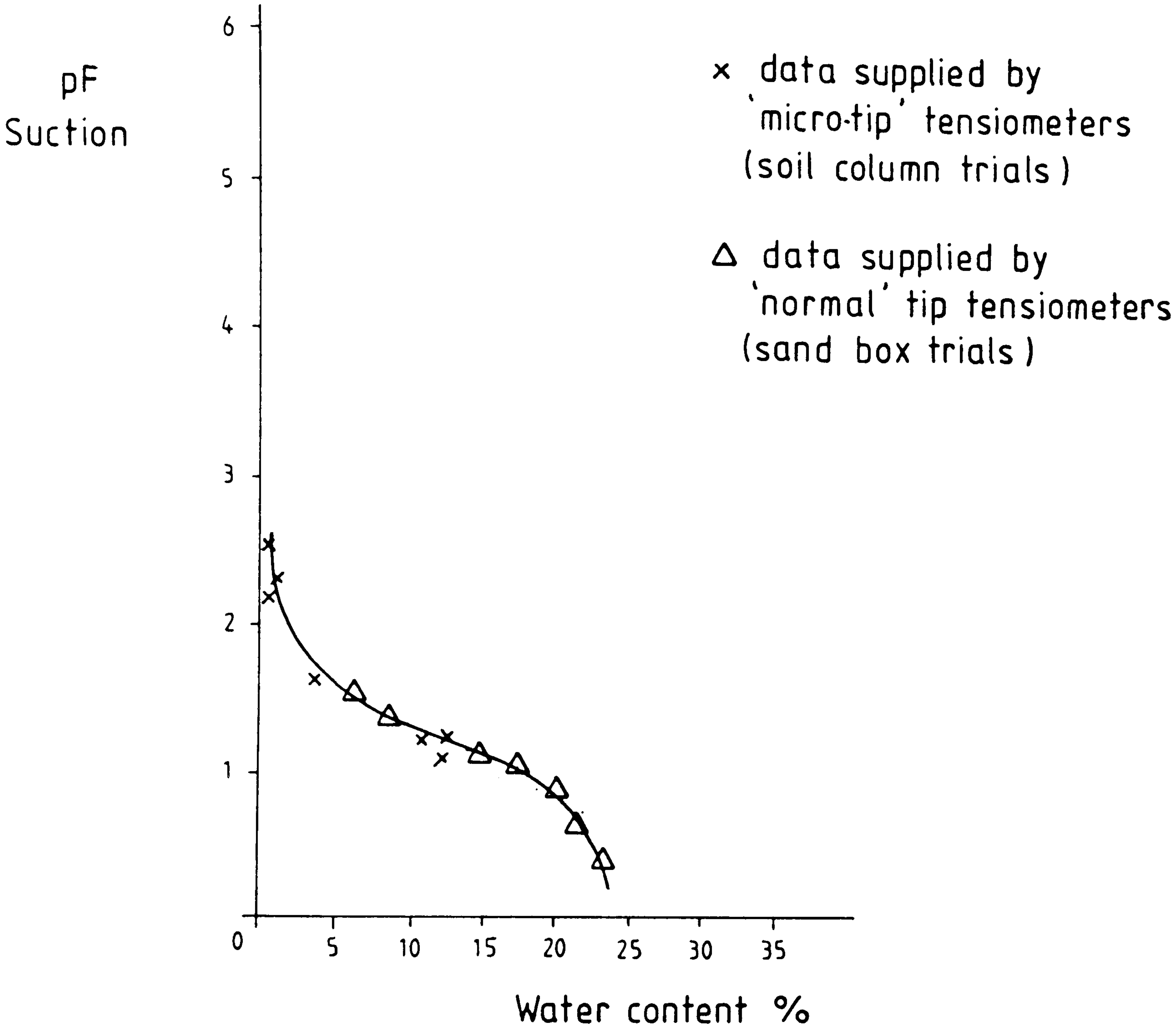


Figure 5·16 Suction/water content drying curve for blown dune sand (filter paper results) thus may not be entirely typical of a real soil mass in the field.

The 2.3 cm long "micro" tips were utilised in soil column studies, which were carried out, after the sand box work, to prove whether the use of a larger test soil sample affected the suction/water content results gained from the smaller samples used in the sand box work. The column layouts are shown in Fig. 5.17, which show that the columns could dry out both from their upper and lower surfaces. Typical drying effects are shown in Fig. 5.18 and Fig. 5.19.

The conclusion of this second experiment was that the micro tips (see Fig. 5.16) gave very similar results to those of the "normal" type and that the only practical difference between the two varieties was that the micro-tips were much harder to de-air (a long syringe had to be used to lift individual air bubbles out of the small bore tubes connected to the micro-tips), but less prone to mechanical breakage when soils dried out and settled (Fig. 5.20).

Thus in the Al-Hasa field trials both micro-tip and normal tip tensiometers were used in the upper soil layers of the 4 monitored soil profiles. In fact, 10 micro tip tensiometers and 8 normal tip types were employed.

This revealed (see Section 5.3) that

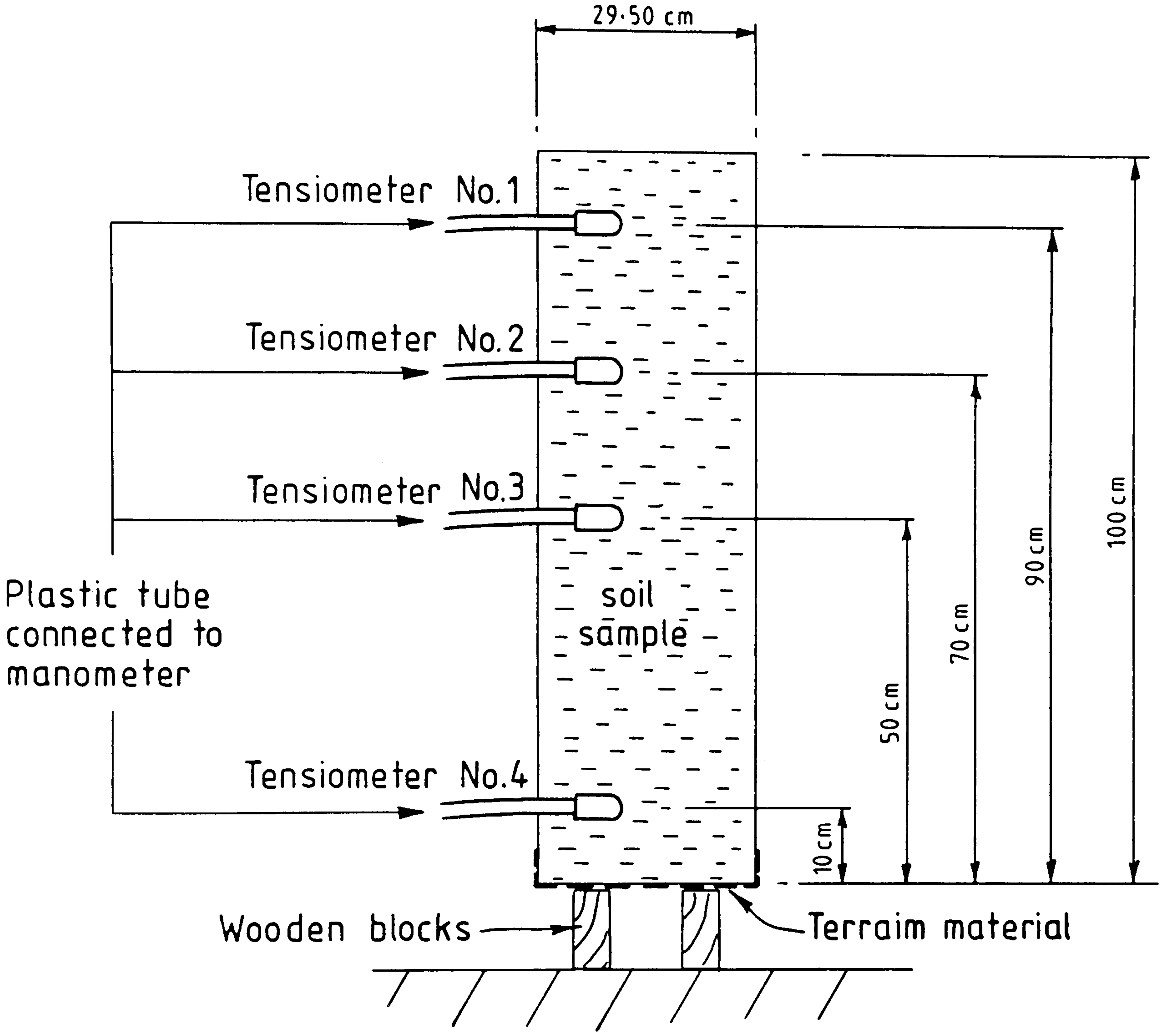


Figure 5·17 General arrangement of soil columns

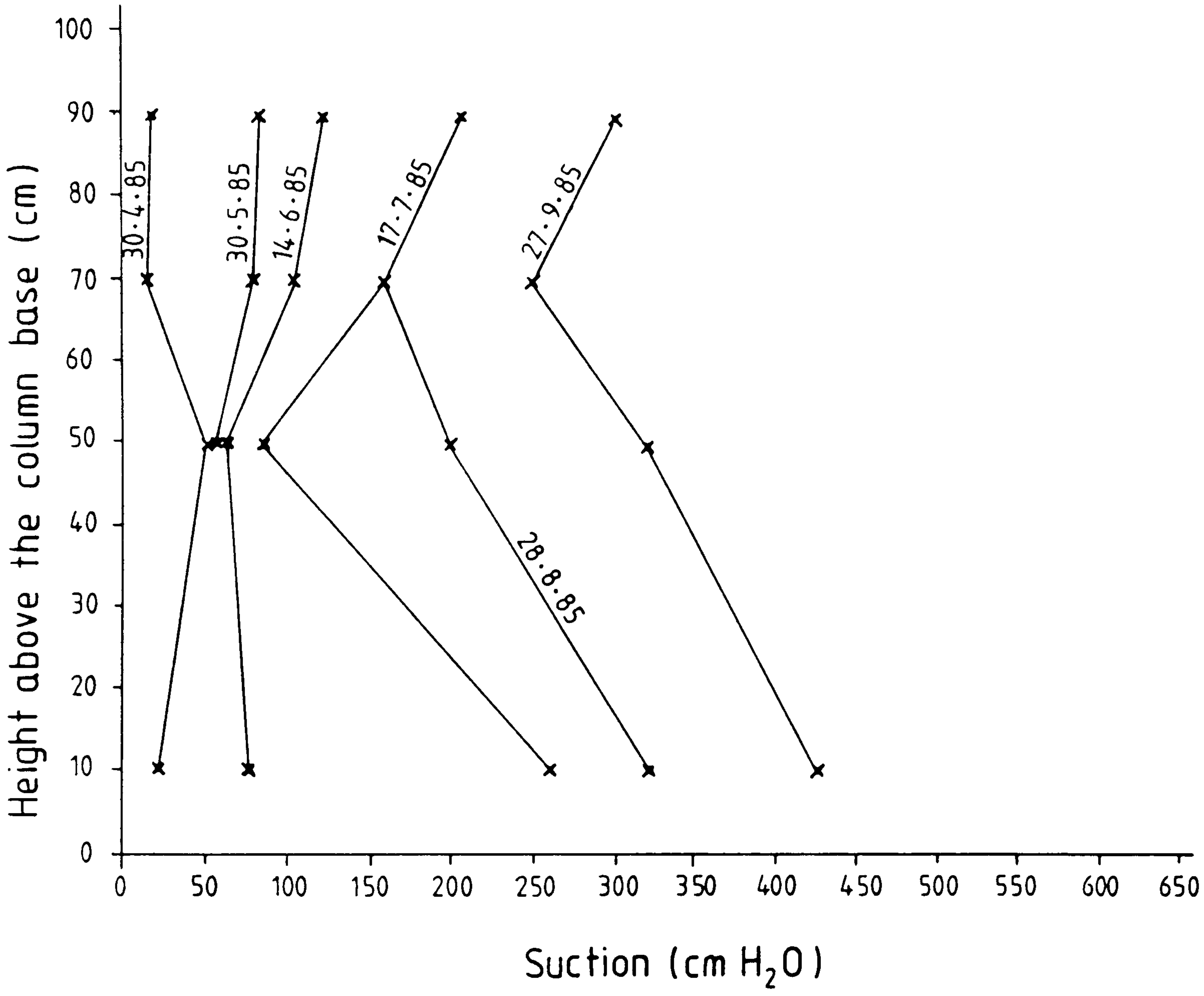


Figure 5·18 Drying out of the Blown Dune Sand

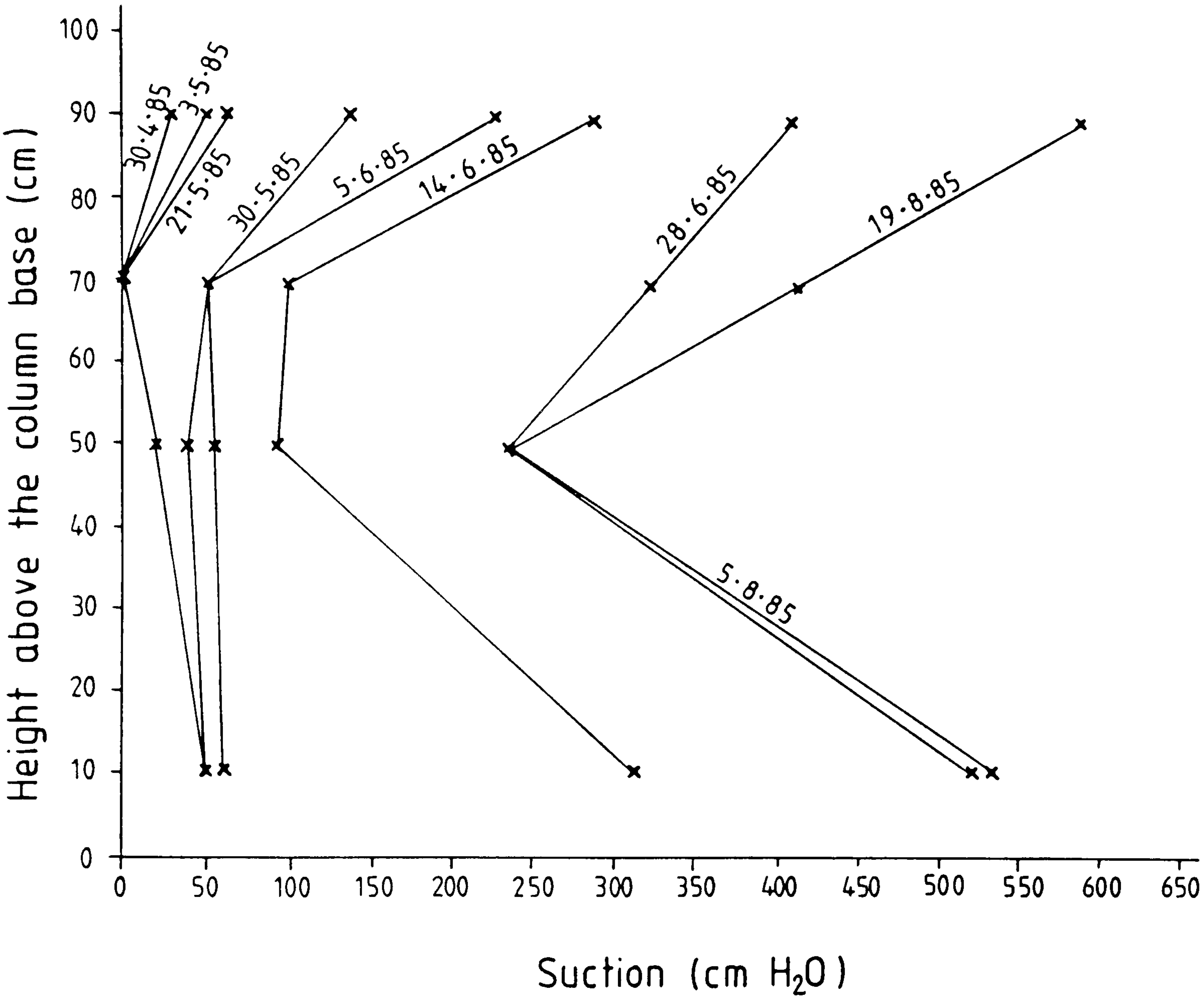
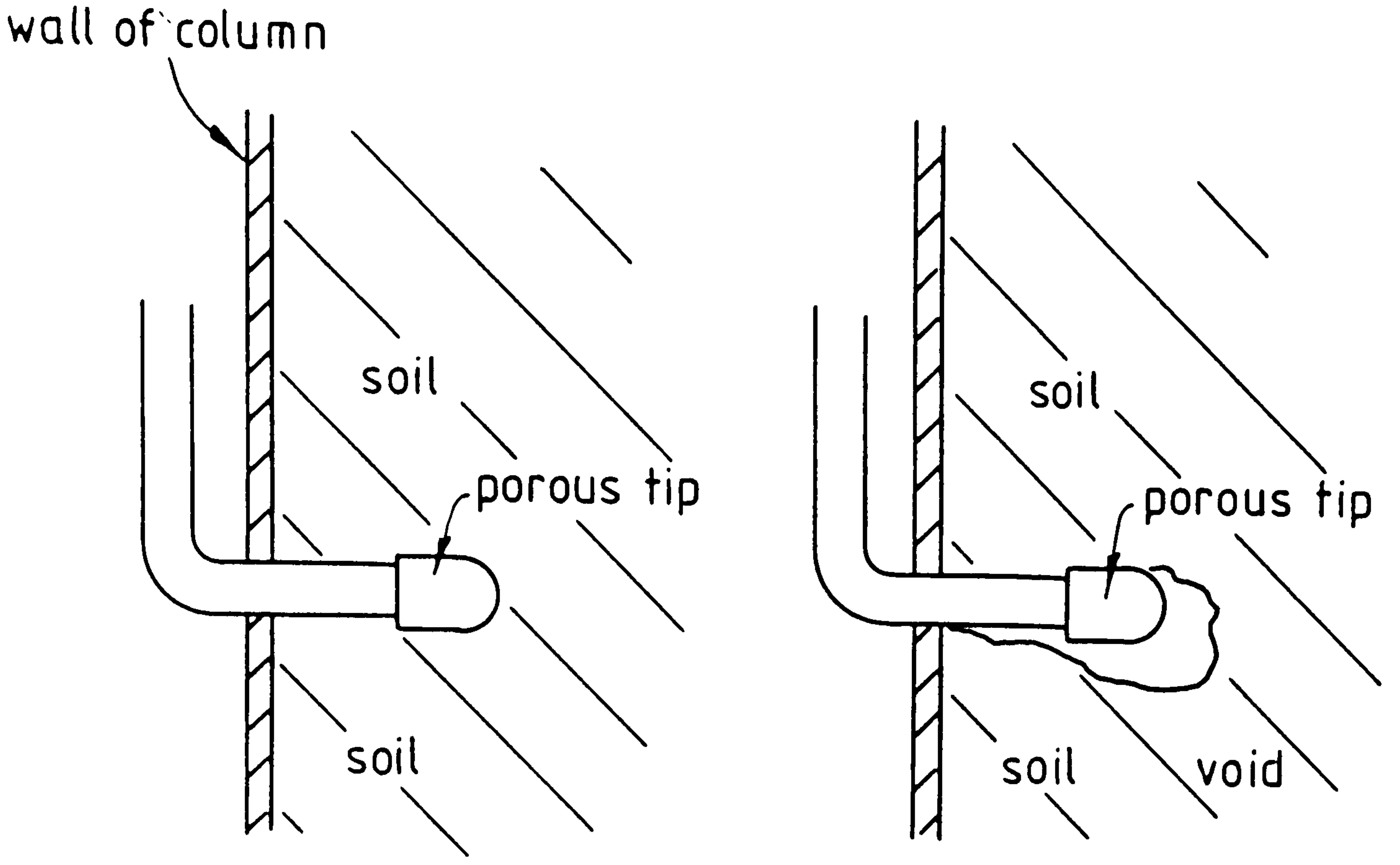
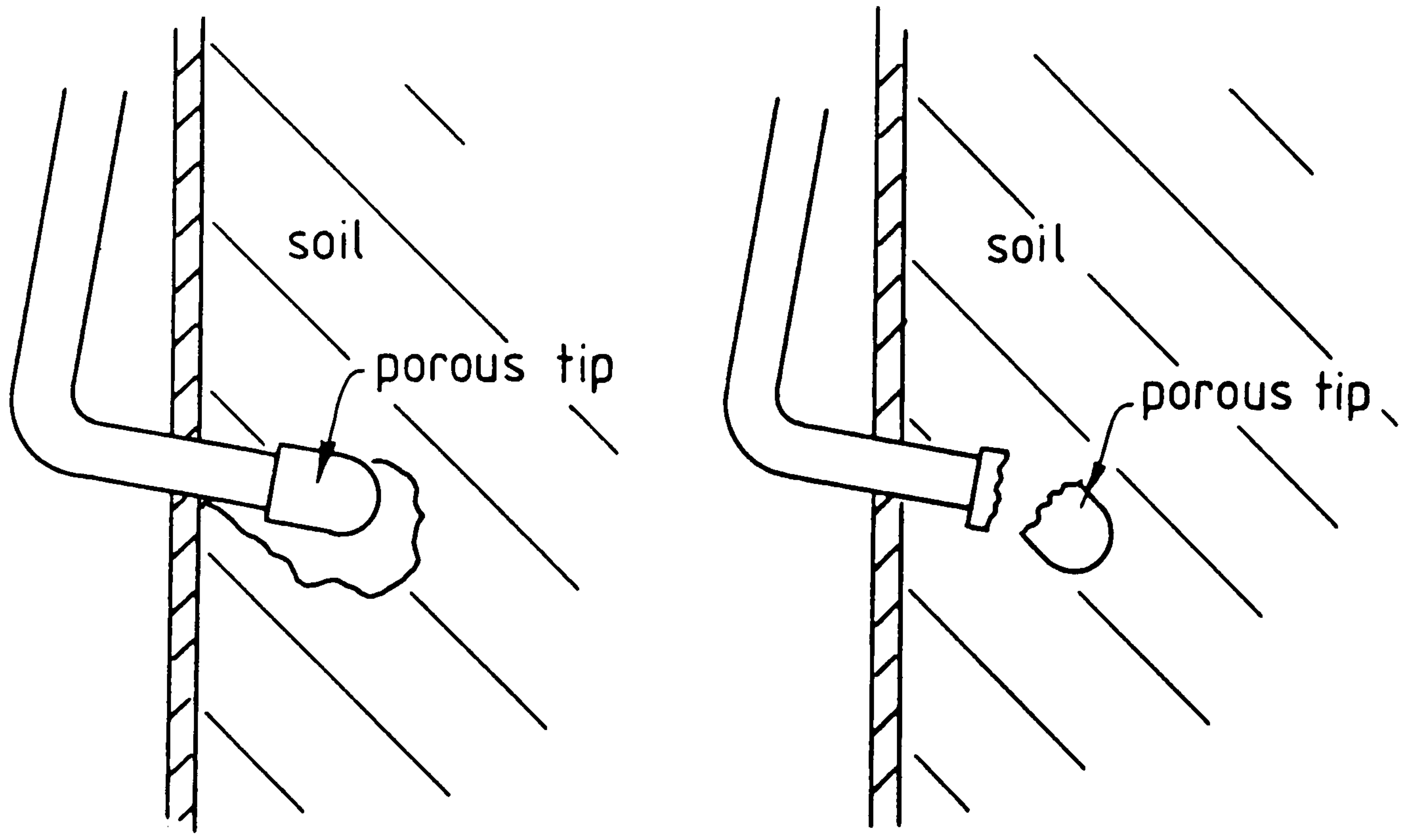


Figure 5·19 Drying out of the Sandy Clay column



(a) as installed

(b) after soil subsided due to drying out of column



(c) tensiometer moves under soil load until held by column wall

(d) porous tip breaks off

Figure 5·20 Failure of tensiometer tips due to soil dessication

(a) the micro tip tensiometers gave results that were very similar to the normal tip instruments. The variations that did occur could easily be explained as due to the inevitable minor changes that typify any natural soil. Thus on an accuracy and sensitivity basis, either type of tip may be used.

and

(b) that the difficulties experienced in de-airing the micro-tips in the laboratory were an even greater nuisance in field conditions, and called for more care and skill than seems likely to be possessed by the Al-Hasa farmers.

The overall conclusion of this evaluation is that "normal" porous tips are practically preferable, but that either type may be used without any loss of accuracy or sensitivity.

5.3 Field Trials of Tensiometers

Tensiometers were utilised as the main measuring system in the four monitored soil profiles at Al-Hasa. (See Chapter 4).

The results gained from locations and depths where more than a single tensiometer was placed are listed in Tables 5.4 to 5.11, from which the following general points can be made:-

TABLE 5.4

Tensiometer Data Gained at 25 cm depth in Profile No. 1, Al-Hasa

Gravimetric Moisture Content %		Tensiometer Readings (pF)				
From Neutron Probe	From Sample Analysis	Tensiometer No. 11	Tensiometer No. 23	Microtensiometer No. 108	Microtensiometer No. 109	Microtensiometer No. 112
6.50	-	2.21	2.20	2.00	2.00	2.00
5.80	-	2.25	2.30	2.30	2.30	2.30
6.00	-	2.40	2.40	2.40	2.40	2.40
5.60	5.81	2.30	2.30	2.30	2.30	2.30
5.20	5.45	2.20	2.30	2.20	2.20	2.20
8.20	-	1.80	1.80	1.80	1.80	1.80
4.30	-	2.20	2.20	2.20	2.30	2.30
4.20	-	2.30	2.30	2.20	2.20	2.20

TABLE 5.5

Tensiometer Data Gained at 50 cm and 75 cm depths, Profile No. 1, Al-Hasa

Gravimetric Moisture Content (%)		Tensiometer Readings (pF)	
From Neutron Probe	From Sample Analysis	Tensiometer No. 10 (at 75 cm depth)	Tensiometer No. 73 (at 75 cm depth)
18.20	-	1.70	2.00
21.00	-	1.90	2.10
20.80	21.00	1.80	2.00
20.10	20.50	1.80	2.10
23.70	-	0.00	1.90
23.60	-	1.30	1.30
10.20	-	2.50	2.60

TABLE 5.6

Tensiometer Data Gained at 20 cm depth. Profile No. 2, Al-Hasa

Gravimetric moisture content (%)		Tensiometer readings (pF)				
From Neutron Probe	From sample analysis	Tensiometer No. 5	Tensiometer No. 8	Tensiometer No. 13	Microtensiometer No. 103	Microtensiometer No. 105
18.00	-	2.70	2.70	2.70	2.70	2.70
19.00	-	2.50	2.70	2.50	2.60	2.50
16.20	-	2.80	2.70	2.70	2.70	2.70
21.00	20.90	2.30	2.30	2.50	2.40	2.30
21.60	20.85	2.10	2.20	2.30	2.20	2.30
24.00	-	1.60	1.60	1.60	1.60	1.60
24.50	-	1.60	1.80	1.80	1.80	1.80
16.30	-	2.80	2.80	2.80	2.80	2.80

TABLE 5.7

Tensiometer Data Gained at 50 cm depth. Profile No. 2, Al-Hasa

Gravimetric Moisture Content %		Tensiometer Readings (pF)		
From Neutron Probe	From Sample Analysis	Tensiometer No. 3	Tensiometer No. 12	Tensiometer No. 15
37.00	-	1.50	0.00	1.60
44.00	-	1.30	0.00	1.40
35.00	-	1.60	0.00	1.50
36.50	36.20	1.70	0.00	1.70
36.50	36.00	1.70	0.00	1.70
22.50	-	2.90	1.30	2.90
23.70	-	2.90	1.30	2.80
23.50	-	2.90	2.70	2.80

TABLE 5.8

Tensiometer Data Gained at 15 cm depth. Profile No. 3, Al-Hasa

Gravimetric Moisture Content (%)		Tensiometer Readings (pF)			
From Neutron Probe	From Sample Analysis	Tensiometer No. 4	Tensiometer No. 6	Microtensiometer No. 100	Microtensiometer No. 111
14.50	-	2.40	2.30	2.40	2.40
14.70	-	2.38	2.20	2.40	2.40
15.20	-	2.40	2.30	2.30	2.30
16.30	16.70	2.50	2.40	2.50	2.40
17.00	17.10	2.60	2.30	2.40	2.30
15.30	-	2.60	2.50	2.40	2.30
15.60	-	2.70	2.60	2.80	2.70
12.60	-	2.80	2.70	2.80	2.70

TABLE 5.9

Tensiometer Data Gained at 50 cm depth. Profile No. 3, Al-Hasa

Gravimetric Moisture Content (%)		Tensiometer Readings (pF)	
From Neutron Probe	From Sample Analysis	Tensiometer No. 7	Tensiometer No. 19
15.50	-	2.90	2.90
15.00	-	2.95	2.90
16.20	-	2.70	2.90
15.00	14.75	2.90	2.90
14.60	13.21	2.80	2.80
14.60	-	2.90	2.90
14.20	-	2.95	2.90
14.00	-	2.90	2.90

(All readings at limit of tensiometer's range)

TABLE 5.10

Tensiometer Data Gained at 18 cm depth. Profile No. 4, Al-Hasa

Gravimetric Moisture Content (%)		Tensiometer Readings (pF)			
From Neutron Probe	From Sample Analysis	Tensiometer No. 1	Tensiometer No. 18	Microtensiometer No. 107	Microtensiometer No. 110
12.40	-	2.40	2.50	2.50	2.50
12.00	-	2.40	2.50	2.40	2.40
11.50	-	2.50	2.50	2.50	2.50
11.70	11.35	2.50	2.60	2.50	2.50
11.50	11.20	2.50	2.60	2.50	2.50
11.10	-	2.40	2.60	2.50	2.50
11.00	-	2.40	2.60	2.50	2.50
9.70	-	2.80	2.80	2.80	2.80

TABLE 5.11

Tensiometer Data Gained at 50 cm depth. Profile No. 4, Al-Hasa

Gravimetric Moisture Content (%)		Tensiometer Readings (pF)	
From Neutron Probe	From Sample Analysis	Tensiometer No. 2	Tensiometer No. 14
15.00	-	2.00	2.10
15.20	-	2.00	2.10
14.20	-	2.30	2.40
20.88	19.80	1.70	1.80
16.40	15.50	2.00	2.00
20.10	-	1.80	1.80
9.50	-	2.90	2.90
10.80	-	2.50	2.50

(a) microtensiometers give results generally similar to those of the tensiometers with the normal sized tips. (Tables 5.4, 5.6, 5.8, and 5.10)

(b) the results gained are generally consistent, though two tensiometers (No. 10, Table 5.5; No. 12, Table 5.7) invariably read lower than do the other instruments set in the same soil horizon and at the same level

(c) the relative accuracy of the tensiometers appears good, especially if one considers the slight natural variations that appear in all soil horizons and the effect that these can have on soil moisture characteristics.

When typical results are graphed against the data yielded by the laboratory filter paper method, more interesting factors appear. These are best considered by looking at the four profiles individually.

In profile No. 1, daily drip feed irrigation onto the soil surface resulted in a marked increase in soil moisture content down to the groundwater level (95 cm to 140 cm below ground surface). The sandy upper 25 cms had between 4 and 8% soil moisture (Figs. 5.21 and 5.22); at 50 cm depth, the

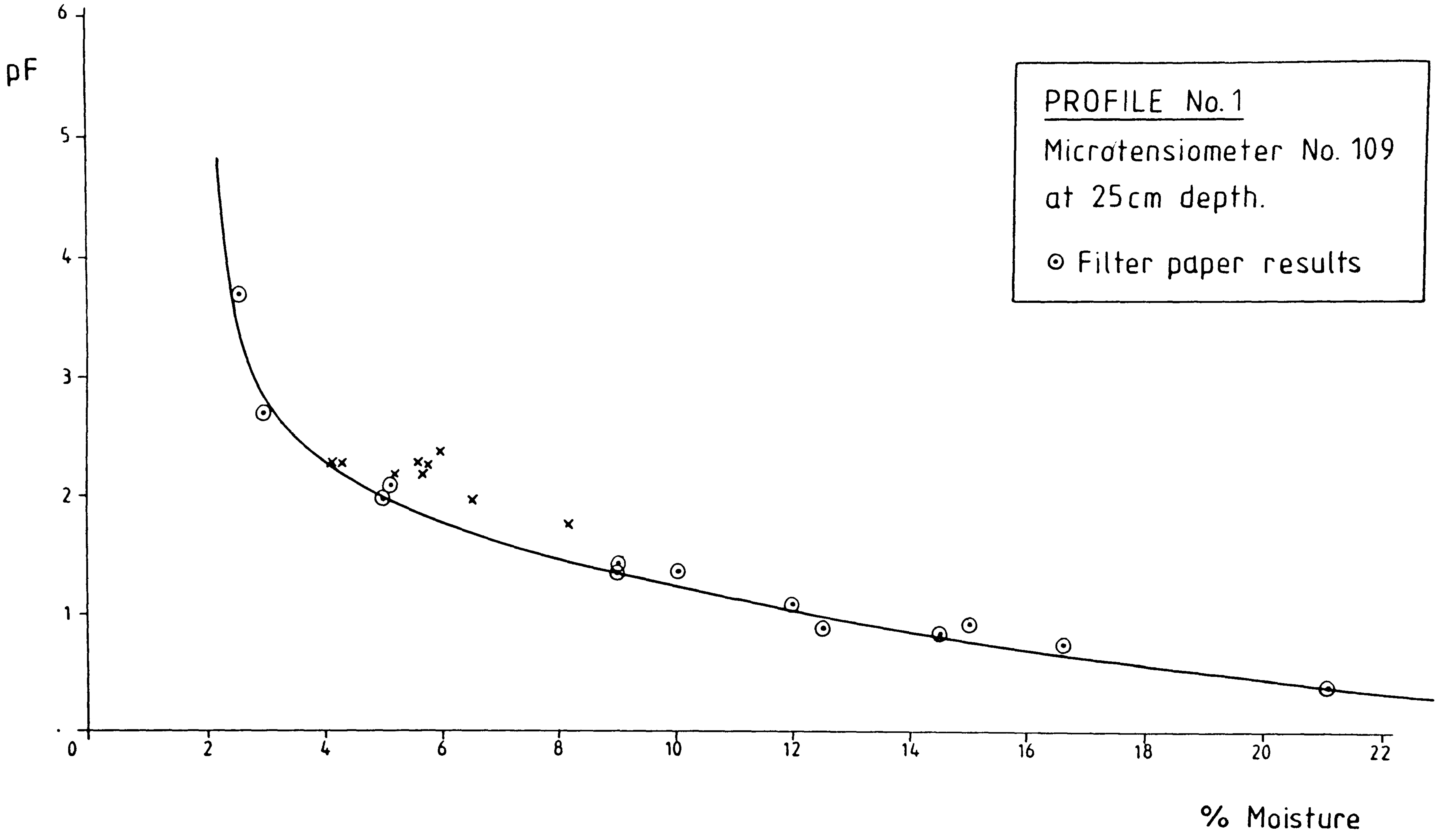

pF
6
5
4
3
2
1
0
2
4
6
8
10
12
14
16
18
20
22
% Moisture
PROFILE No. 1
Microtensiometer No. 109
at 25cm depth.
⊙ Filter paper results

Figure 5·21

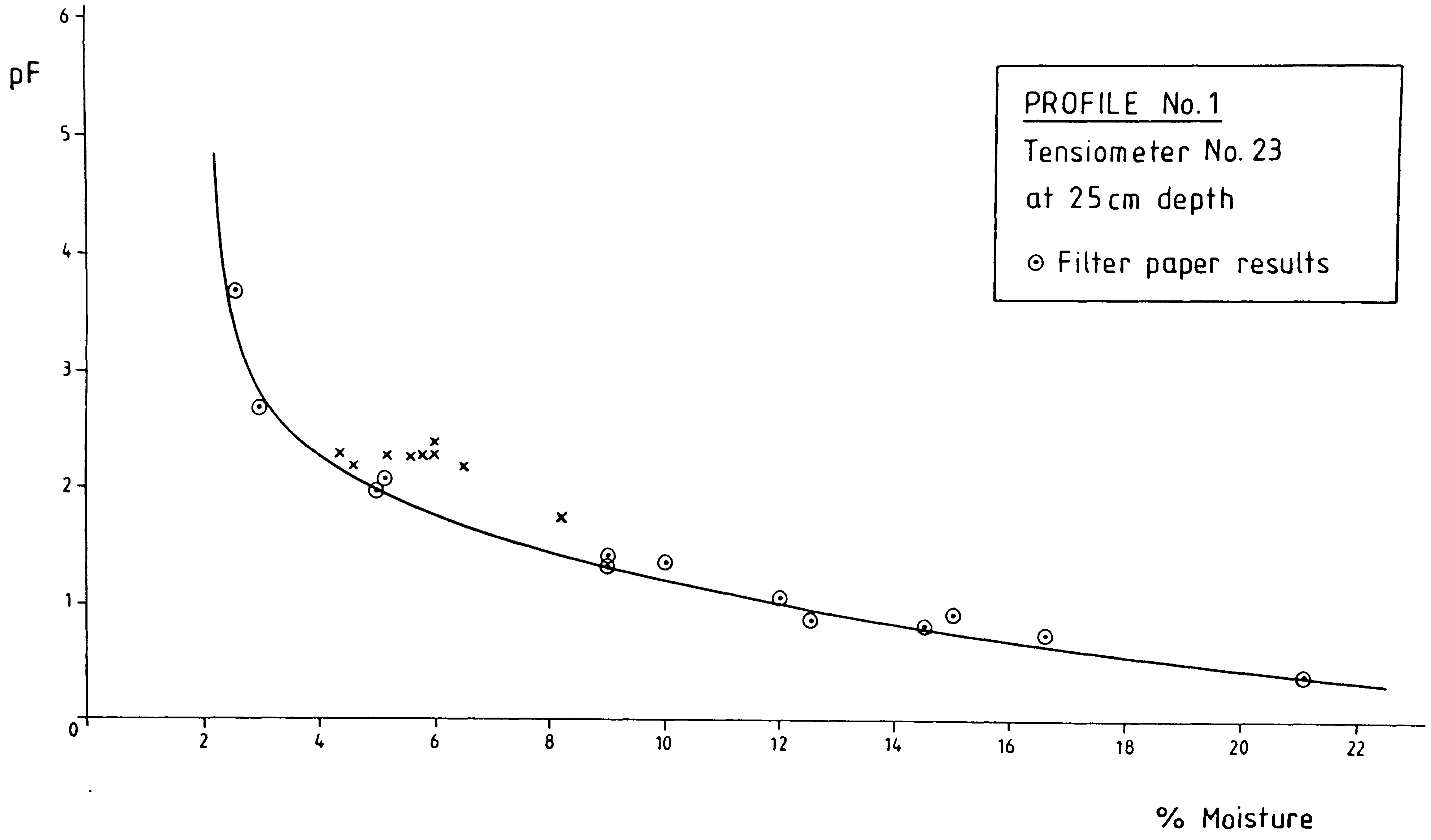

6
5
4
3
2
1
0
pF
2
4
6
8
10
12
14
16
18
20
22
% Moisture
PROFILE No. 1
Tensiometer No. 23
at 25 cm depth
⊙ Filter paper results

Figure 5·22


pF
6
5
4
3
2
1
0
2
4
6
8
10
12
14
16
18
20
22
24
% Moisture
PROFILE No 1
Tensiometer No. 9
at 50 cm depth
⊙ Filter paper results

Figure 5·23


PROFILE No. 1
Tensiometer No. 10
at 75 cm depth
⊙ Filter paper results
pF
6
5
4
3
2
1
0
2
4
6
8
10
12
14
16
18
20
22
24
% Moisture

Figure 5·24


PROFILE No.1
Tensiometer No.70
at 90 cm depth
⊙ Filter paper results
pF
6
5
4
3
2
1
0
2
4
6
8
10
12
14
16
18
20
22
24
% Moisture

Figure 5·25

soil moisture level tended towards 16% (Fig. 5.23); whilst at 75 cm depth, the average moisture content was 20.5% over the study period. (Fig. 5.24). Finally at 90 cm depth, the soil moisture content varied from 22.6% to 26%. (Fig. 5.25)

Perhaps the most noticeable feature of Figs. 5.21 to 5.25 is that (for any particular soil moisture content), the tensiometers indicate a higher suction than did the laboratory filter paper method. Discrepancies of up to 83% in excess of the laboratory predicted suction occur at some levels.

Profile No. 2 also was undergoing daily surface irrigation. This gave rise to between 16% and 24.5% moisture content at a depth of 20 cm. (Figs. 5.26 and 5.27); to 22.5% to 44% at a 50 cm depth (Fig. 5.28), just above the standing groundwater level (here abnormally high because the underlying hard pan impedes downward drainage and the artificial drainage works had been incorrectly connected and so had failed). Unlike the results of Profile No. 1, the tensiometer data in Profile No. 2 closely fits the laboratory derived suction/water content curve.

Profile No. 3 was in the saline, uncultivated soil, in which no standing water level was encountered. At a depth of 15 cm the soil moisture levels varied from 12.5% to 17% (Figs. 5.29 and 5.30), whilst at 50 cm depth (Fig. 5.31) the

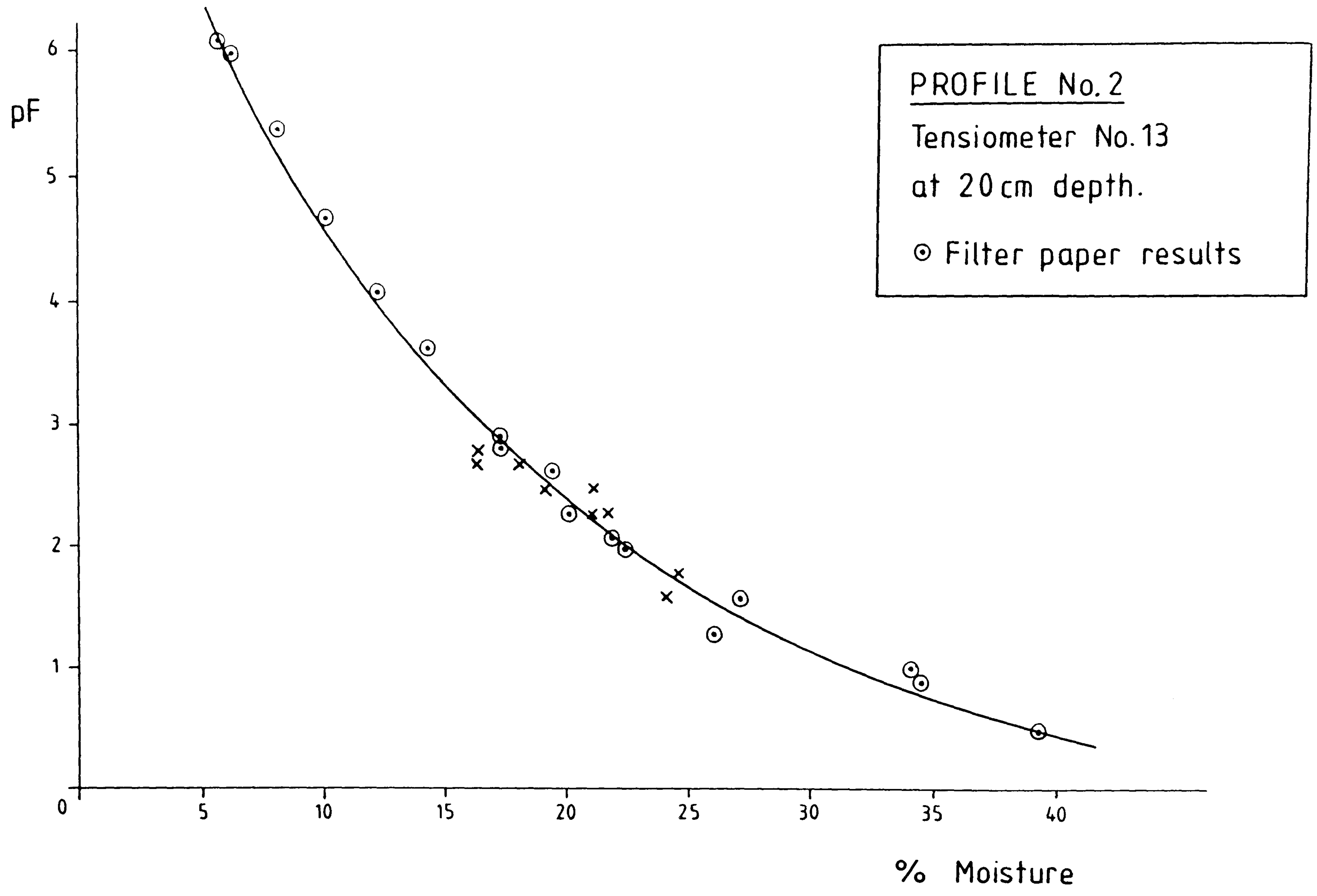

PROFILE No. 2
Tensiometer No. 13
at 20 cm depth.
⊙ Filter paper results
pF
6
5
4
3
2
1
0
5
10
15
20
25
30
35
40
% Moisture

Figure 5·26

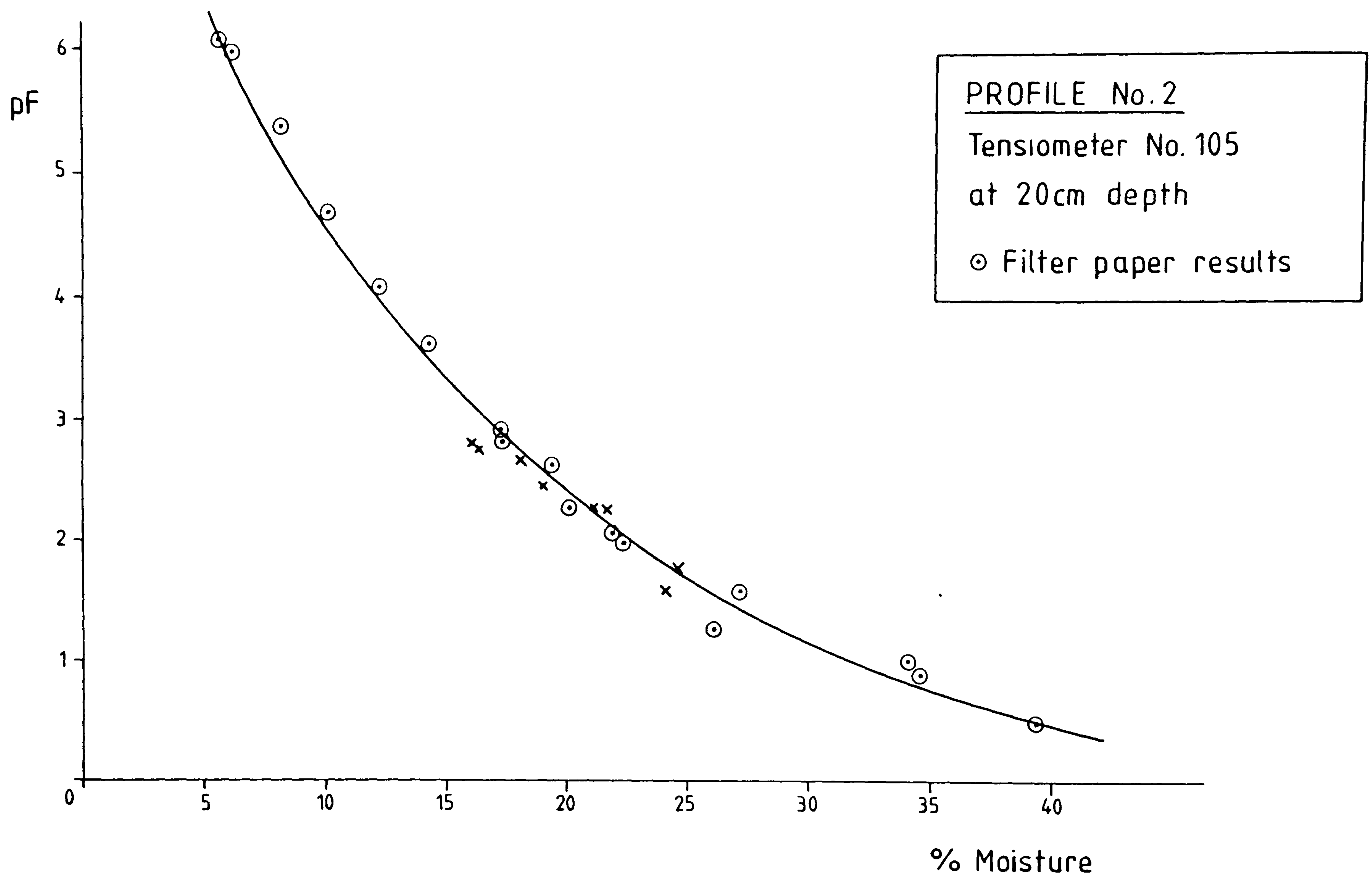

pF
6
5
4
3
2
1
0
5
10
15
20
25
30
35
40
% Moisture
PROFILE No. 2
Tensiometer No. 105
at 20cm depth
⊙ Filter paper results

Figure 5·27

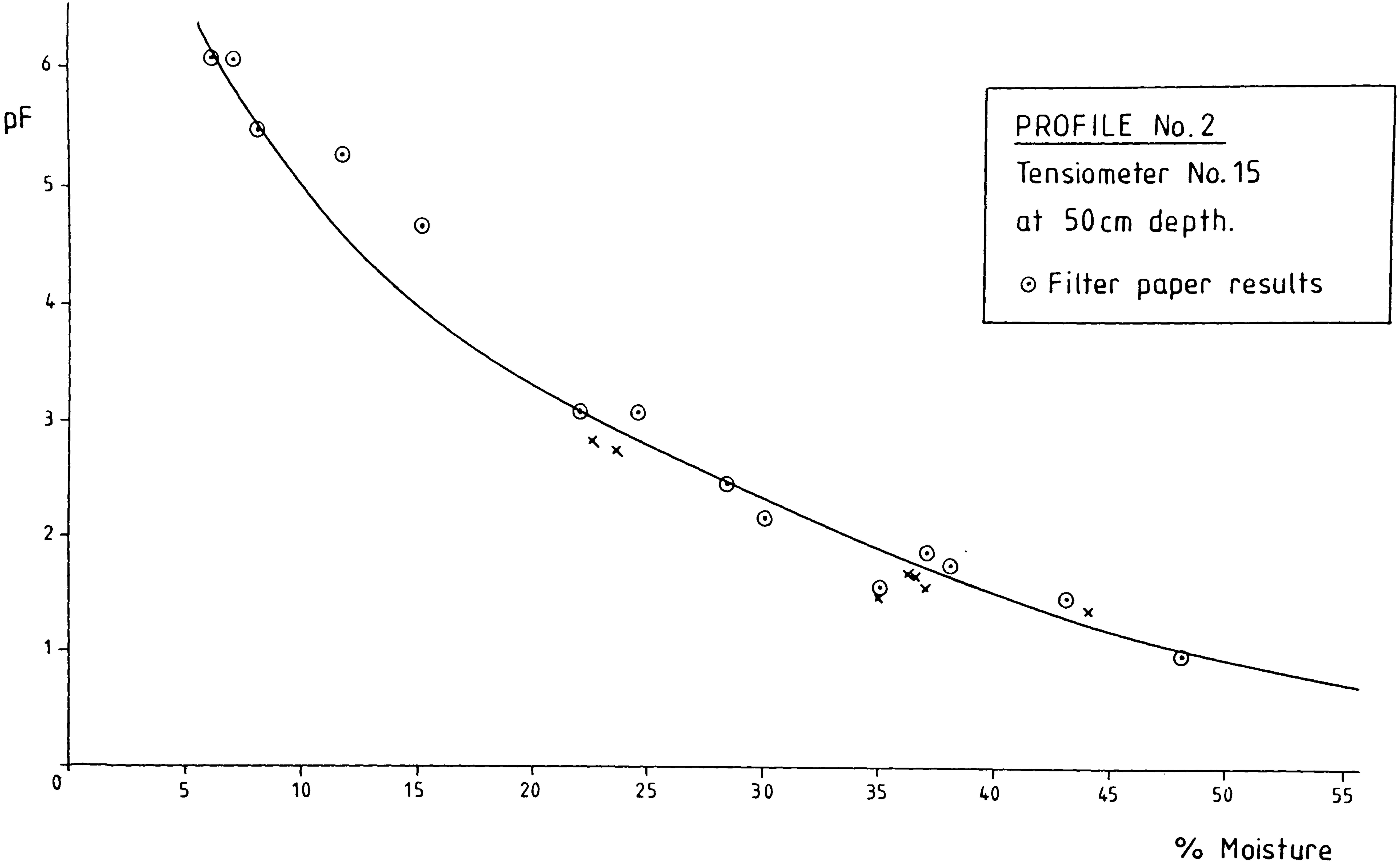

pF
6
5
4
3
2
1
0
5
10
15
20
25
30
35
40
45
50
55
% Moisture
PROFILE No. 2
Tensiometer No. 15
at 50 cm depth.
⊙ Filter paper results

Figure 5·28

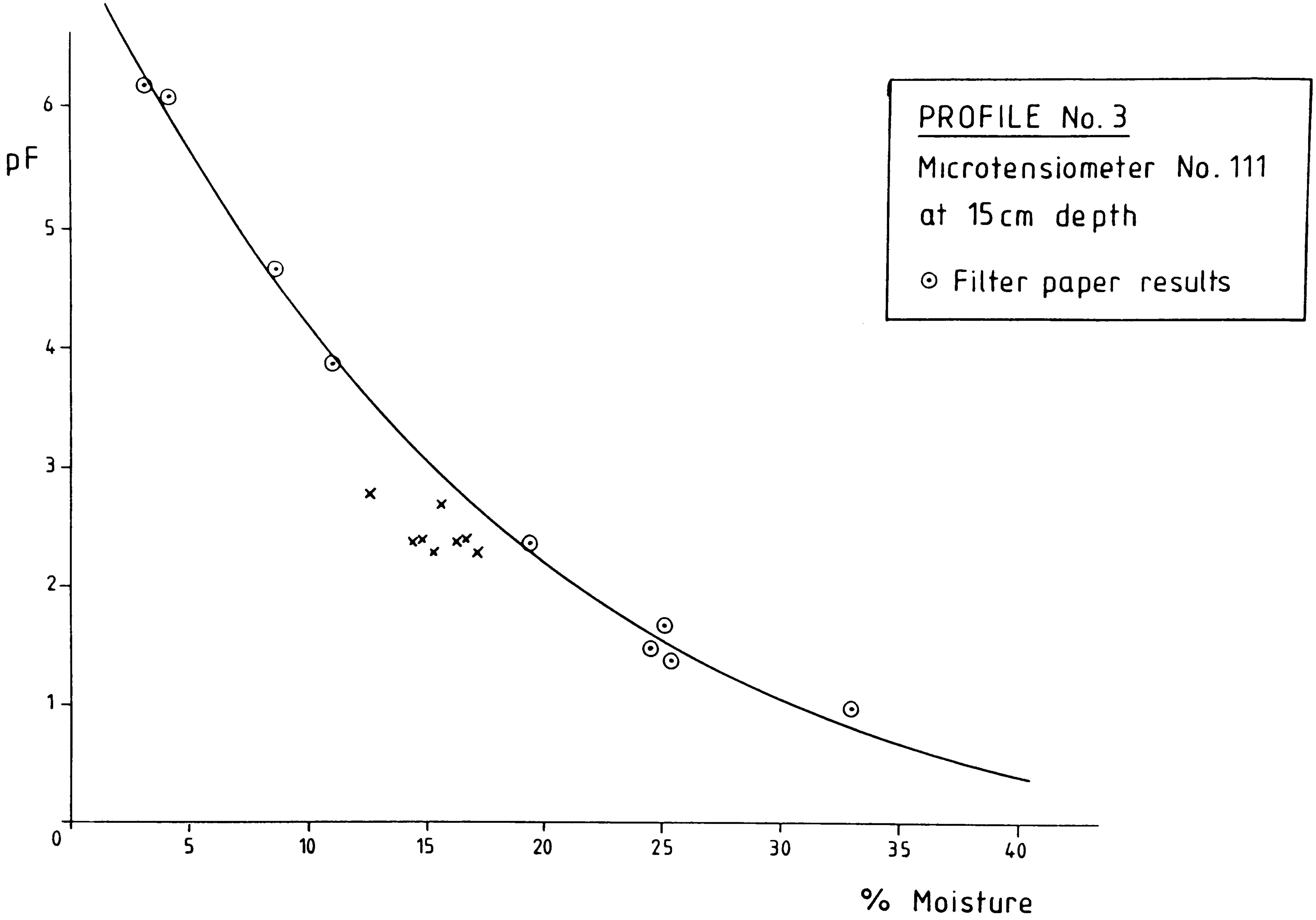

PROFILE No. 3
Microtensiometer No. 111
at 15 cm depth
⊙ Filter paper results
pF
6
5
4
3
2
1
0
5
10
15
20
25
30
35
40
% Moisture

Figure 5·29

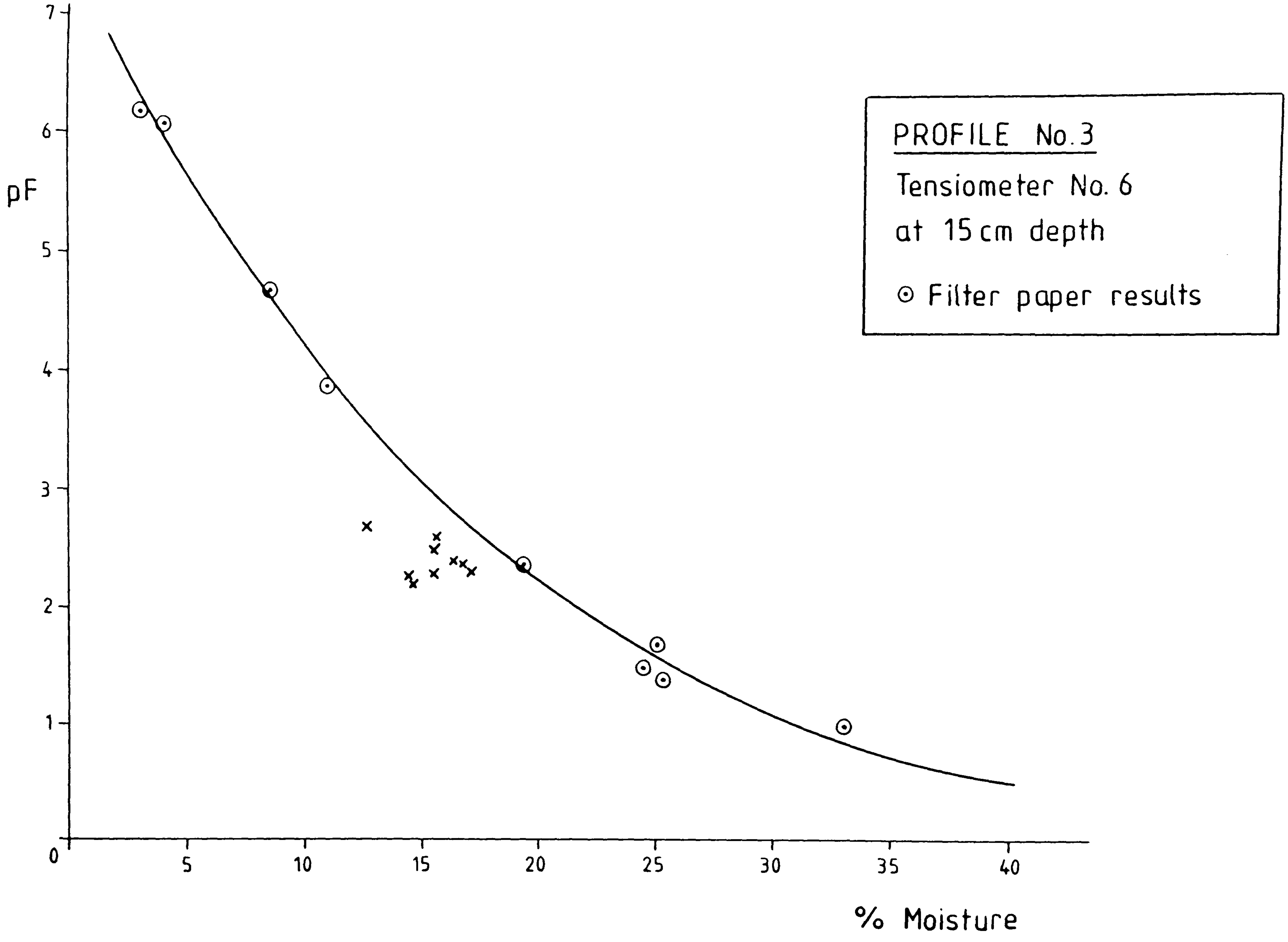

PROFILE No. 3
Tensiometer No. 6
at 15 cm depth
⊙ Filter paper results
pF
7
6
5
4
3
2
1
0
5
10
15
20
25
30
35
40
% Moisture

Figure 5·30


7
6
5
4
3
2
1
0
pF
5
10
15
20
25
30
35
40
45
50
55
60
% Moisture
PROFILE No. 3
Tensiometer No. 19
at 50 cm depth
⊙ Filter paper results

Figure 5·31

suctions where always at the maximum levels that a tensiometer can read (pF of 2.9), and the soil moisture levels varied from 13% to 16.5%. The graph of the tensiometer readings at this depth (Fig. 5.31) cannot thus be accepted as accurate, since the suctions are likely to be far in excess of those shown by the tensiometers. Oddly enough, whilst conditions at the 75 cm depth resemble those of Fig. 5.27, with recorded suctions at the limit of tensiometer reliability, at 90 cm depth much wetter soil (18.5% to 27.5% moisture content) appeared, possibly as a result of heavy rain in October 1985 percolating down the soil column. (Fig. 5.32).

Where the results from Profile No. 3 are not limited by the working range of tensiometers, it is obvious that - in Fig. 5.32 - the tensiometers tend to give suction readings that are lower than those produced in the laboratory filter paper tests.

The final profile (No. 4) gave in its uppermost layer (18 cm depth) tensiometer readings that were only slightly above those preducted by the laboratory tests (Figs. 5.33 and 5.34) and soil moisture contents from 9.5% to 12.5%. At 50cm depth, the soil moisture range rose from 9.5% to 21%, and again the tensiometer produced suctions which tend to be somewhat higher than those predicted by the laboratory method (Fig. 5.35). This position persisted down to the

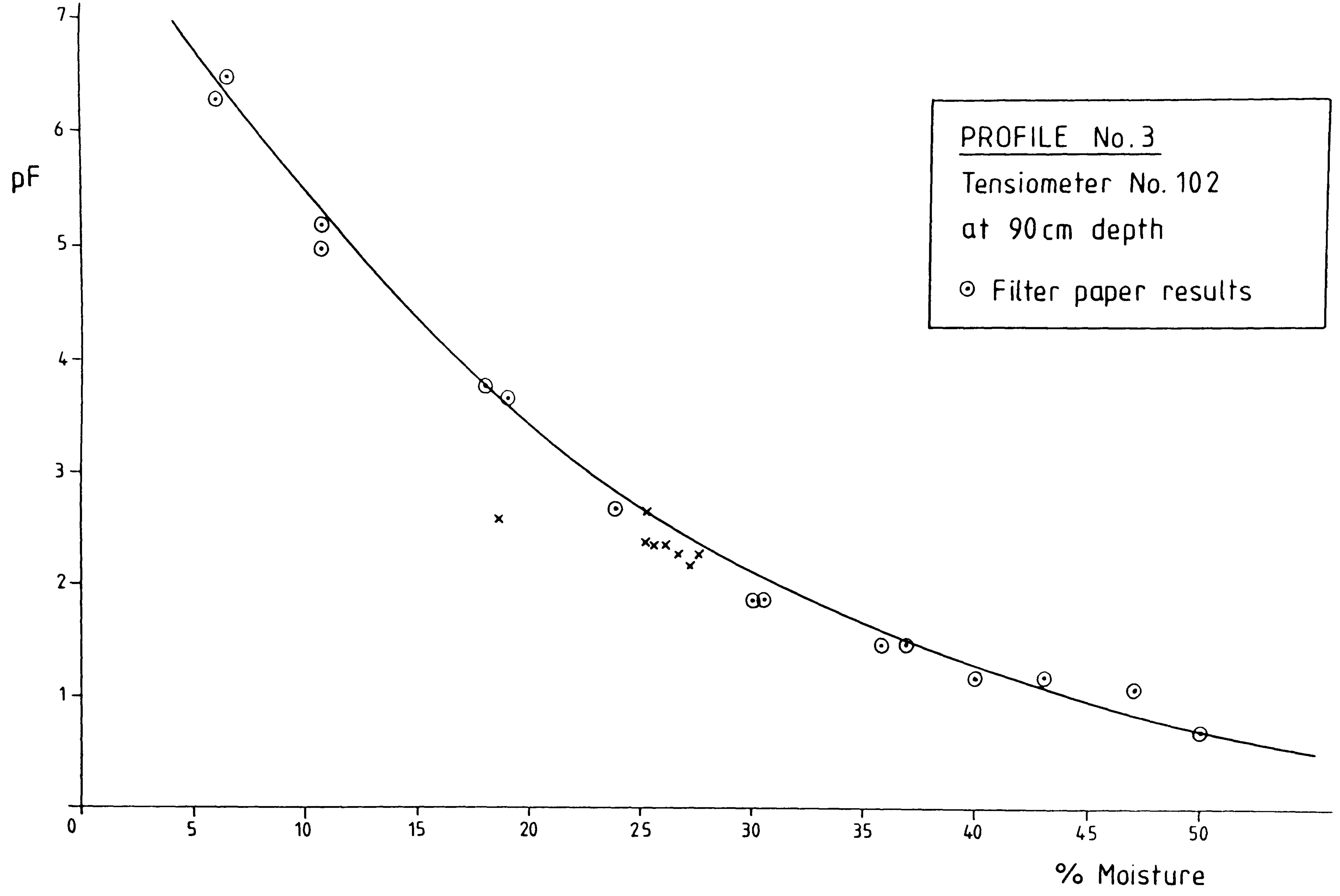

PROFILE No. 3
Tensiometer No. 102
at 90 cm depth
⊙ Filter paper results
pF
7
6
5
4
3
2
1
0
5
10
15
20
25
30
35
40
45
50
% Moisture

Figure 5·32

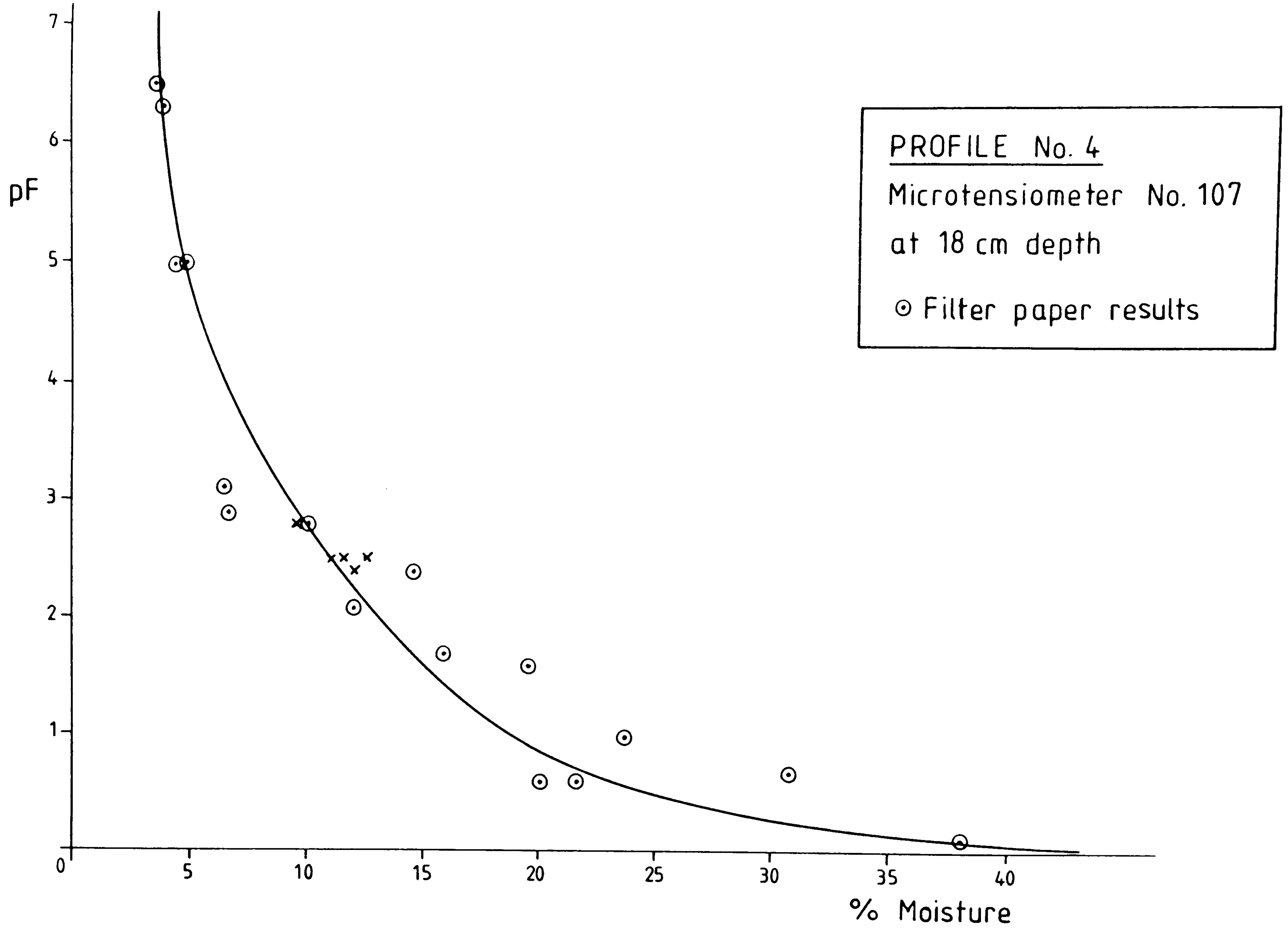

PROFILE No. 4
Microtensiometer No. 107
at 18 cm depth
⊙ Filter paper results
pF
7
6
5
4
3
2
1
0
5
10
15
20
25
30
35
40
% Moisture

Figure 5·33

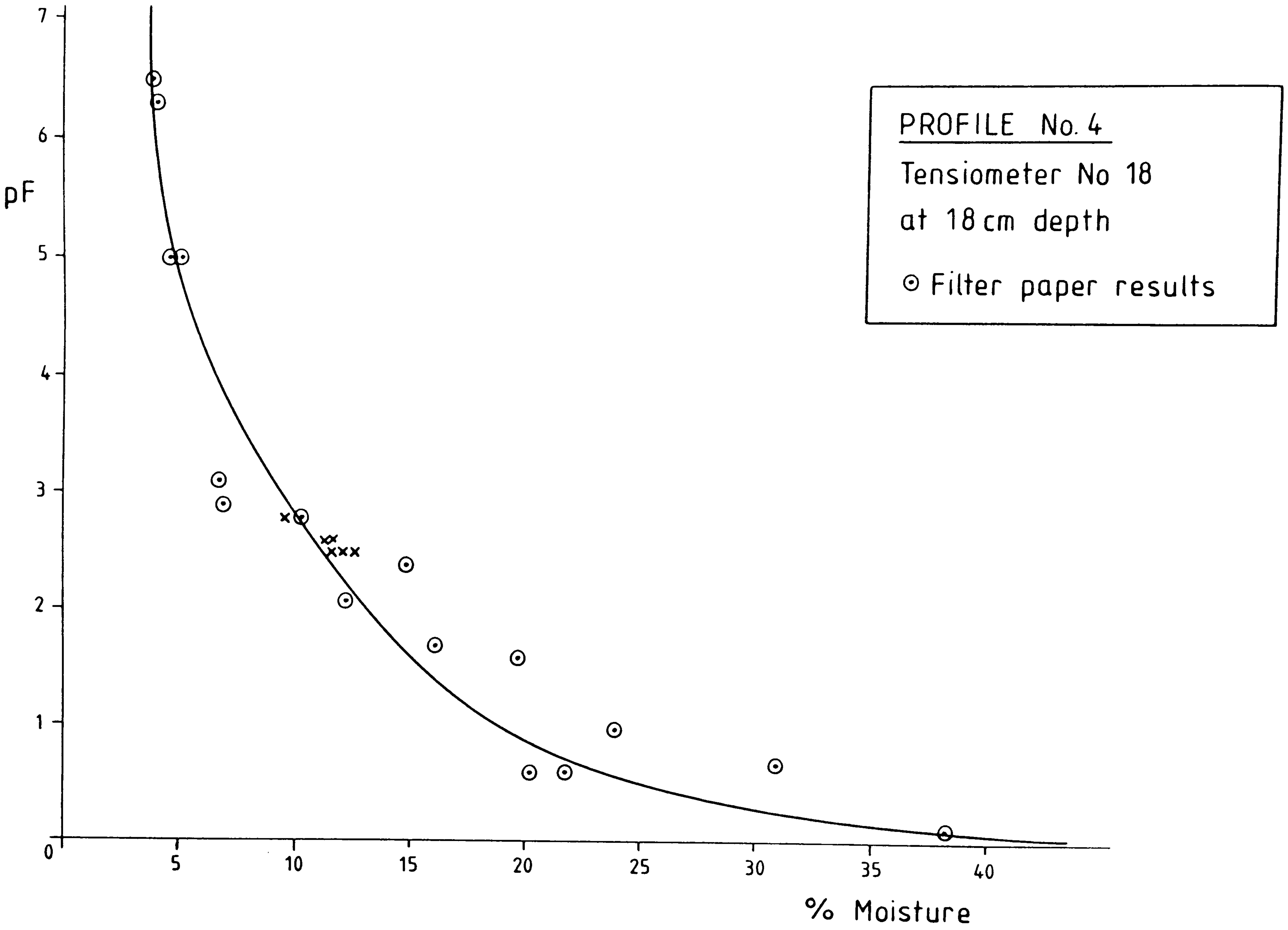

PROFILE No. 4
Tensiometer No 18
at 18 cm depth
⊙ Filter paper results
pF
7
6
5
4
3
2
1
0
5
10
15
20
25
30
35
40
% Moisture

Figure 5·34

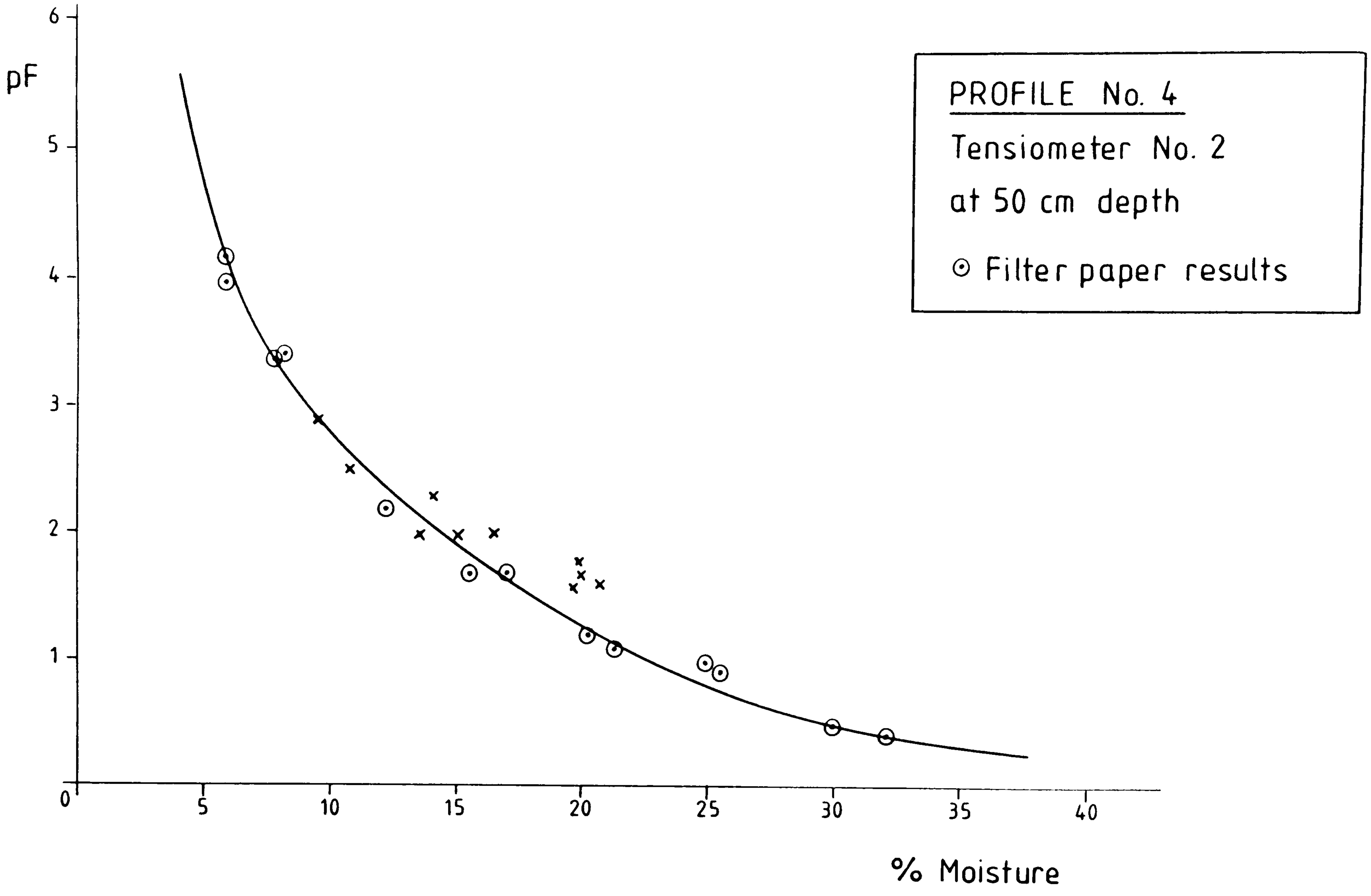

pF
6
5
4
3
2
1
0
5
10
15
20
25
30
35
40
% Moisture
PROFILE No. 4
Tensiometer No. 2
at 50 cm depth
⊙ Filter paper results

Figure 5·35

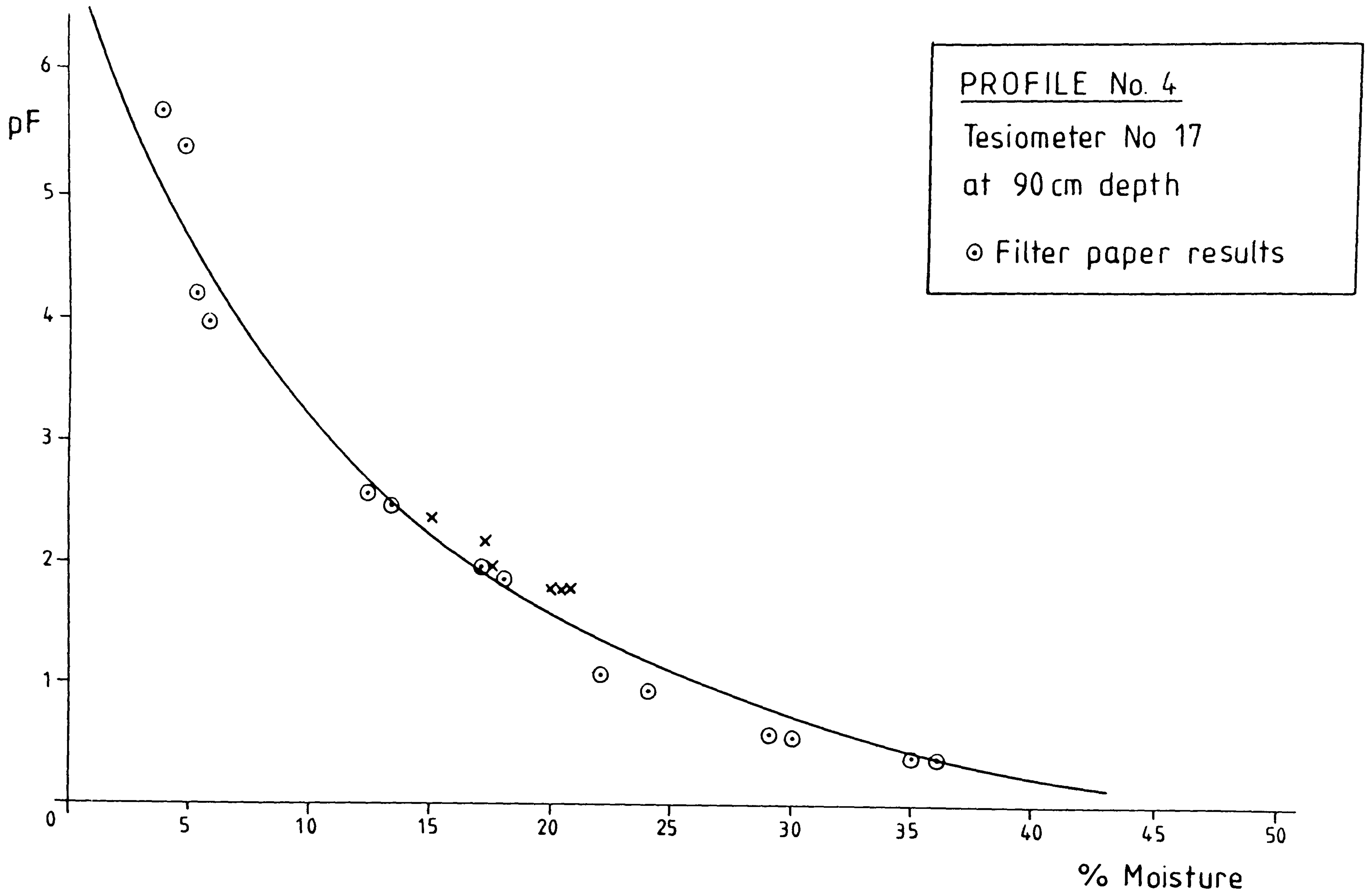

PROFILE No. 4
Tesiometer No 17
at 90 cm depth
⊙ Filter paper results
pF
6
5
4
3
2
1
0
5
10
15
20
25
30
35
40
45
50
% Moisture

Figure 5·36

lowest tensiometer (at 90 cm) depth (Fig. 5.36).

Thus the odd position is that, in profile No. 1 tensiometers indicate suctions well above those that the soil moisture state should be to support, whilst in profile No. 3 the tensiometers give results rather lower than would be expected from the laboratory data. In profiles Nos. 2 and 4, the tensiometer data is much closer to that produced by the filter paper work.

A similar situation was apparent in some of the data obtained from the sand box studies (see Figs. 5.5, 5.8, 5.9, 5.10, 5.11, 5.12 where the measured suctions in the blown dune sand invariably are higher than are those in the sandy clay).

The explanation for this unusual situation seems to lie in the relationship between the pore size of the porous tip and that of the soil that surrounds it and is considered further in Chapter 7.

When the greatest measured discrepancies - in percentage terms - between the tensiometers and the results given by the filter paper work are plotted against the combined silt and clay fractions for the various soil horizons (Fig. 5.37), a relationship becomes apparent, which suggests that tensiometers are least likely to give results different to

Figure 5·37 Relationship between tensiometer readings and those of the filter paper method, if the soil is a loam with a combined silt and clay fraction of 55% or more.

Figure 5.37 is, of course, limited in that it can show only the data from 10 of the monitored soil horizons (no meaningful information could be plotted from the very dry layers in profile No. 3), and much more investigation would have had to be carried out to define the apparent effect on soil type of tensiometer readings.

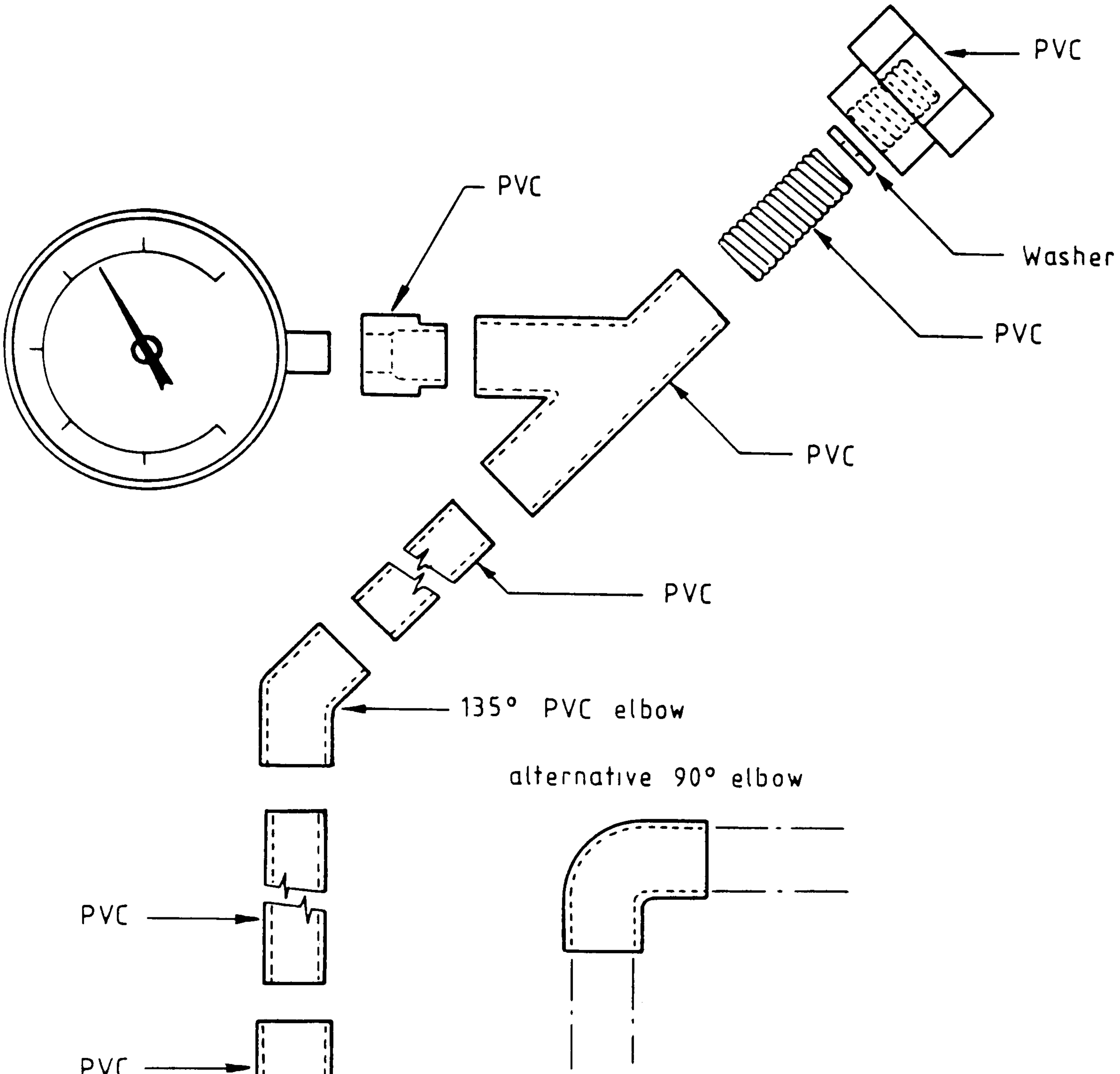
A discussion of this situation is given in Chapter 7, but from the viewpoint of controlling irrigation at Al-Hasa, the phenomenon is something of a nuisance, since corrective factors would have to be brought in for those clayier and sandier soils that do occur in the oasis. Luckily most of the soils do fall into the loam class and errors would thus not be too excessive.

5.4 Summary

The results gained show that cheap tensiometers are capable of providing accurate soil moisture data if care is taken to include the effects that soil grain distribution may have on the tensiometers.

The proposal that tensiometers be employed for irrigation control does imply that a local centre be established with the facilities to calibrate and test both the instruments' vacuum gauges and the complete tensiometers themselves. The equipping of this centre would be a minor cost since all that is required is a test room with manometer boards and test pumps, and storage space for the components and the completed tensiometers.

The use of cheap Bourdon gauges and commercially available porous tips suggests that the centre could produce its own tensiometers in lengths tailored to the rooting depths of various crop types. A possible design for such a tensiometer (assembled and glued from commonly available plastic fittings) is shown on Figure 5.38.



Adhesives

PVC to PVC - TANGIT CEMENT

PVC to PERSPEX - TANGIT CEMENT

PERSPEX to CERAMIC TIP - ARALDITE (Rapid)

Tensiometer body materials

ALL STANDARD DOMESTIC SANITARY COMPONENTS.

Figure 5·38

References

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5.11 Personal Communication with Mr. T. Sharrock, Department of Building and Civil Engineering, Liverpool Polytechnic

CHAPTER SIX

Gypsum Blocks and Soil Moisture Cells

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Gypsum Blocks and Soil Moisture Cells

6.1 Introduction

Gypsum blocks and soil moisture cells are always associated with their originator and developer, Dr. G.J. Bouyoucos, who first published almost every important fact on their use, in the period from 1940 to 1972 (Refs. 6.1, 6.2, 6.3).

Bouyoucos started by seeking a tensiometer replacement that would have a longer measurement range, and which would be more robust and more sensitive. This lead him to consider the use of electrical resistance measuring methods, and to develop (initially) a gypsum block coating for the electrical electrodes. The gypsum coating he found essential to ensure that the electrodes were in proper contact with the surrounding soil, and in a medium that quickly came into moisture equilibrium with the soils. An additional advantage of the gypsum coating was that any stray natural eddy currents were "buffered" and thus spurious readings avoided. The choice of gypsum as a coating came after a long evaluation of materials as variable as sand/cement mixtures, dental cements, baked clays, etc. (Ref. 6.1).

Having found that a 1:1 gypsum and distilled water slurry to be the best coating medium, Bouyoucos then had to evolve an effective internal electrode, and - by trial and error - found that two parallel meshes of stainless steel worked well. It is worth noting that Bouyoucos himself lacked any training in electrical antennae design, and that later workers (Ref. 6.4) with this technical background have claimed to produce superior devices by devising more efficient electrodes.

Bouyoucos' pre-1948 work led to workable gypsum blocks that could produce useful soil moisture curves (Fig. 6.1), though it is noticeable that these devices could respond effectively only when the various soils were in their drier states, and that, in wet soils, no meaningful readings could be obtained.

A second problem of the basic gypsum blocks was that gypsum is slightly soluble (to be extent of 2,000 to 2,5000 mg/kg) in soil waters, and that disintegration of blocks could occur in as short a period as 3 months in more aggressive soil waters.

Because of these problems, Bouyoucos and his co-workers evaluated the merits of other coating materials. A result

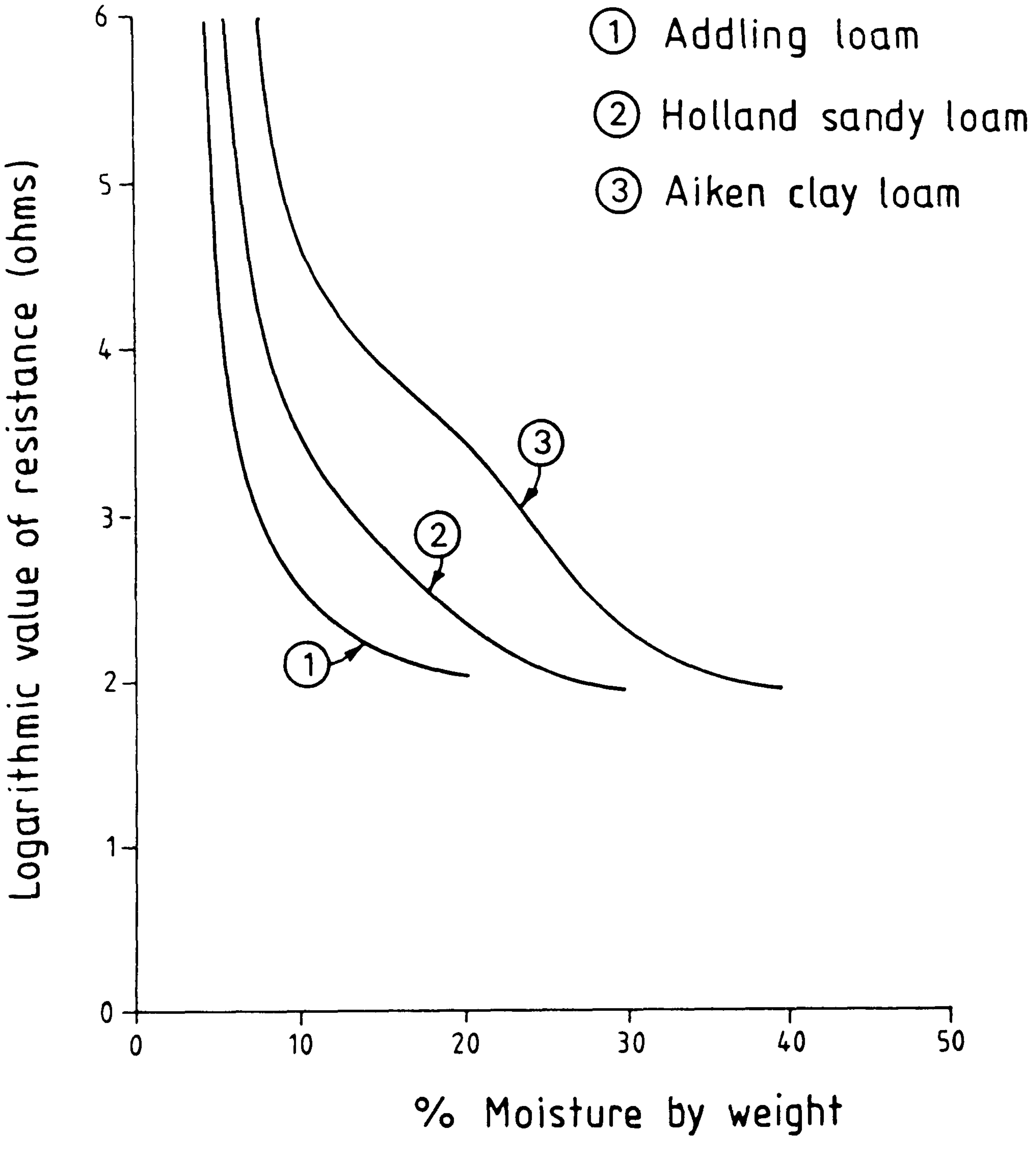

Figure 6·1 Typical resistance / water content curves (after Bouyoucos) of this work was the discovery that nylon cloth wrapped around the electrodes gavea more durable blocks, but unforunately did not give as high a protection from natural eddy currents as had the original gypsum coating. Thus a further improvement was to coat the nylon cloth with a gypsum slurry, and to cover the outside of this either with a pierced metal casing, or with a spray coating of an alcohol soluble nylon resin. These improved blocks (usually described as "soil moisture cells") proved to have field lives of at least several years, and were soon available from commercial manufacturers. (Ref. 6.2).

Tests on the new composite blocks soon showed other advantages, and in particular a marked increase in resistance measurements over those of the original type of simple gypsum block (Fig. 6.2). This increase in resistance readings obviously offers greater accuracy in measuring soil moisture levels, and a greater measurement sensitivity in the wetter soil states. (Fig. 6.3).

Currently, commercial soil moisture cells are cheaply available, together with field portable resistance measuring meters. The older simple gypsum blocks are also available, presumably to cater for conservative tastes.

More recently, other workers (Ref. 6.4) have devised modern internal electrodes in gypsum coatings, which they claim are

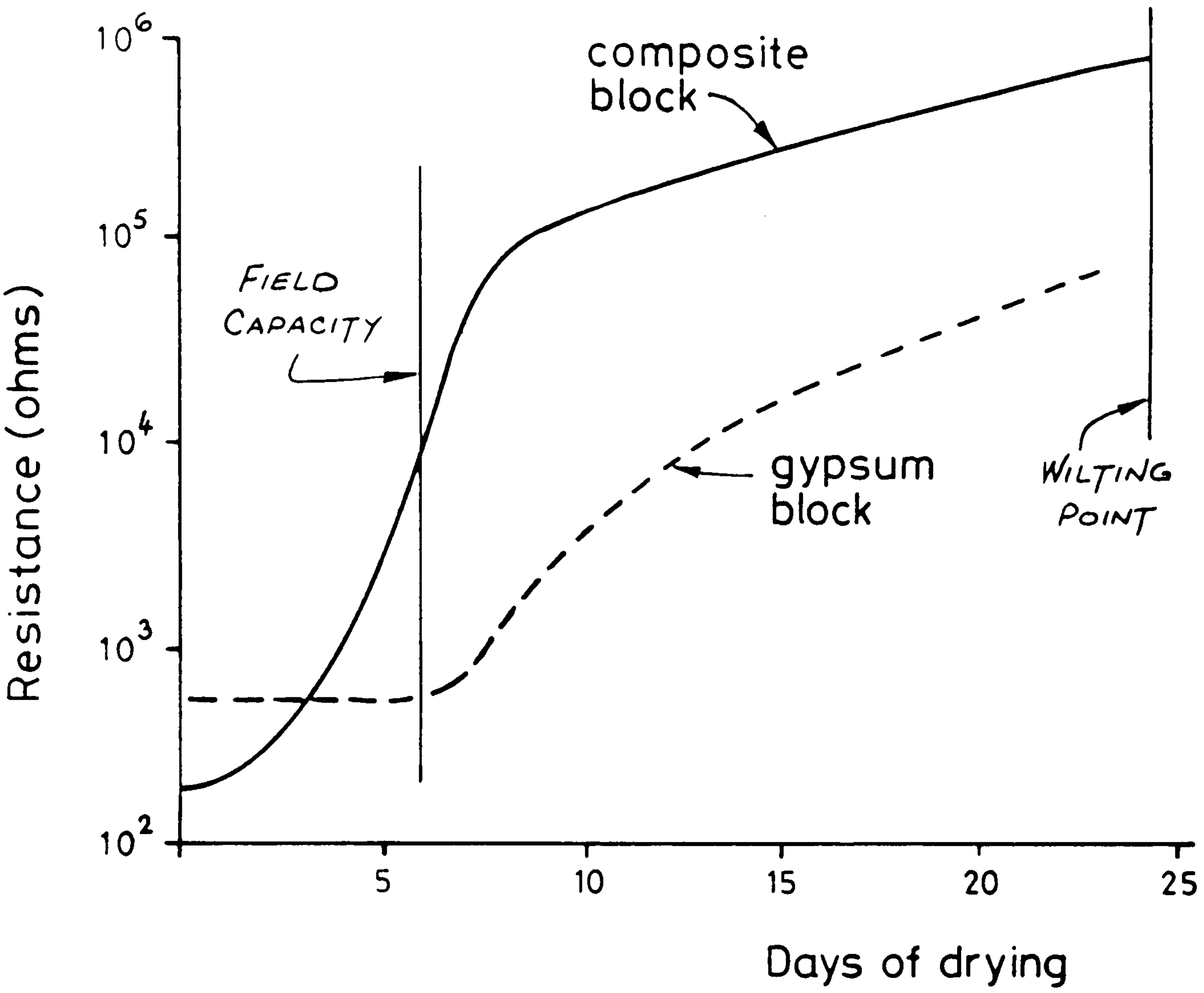

Figure 6·2 Comparison of composite gypsum blocks
(after Bouyoucos)
(Brookston Clay Loam soil)

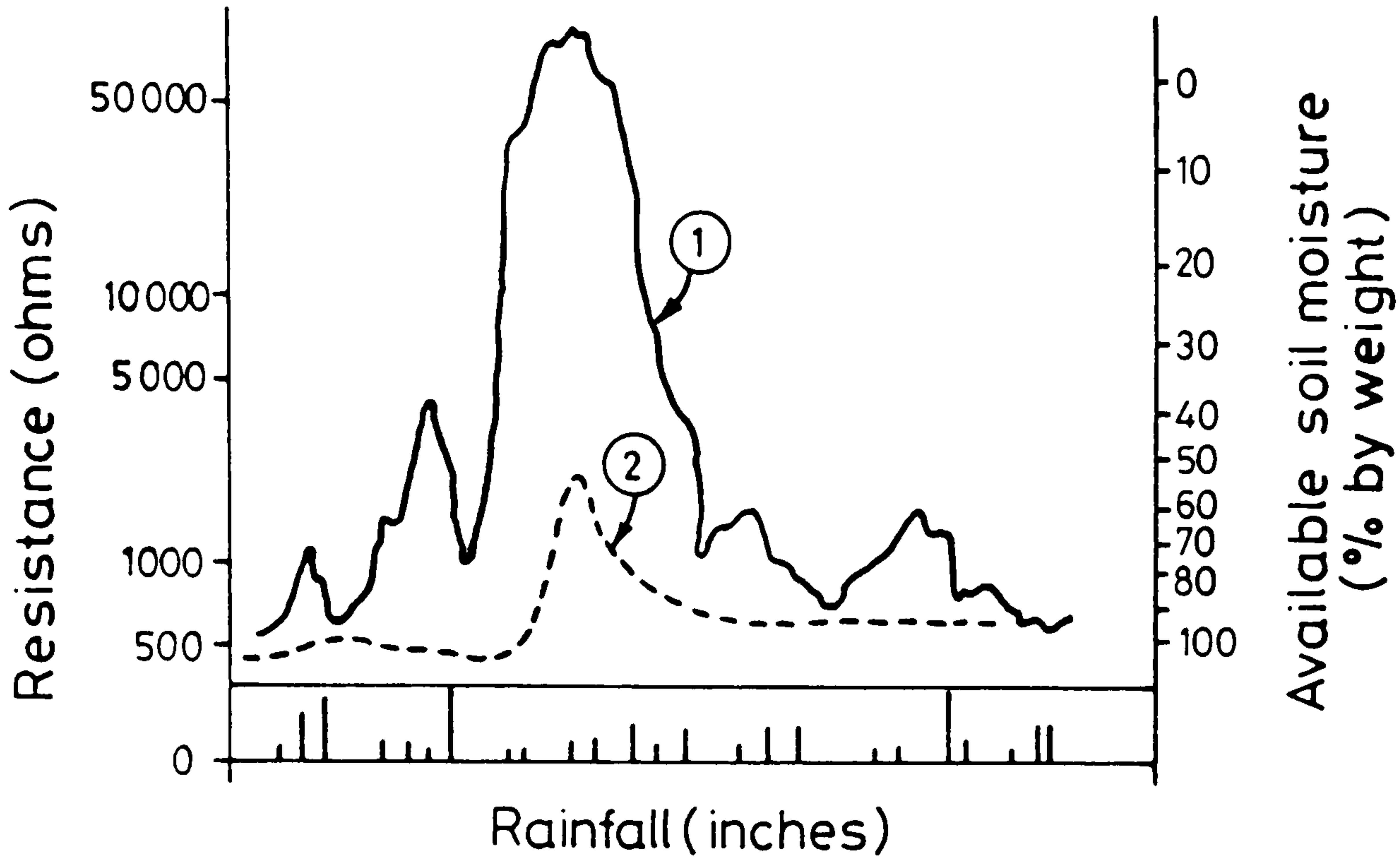

Figure 6·3 Monitoring of soil moisture levels at 6 inch ① & 36 inch ② depth over 3 month period (after Bouyoucos) accurate to 99% of the actual soil moisture level, are insensitive to soil temperature variations, and are sensitive and readable even in a saturated soils (Fig. 6.4). These devices, however, are as yet not available on the commercial market, and could not be used in the Al-Hasa field trials.

Gypsum blocks and soil moisture cells obviously produce electrical readings and thus have the inherent capacity to be read by electronic data loggers and to activate computer controlled irrigation systems. Some workers (Ref. 6.5) have already achieved this with simple and cheap direct current systems. Normally direct current systems would be considered inappropriate, since direct currents generate the spurious eddy currents that initially gave Bouyoucos so much trouble. However, the rapid sampling speeds of modern data loggers and computer controllers does allow the use of micro-second long direct current pulses, that are too brief to generate the unwanted eddy currents. Thus the exciting possibility of a cheap and simple automated control of irrigation releases appears possible, and trials of gypsum blocks and soil moisture cells in the Al-Hasa conditions seemed to be a worthwhile effort.

6.2 Calibrating Gypsum Blocks and Soil Moisture Cells

Bouyoucos soon realised (Ref. 6.2) that individual variations could occur in the manufacture of his blocks and cells, and thus that each unit should be calibrated individually.

He also realised that these devices were sensitive to the presence of soluble salts, which increase the electrolitic properties of soil moisture (Fig. 6.5).

Thus he advocated that each block and cell be individually calibrated in the soil in which it was to be used. The method of achieving this is to half fill a pan (120 mm x 200 mm x 100 mm deep) with the soil in question (and packed to its field density), place the gypsum block or soil moisture cell on the packed soil, and then fill the rest of the pan with the same soil packed to the same field density value. With the aid of a connected water reservoir, the soil sample is initially saturated and then progressively drained by placing the reservoir at various lower levels (Fig. 6.6) with the sample pan left on an accurate chemical balance, the soil moisture content can easily be obtained and related to the block or cell's equilibrium resistance value.

It is obviously sensible to use the local groundwater on the fluid in the reservoir, particularly when - as in the Al-Hasa situation - this groundwater is definitely saline.

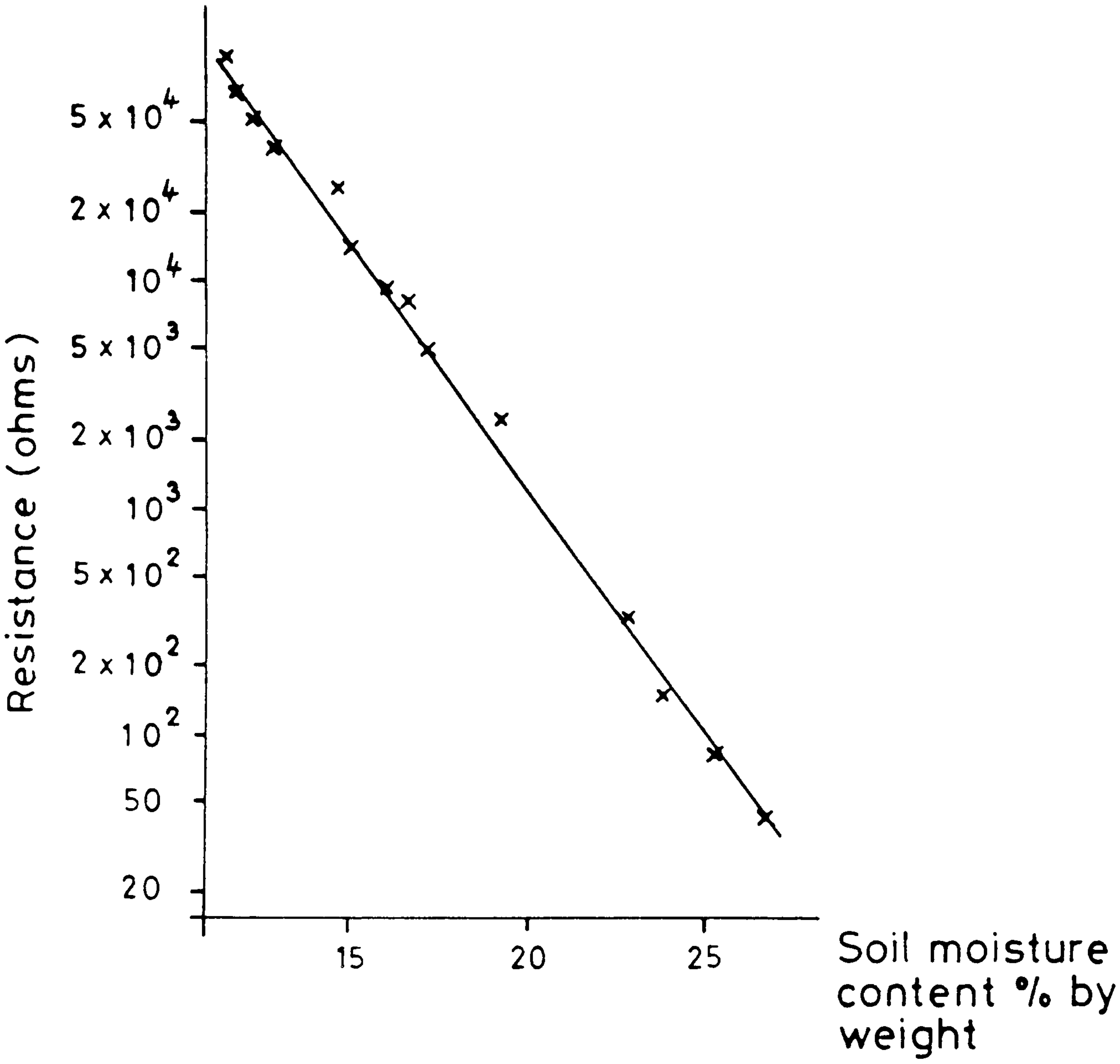

Figure 6·4 Resistance/water content relationship in calcoreous soil (after Kolev)

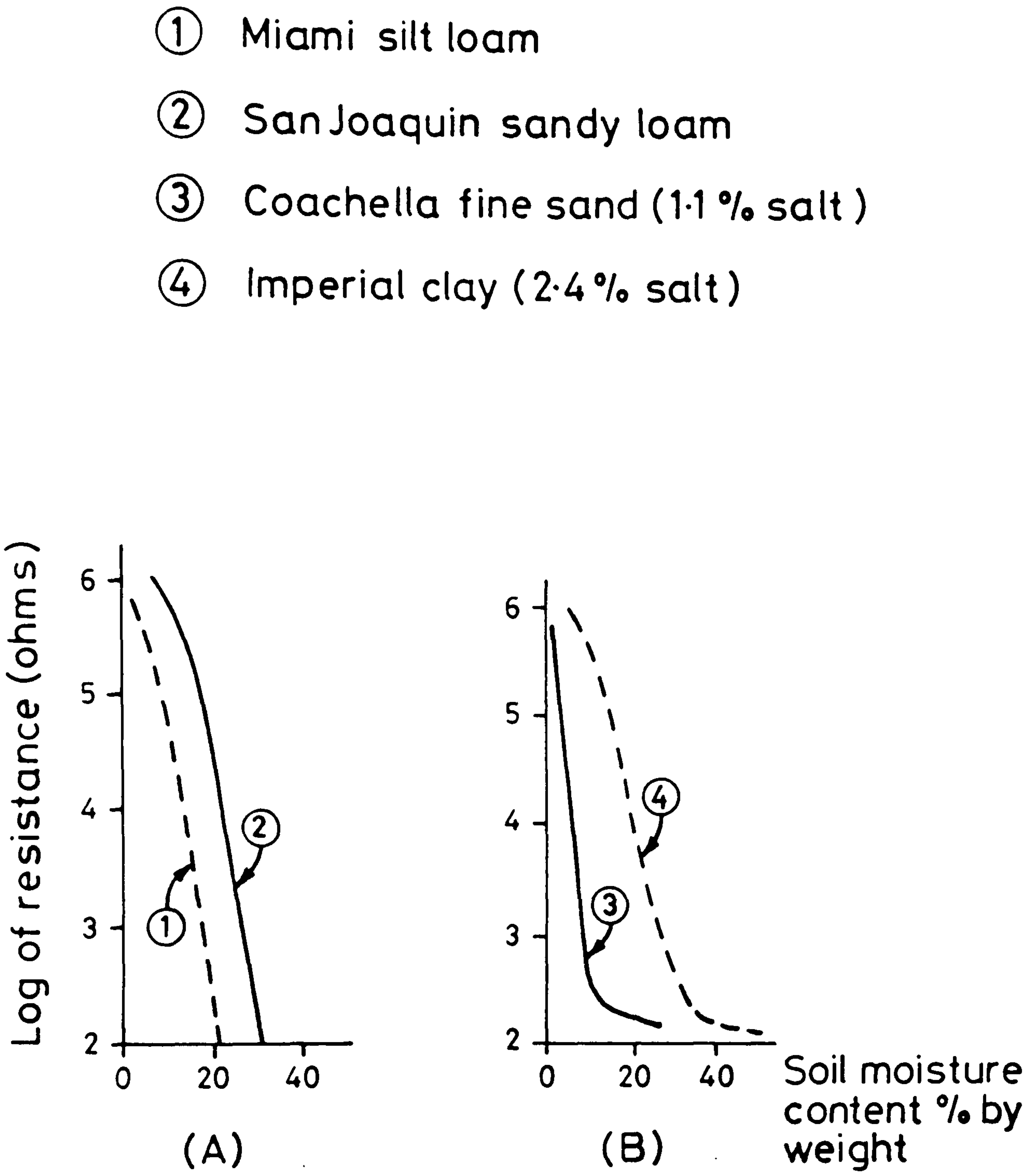

Figure 6·5 Soil moisture / resistance patterns in non saline (A) and saline (B) soils (after Bouyoucos)

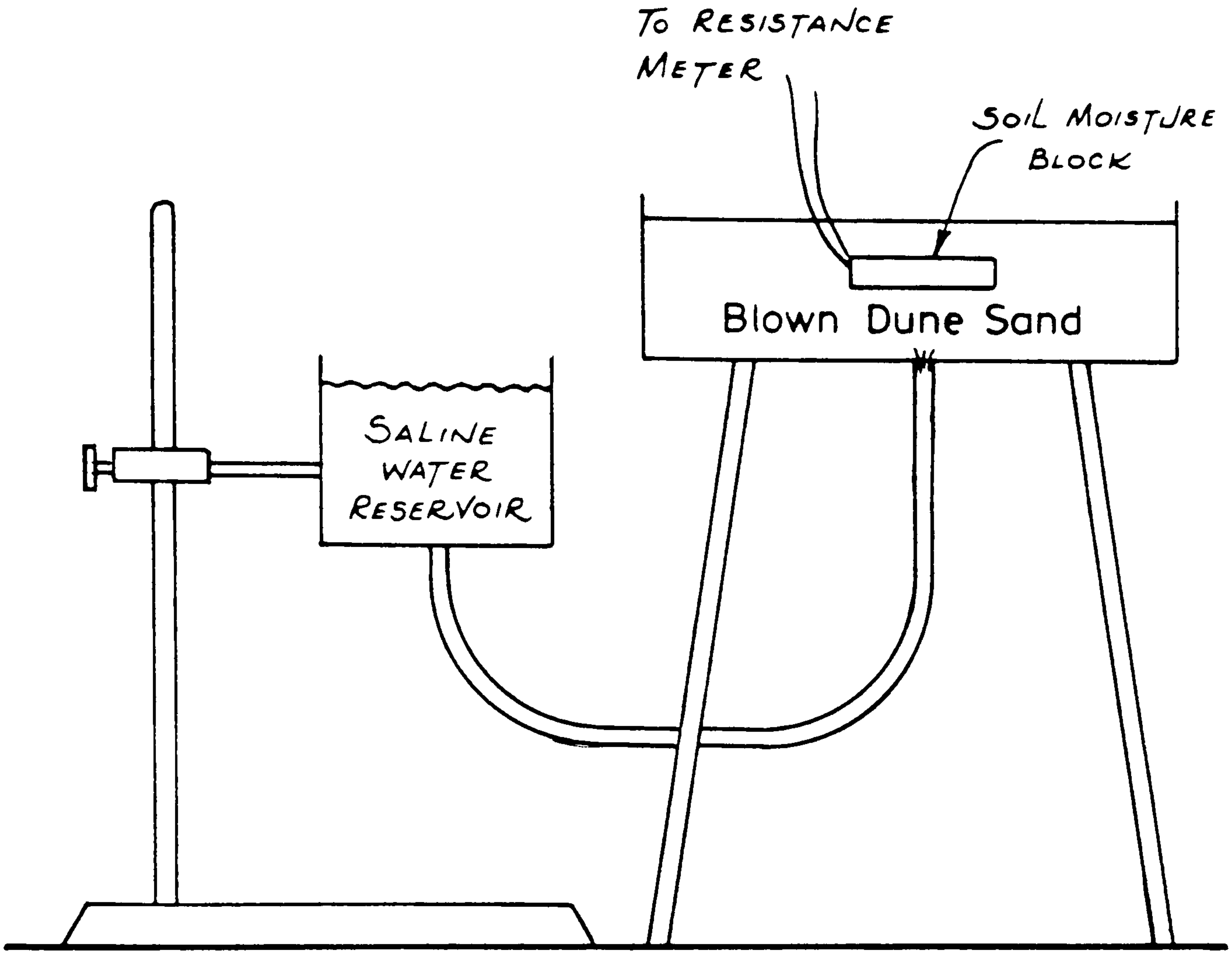

Figure 6·6 Method of mimicing ground water movements

This procedure was followed for the 22 gypsum blocks and soil moisture cells used in the Al-Hasa field trials.

6.3 Field Trials of Gypsum Blocks and Soil Moisture Cells

Gypsum blocks and soil moisture cells were placed in each of the four instrumented soil profiles (see Chapter 4).

The actual blocks and cells were those commercially available from the largest supplier (E.L.E. Ltd.) of soil moisture measuring equipment in Saudi Arabia.

In all 11 gypsum blocks and 11 soil moisture cells were installed in the four profiles and at each chosen level, a block and cell were installed immediately adjacent.

In general terms, the data gained (see Figs. 6.7 to 6.28) showed

(a) that the soil moisture cells are more accurate than are the gypsum blocks in producing field data that fits the instrument laboratory calibration curve (see Figs. 6.7 and 6.8, and Figs. 6.23 and 6.24 as examples)

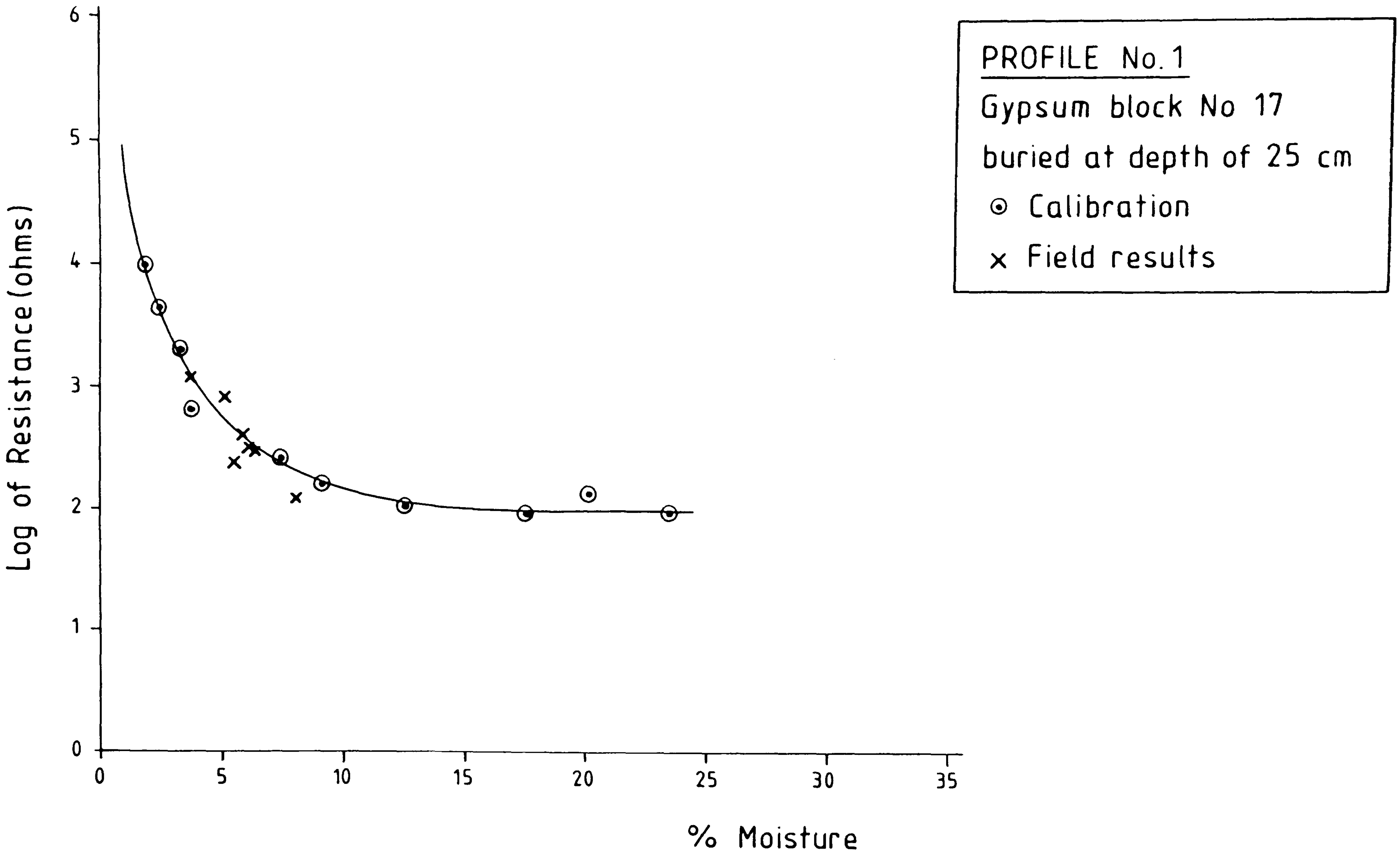
PROFILE No.1
Gypsum block No 17
buried at depth of 25 cm
⊙ Calibration
× Field results
Log of Resistance (ohms)
0
1
2
3
4
5
6
0
5
10
15
20
25
30
35
% Moisture

Figure 6·7

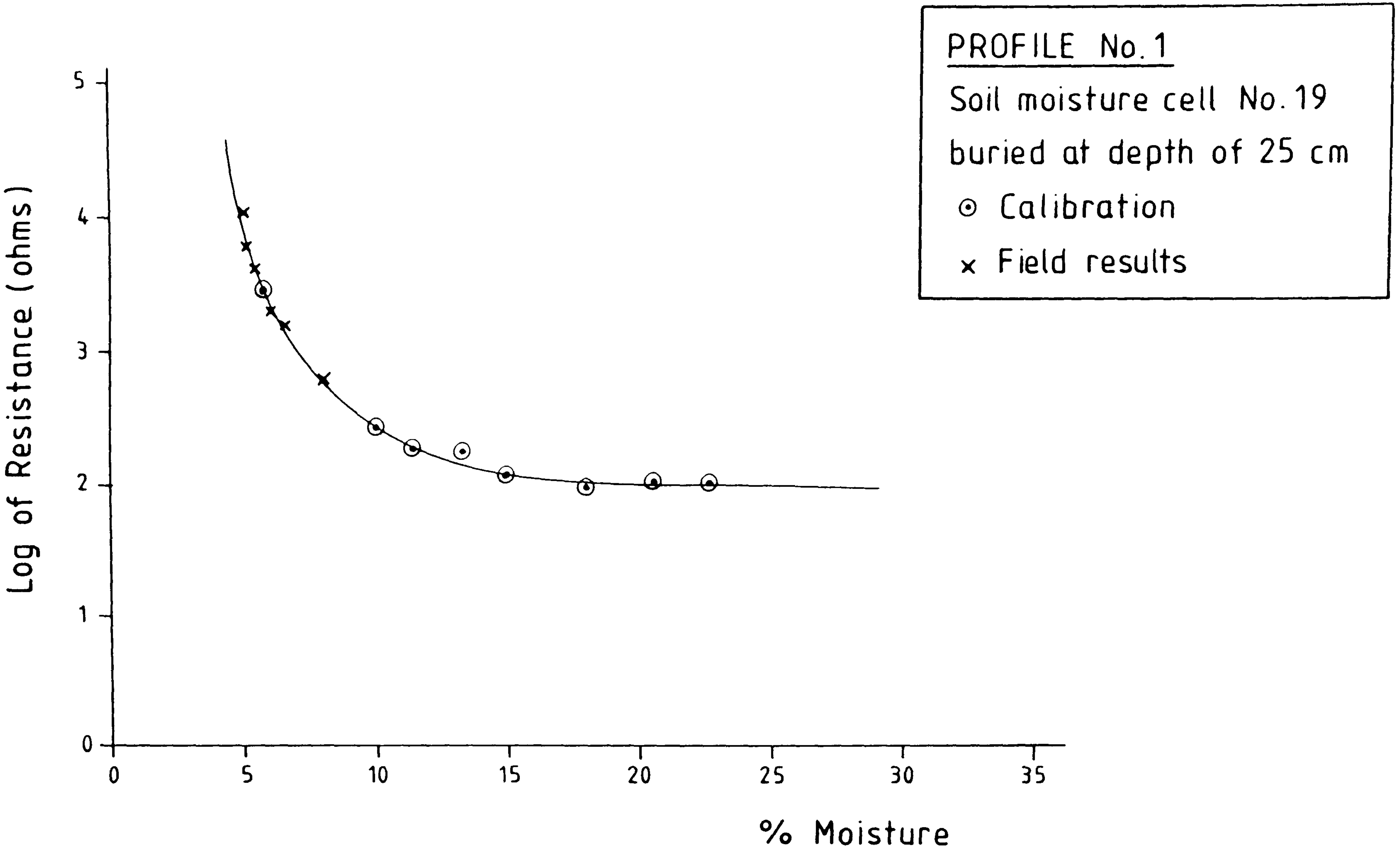
PROFILE No. 1
Soil moisture cell No. 19
buried at depth of 25 cm
⊙ Calibration
× Field results
Log of Resistance (ohms)
0
1
2
3
4
5
0
5
10
15
20
25
30
35
% Moisture

Figure 6·8

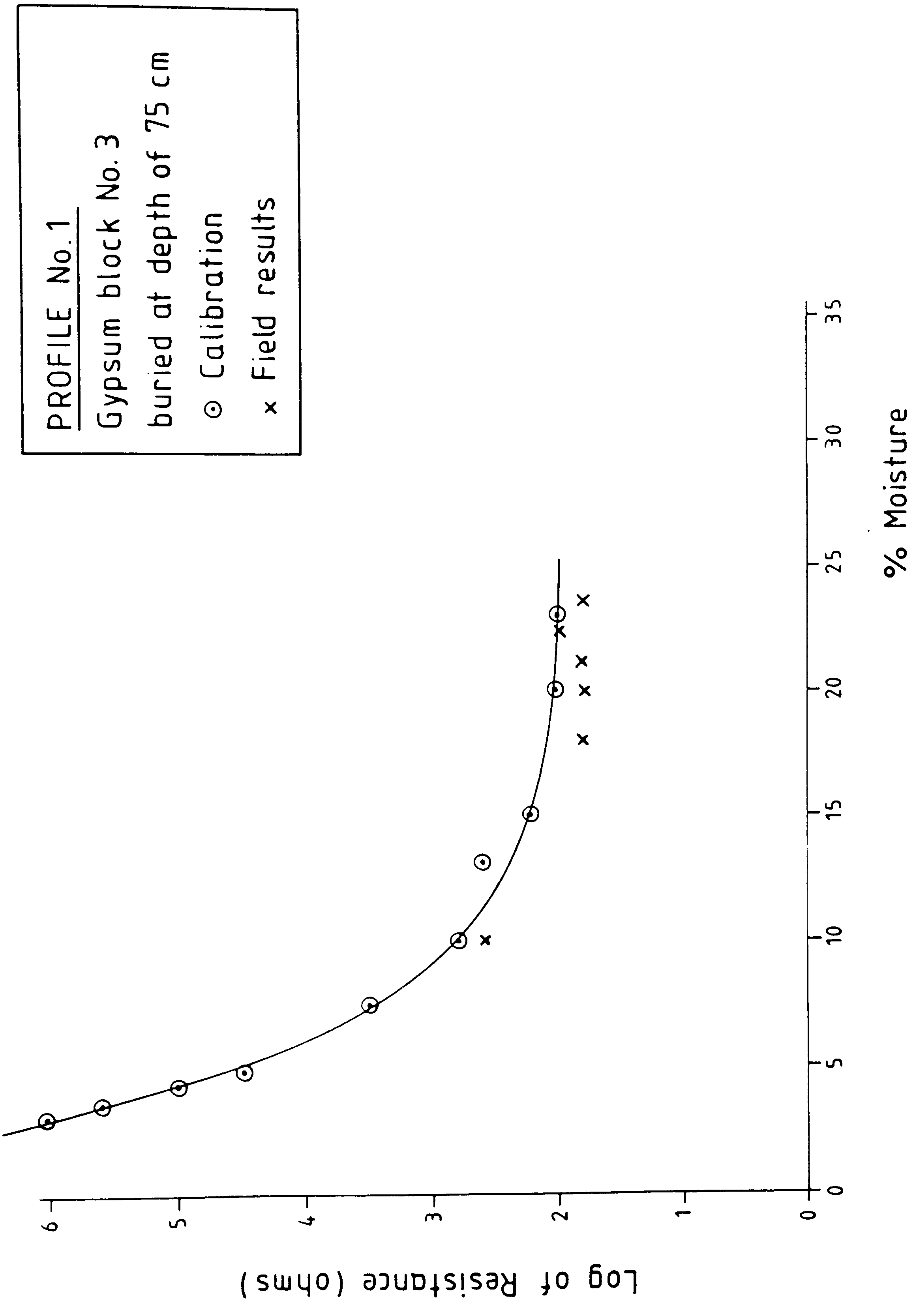
PROFILE No. 1
Gypsum block No. 3
buried at depth of 75 cm
⊙ Calibration
× Field results
Log of Resistance (ohms)
0
1
2
3
4
5
6
% Moisture
0
5
10
15
20
25
30
35

Figure 6·9

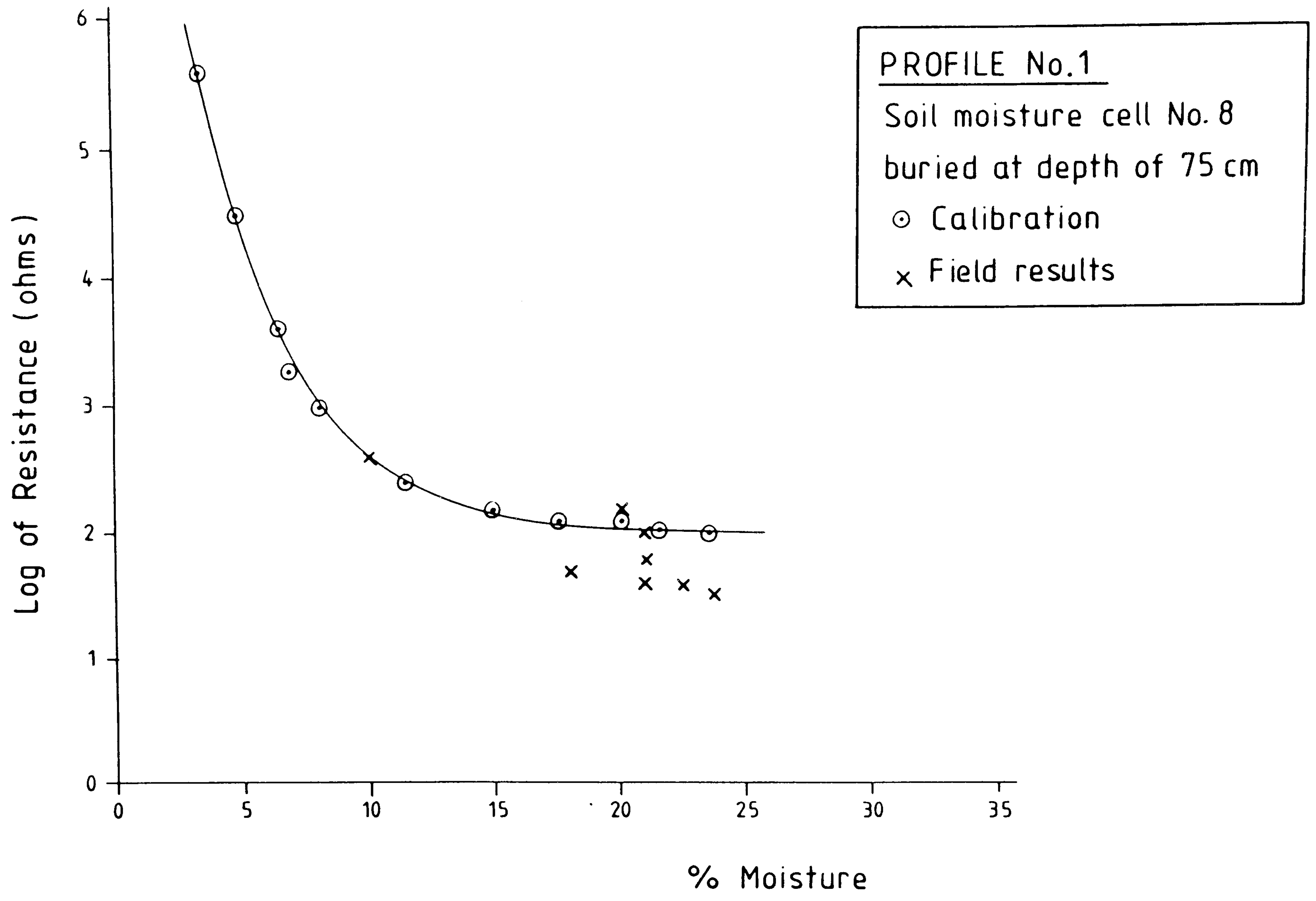
PROFILE No.1
Soil moisture cell No. 8
buried at depth of 75 cm
⊙ Calibration
× Field results
Log of Resistance (ohms)
0
1
2
3
4
5
6
0
5
10
15
20
25
30
35
% Moisture

Figure 6·10

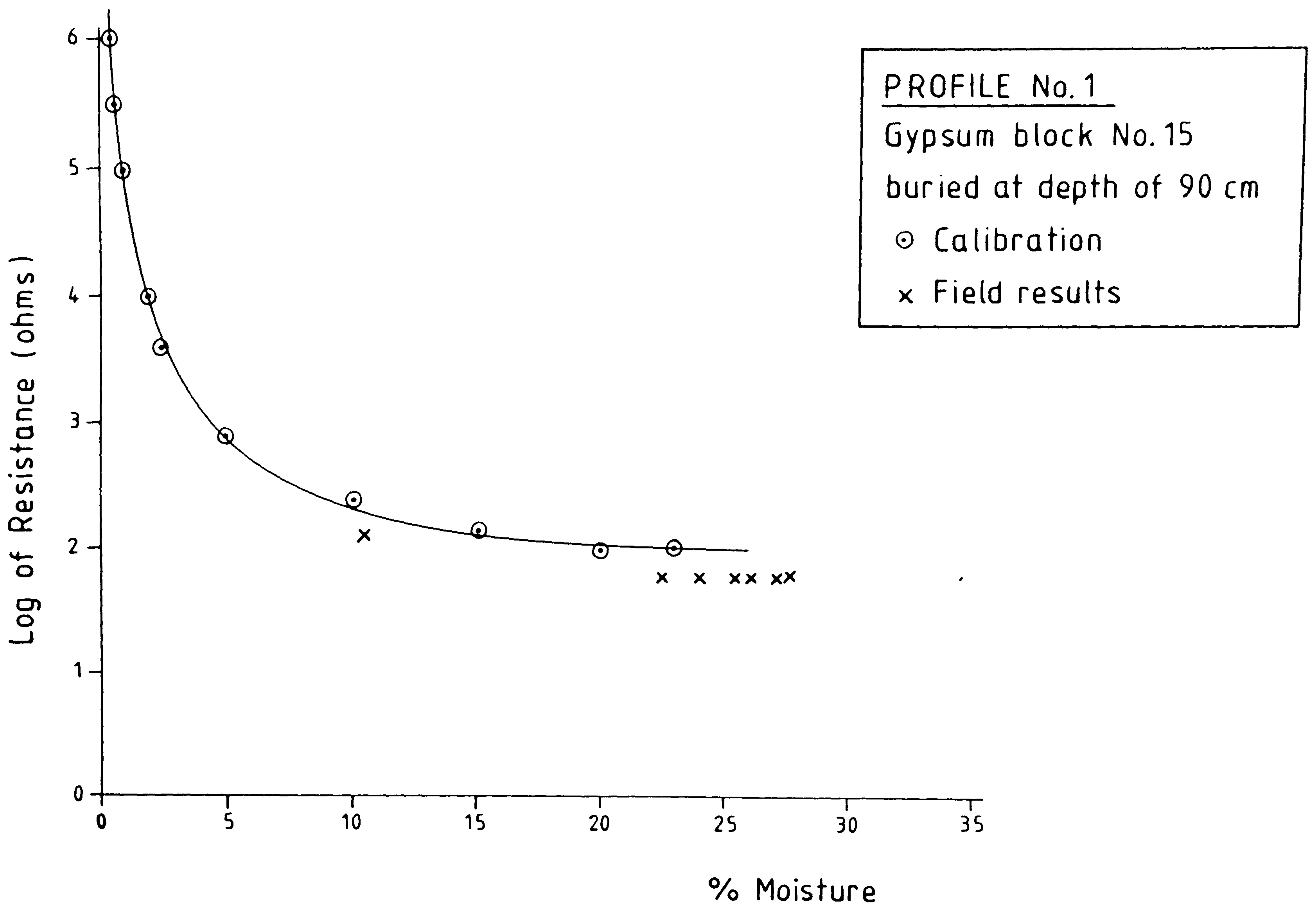
PROFILE No. 1
Gypsum block No. 15
buried at depth of 90 cm
⊙ Calibration
× Field results
Log of Resistance (ohms)
0
1
2
3
4
5
6
0
5
10
15
20
25
30
35
% Moisture

Figure 6·11

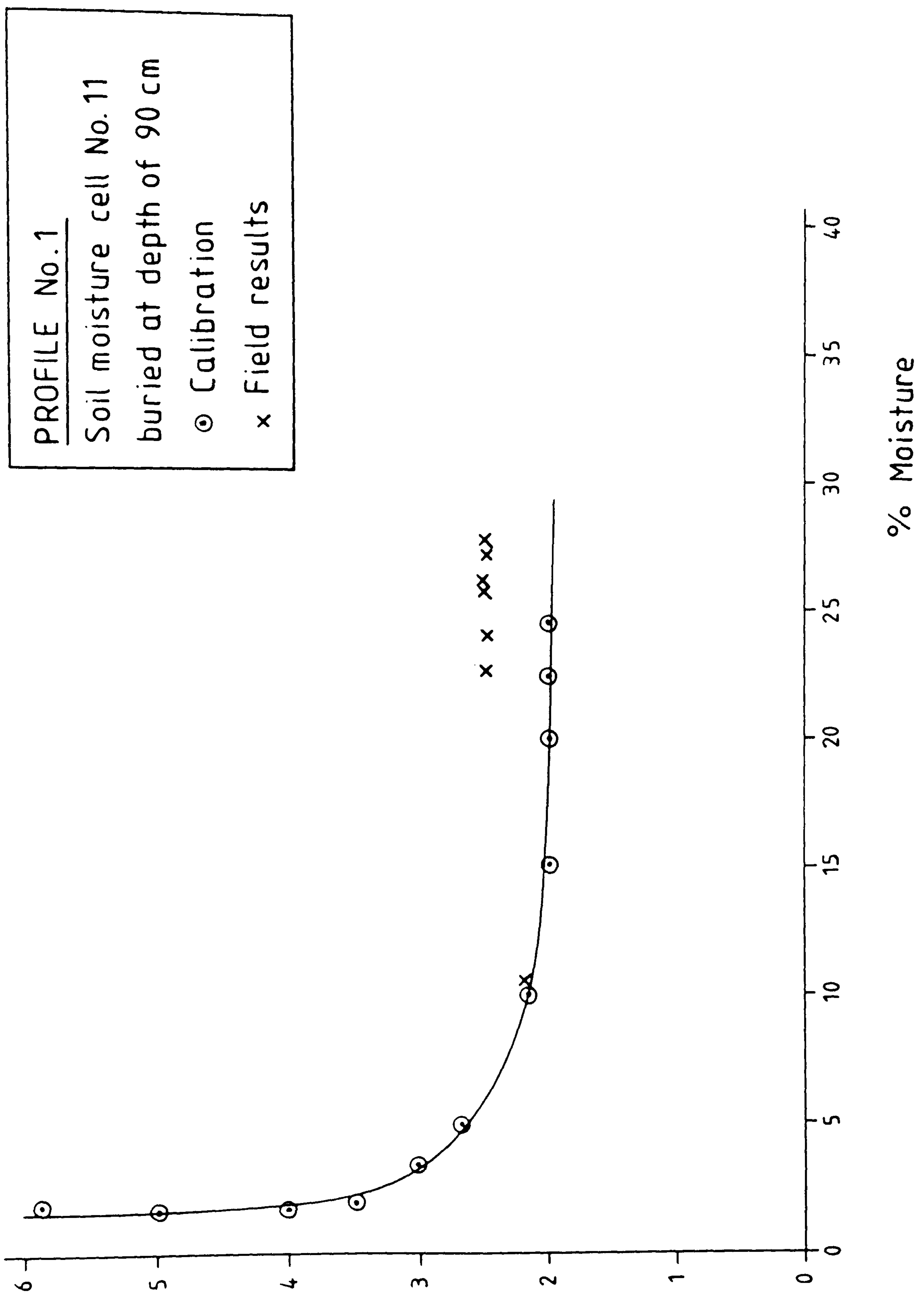
PROFILE No. 1
Soil moisture cell No. 11
buried at depth of 90 cm
⊙ Calibration
× Field results
Log of Resistance (ohms)
0
1
2
3
4
5
6
% Moisture
0
5
10
15
20
25
30
35
40

Figure 6·12

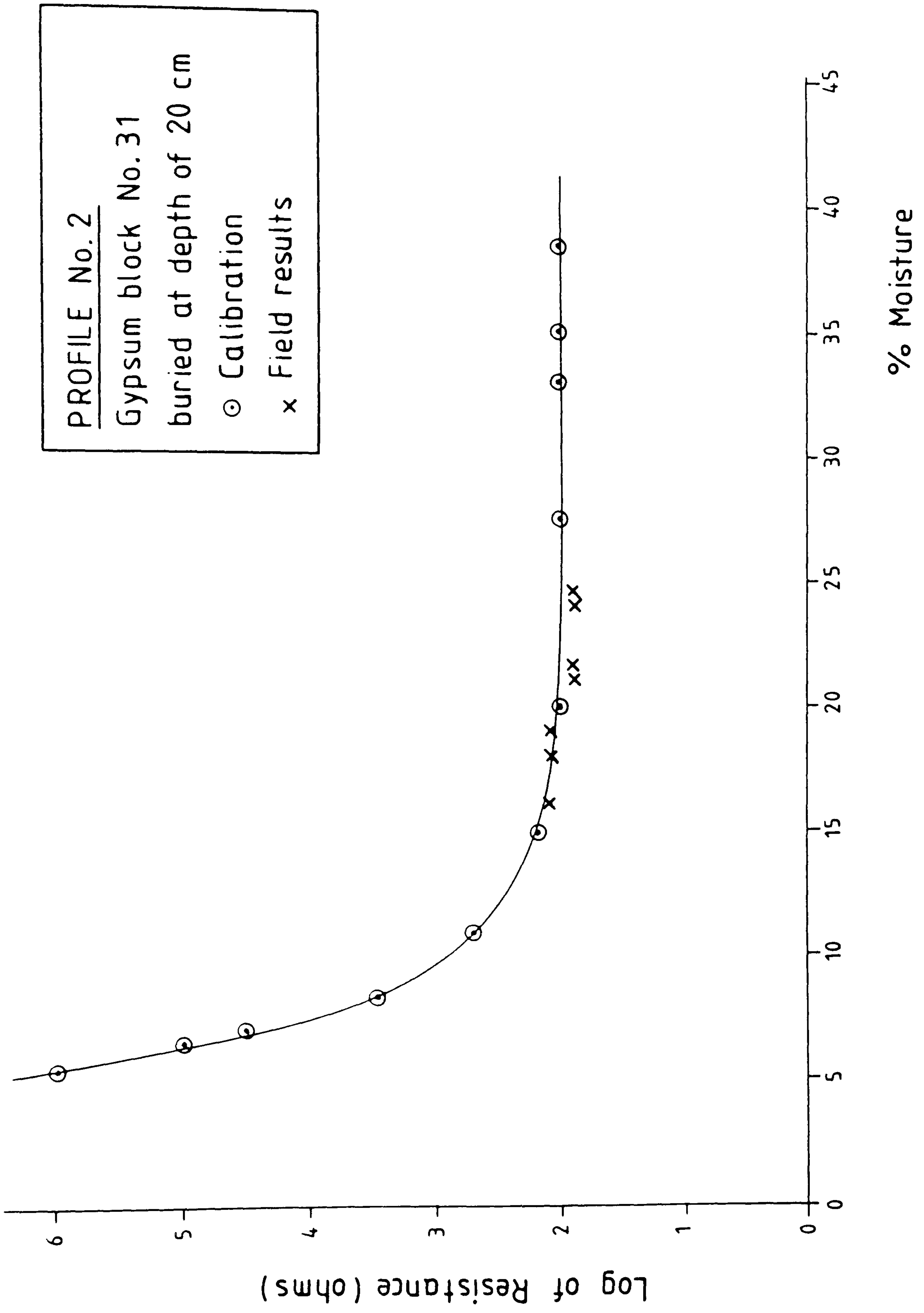
PROFILE No. 2
Gypsum block No. 31
buried at depth of 20 cm
⊙ Calibration
× Field results
Log of Resistance (ohms)
0
1
2
3
4
5
6
% Moisture
0
5
10
15
20
25
30
35
40
45

Figure 6·13

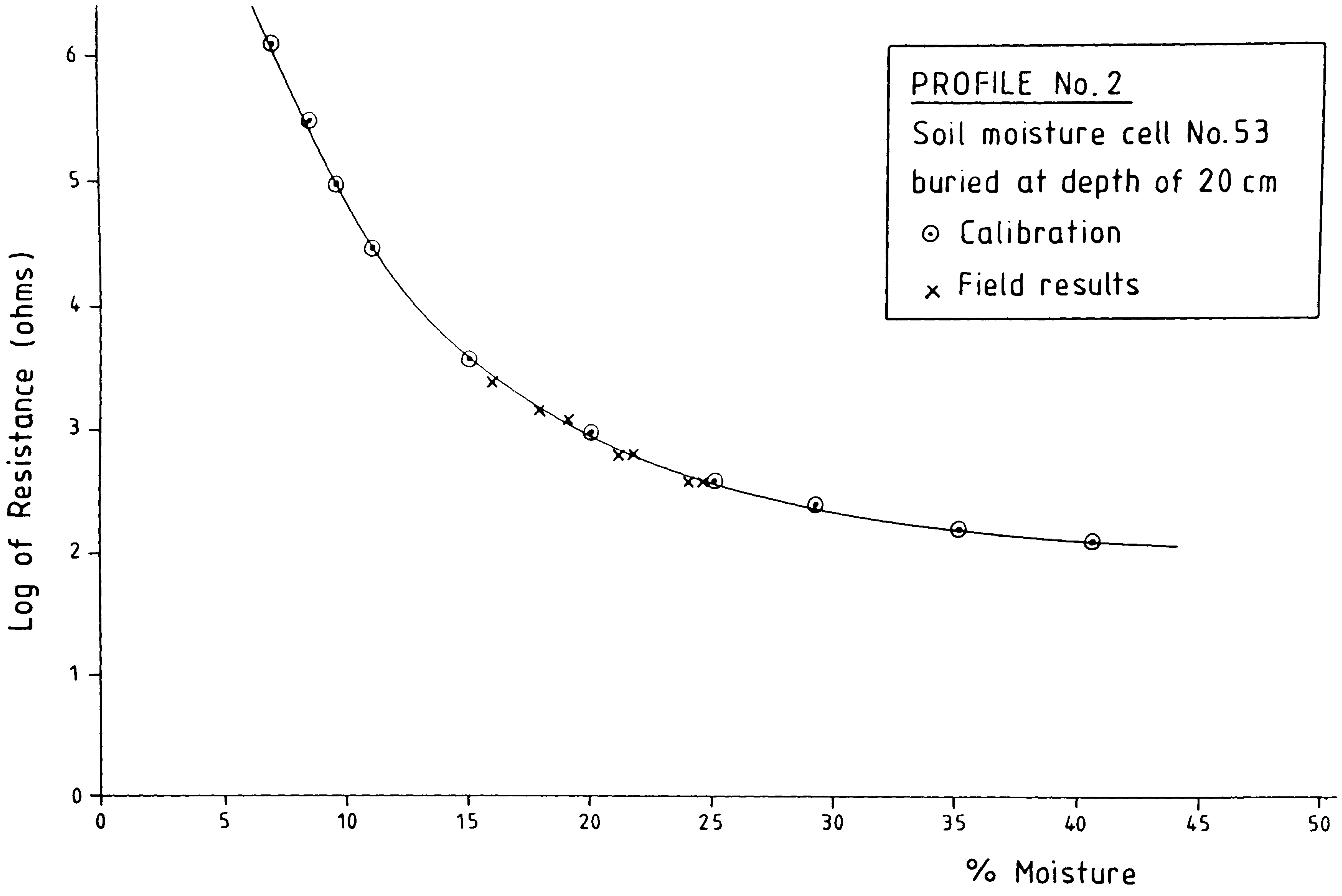
PROFILE No. 2
Soil moisture cell No.53
buried at depth of 20 cm
⊙ Calibration
× Field results
Log of Resistance (ohms)
0
1
2
3
4
5
6
% Moisture
0
5
10
15
20
25
30
35
40
45
50

Figure 6·14

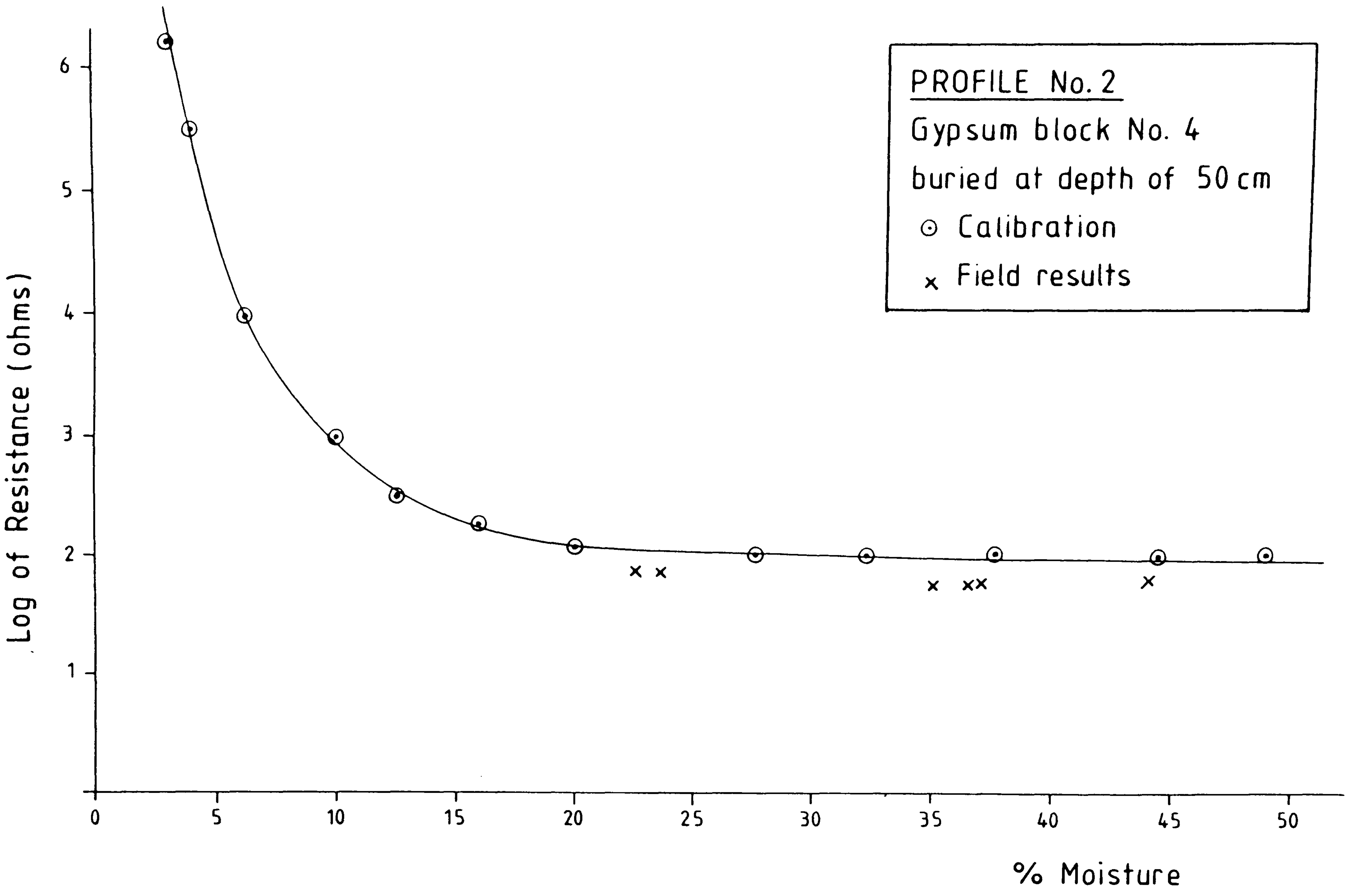
PROFILE No. 2
Gypsum block No. 4
buried at depth of 50 cm
⊙ Calibration
× Field results
Log of Resistance (ohms)
6
5
4
3
2
1
0
5
10
15
20
25
30
35
40
45
50
% Moisture

Figure 6·15

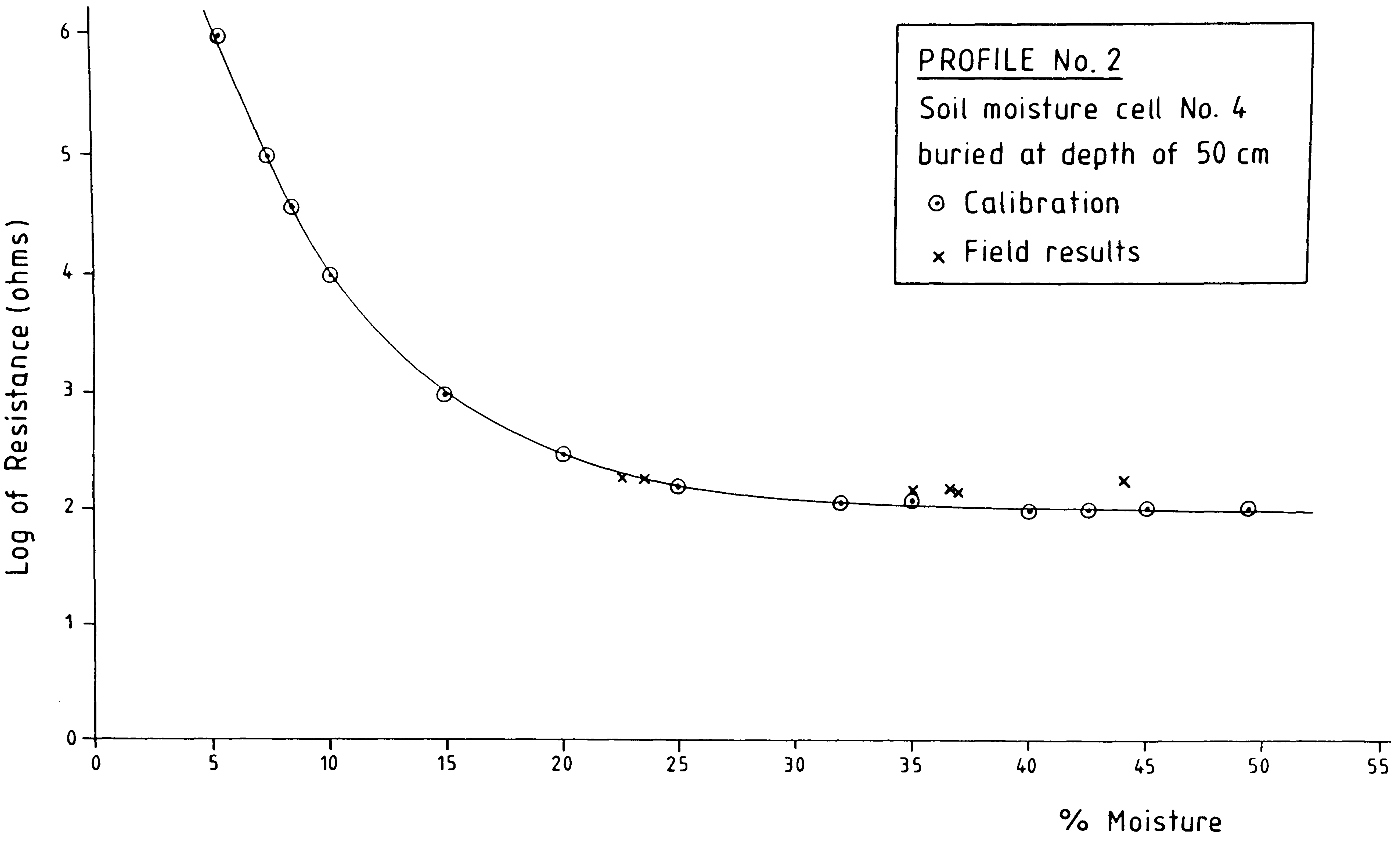
PROFILE No. 2
Soil moisture cell No. 4
buried at depth of 50 cm
⊙ Calibration
× Field results
Log of Resistance (ohms)
0
1
2
3
4
5
6
% Moisture
0
5
10
15
20
25
30
35
40
45
50
55

Figure 6·16

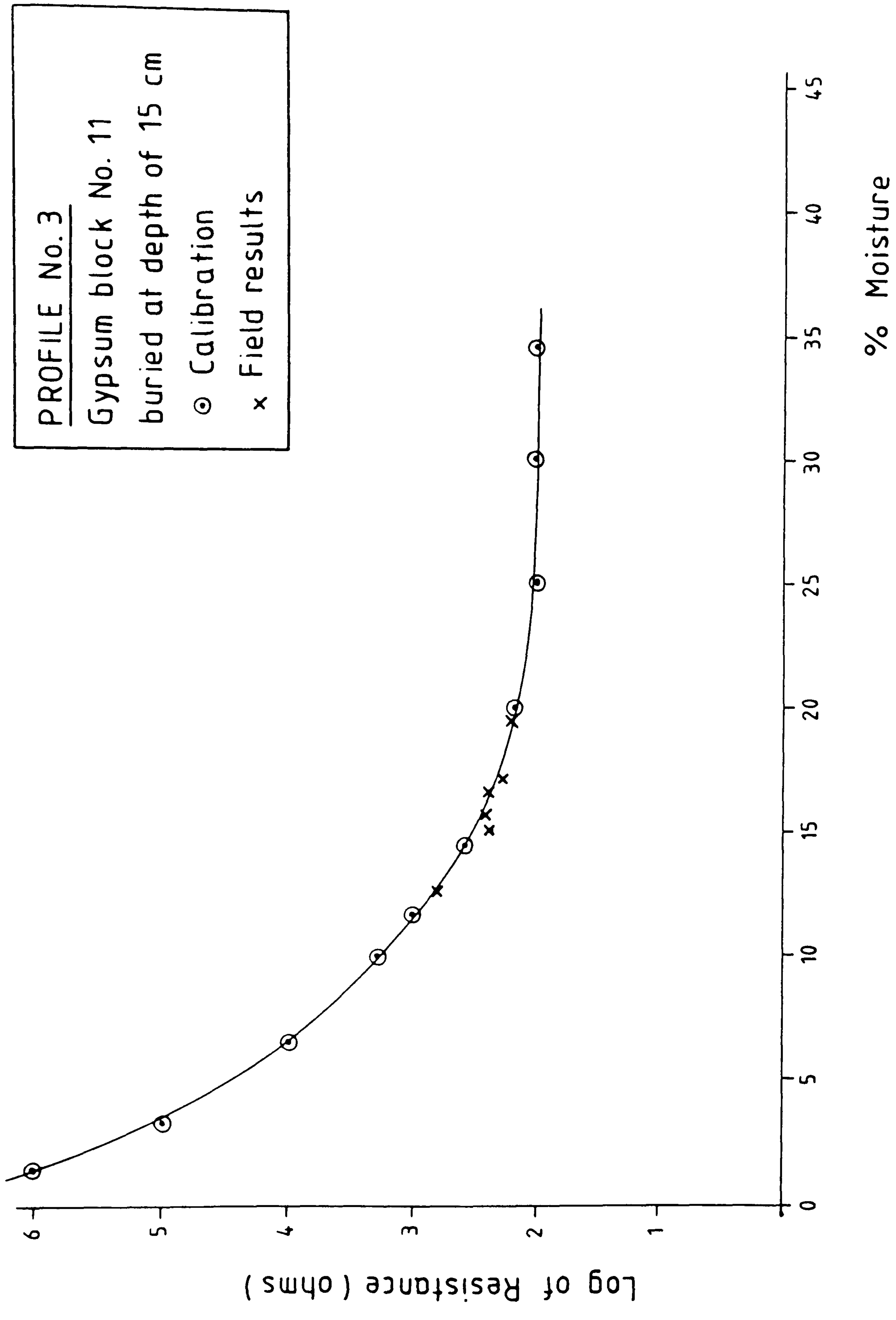
PROFILE No. 3
Gypsum block No. 11
buried at depth of 15 cm
⊙ Calibration
× Field results
Log of Resistance (ohms)
6
5
4
3
2
1
0
5
10
15
20
25
30
35
40
45
% Moisture

Figure 6·17

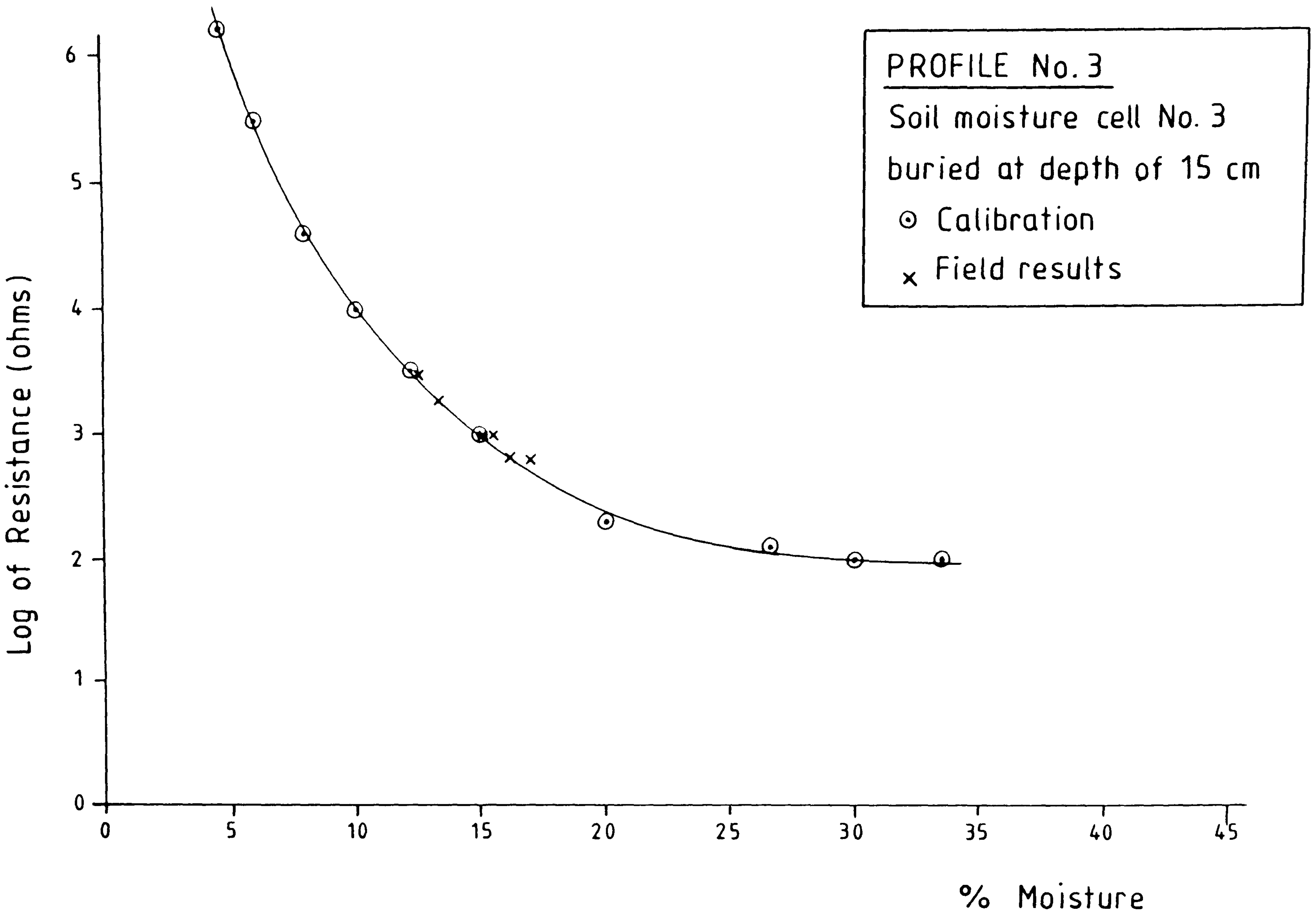
PROFILE No. 3
Soil moisture cell No. 3
buried at depth of 15 cm
⊙ Calibration
× Field results
Log of Resistance (ohms)
0
1
2
3
4
5
6
0
5
10
15
20
25
30
35
40
45
% Moisture

Figure 6·18


PROFILE No. 3
Gypsum block No. 14
buried at depth of 50 cm
⊙ Calibration
× Field results
Log of Resistance (ohms)
% Moisture
0
1
2
3
4
5
6
7
0
5
10
15
20
25
30
35
40
45
50
55
60


PROFILE No. 3
Soil moisture cell No.18
buried at depth of 50 cm
⊙ Calibration
× Field results
Log of Resistance (ohms)
0
1
2
3
4
5
6
7
% Moisture
0
5
10
15
20
25
30
35
40
45
50
55
60

Figure 6·20

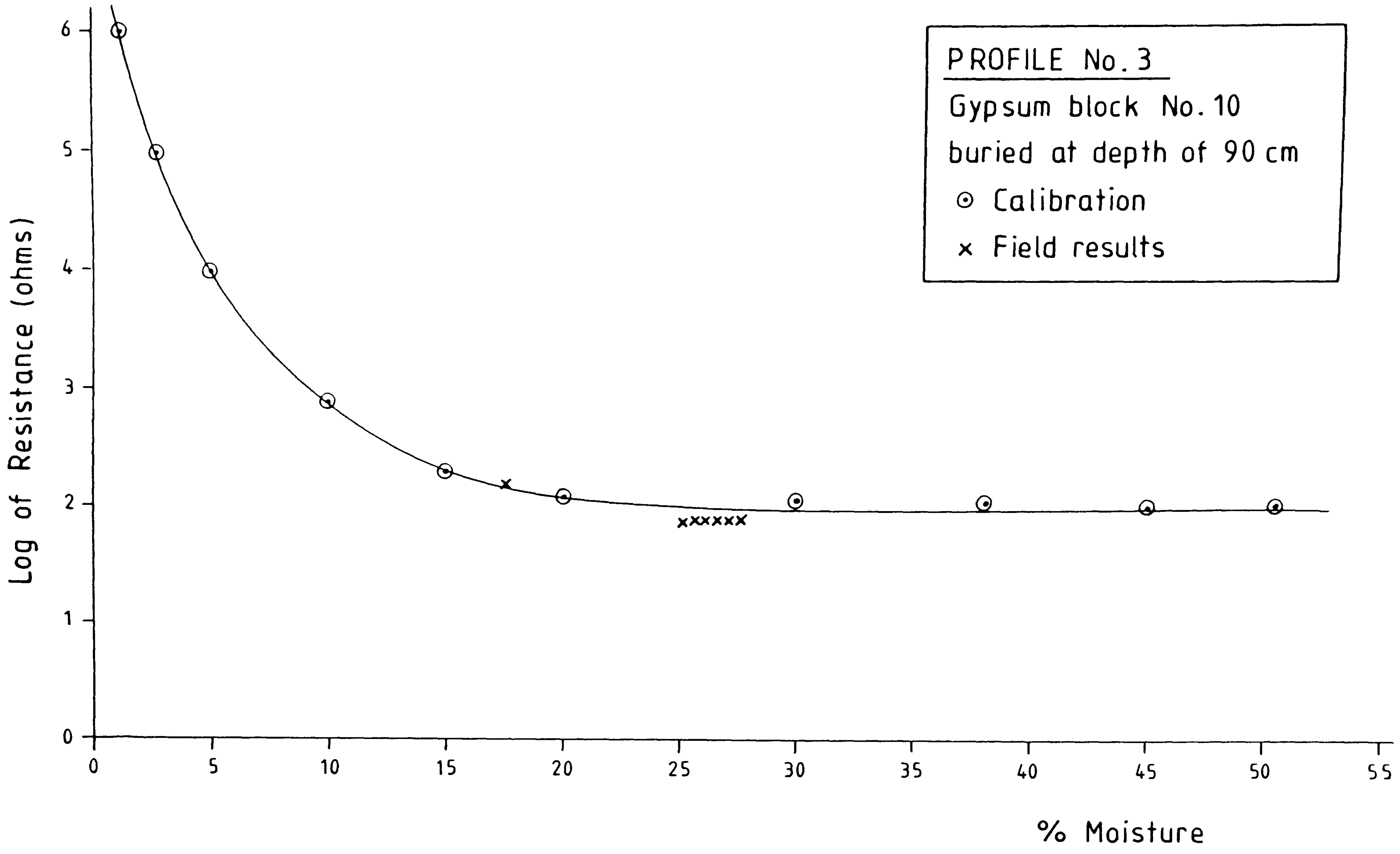
PROFILE No. 3
Gypsum block No. 10
buried at depth of 90 cm
⊙ Calibration
× Field results
Log of Resistance (ohms)
0
1
2
3
4
5
6
% Moisture
0
5
10
15
20
25
30
35
40
45
50
55

Figure 6·21

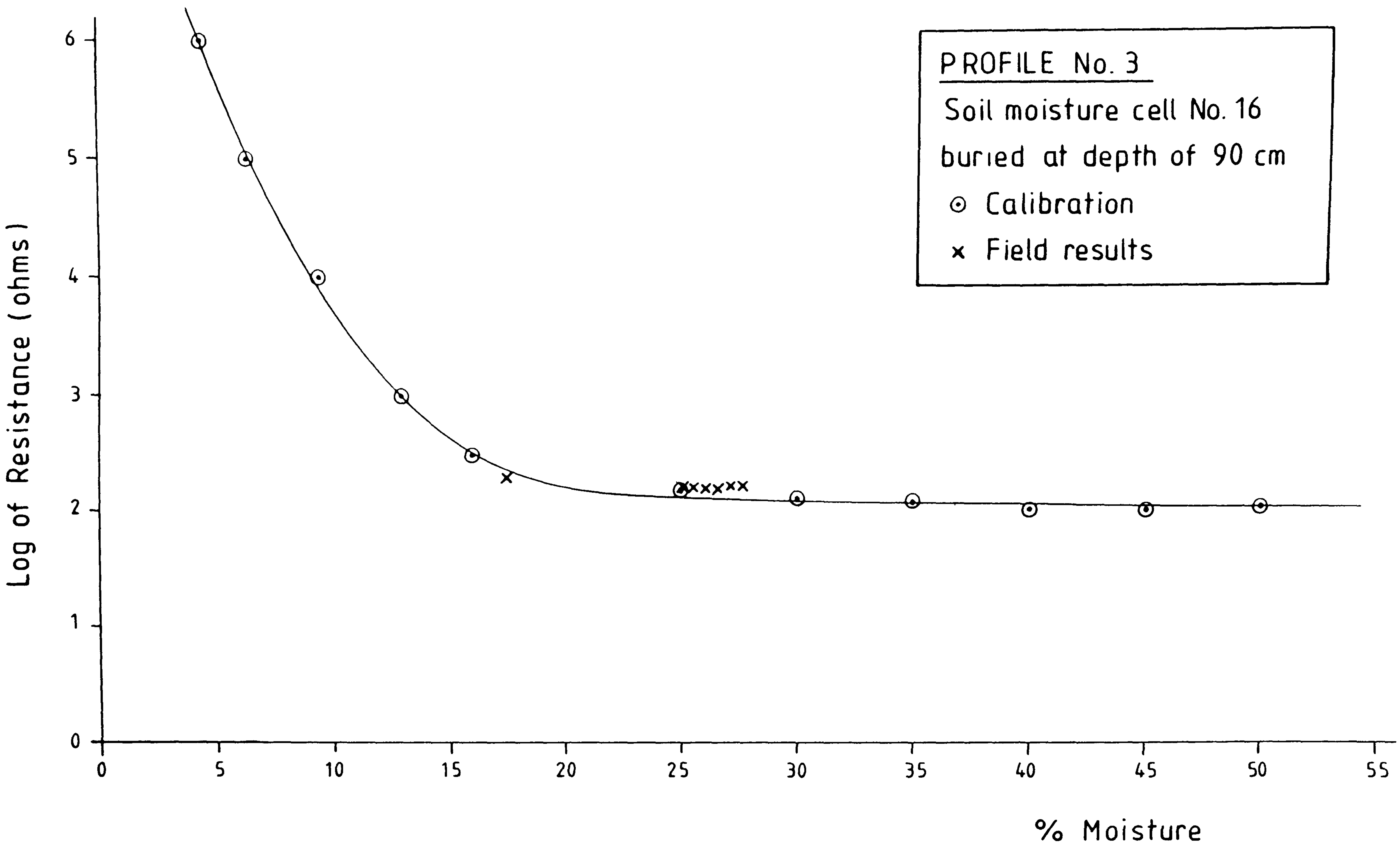
PROFILE No. 3
Soil moisture cell No. 16
buried at depth of 90 cm
⊙ Calibration
× Field results
Log of Resistance (ohms)
0
1
2
3
4
5
6
0
5
10
15
20
25
30
35
40
45
50
55
% Moisture

Figure 6·22

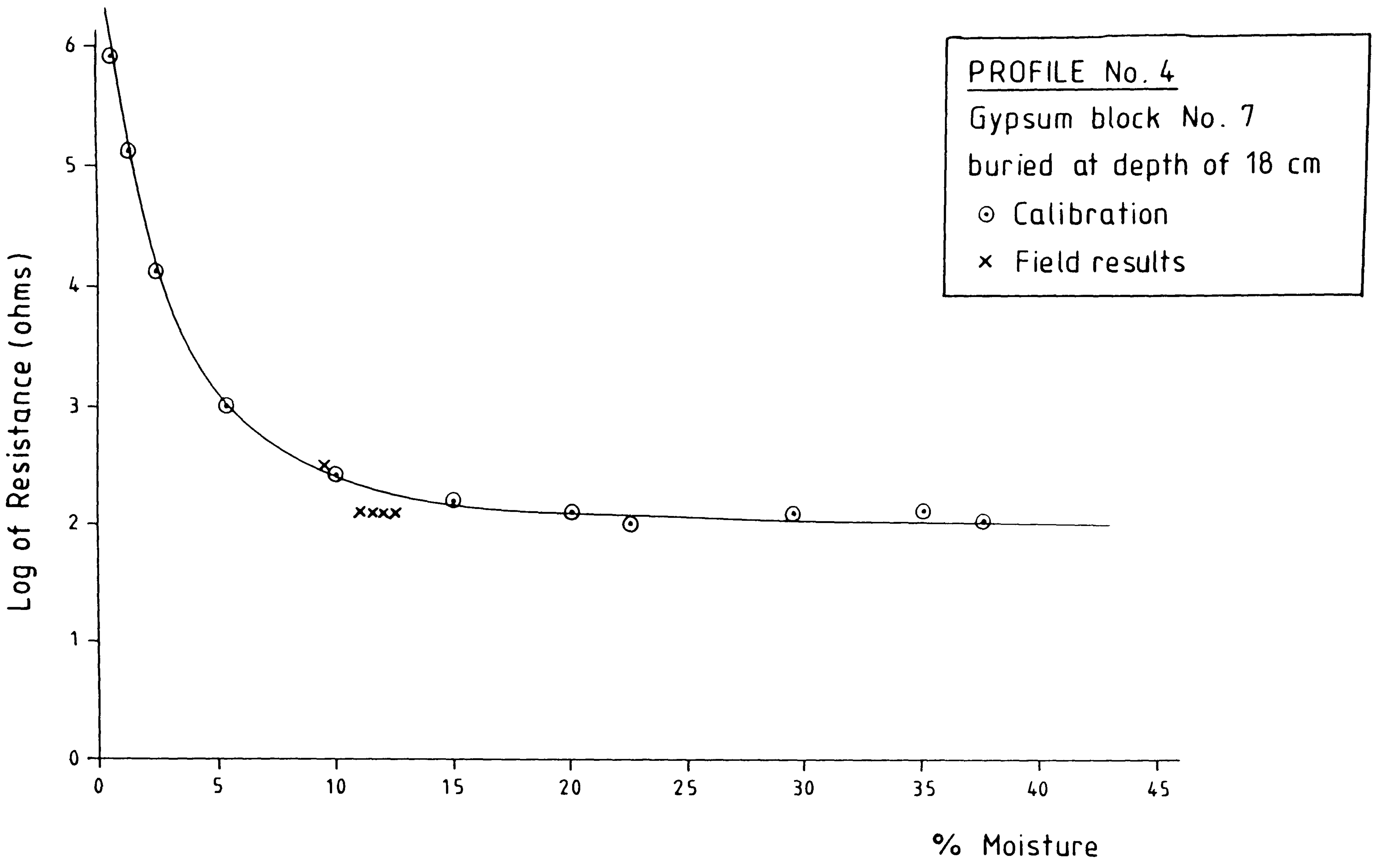
PROFILE No. 4
Gypsum block No. 7
buried at depth of 18 cm
⊙ Calibration
× Field results
Log of Resistance (ohms)
0
1
2
3
4
5
6
0
5
10
15
20
25
30
35
40
45
% Moisture

Figure 6·23

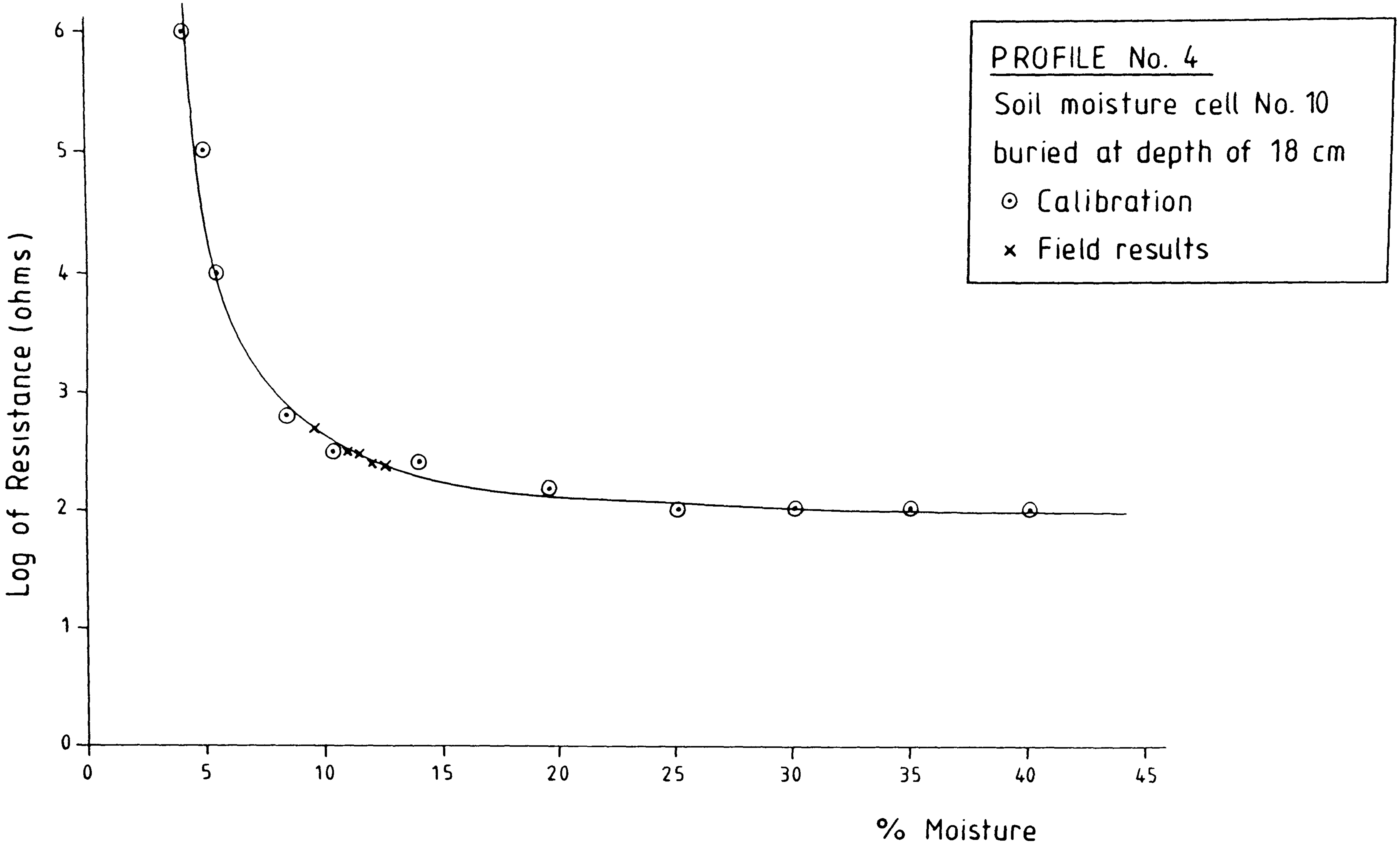
PROFILE No. 4
Soil moisture cell No. 10
buried at depth of 18 cm
⊙ Calibration
× Field results
Log of Resistance (ohms)
6
5
4
3
2
1
0
0
5
10
15
20
25
30
35
40
45
% Moisture

Figure 6·24

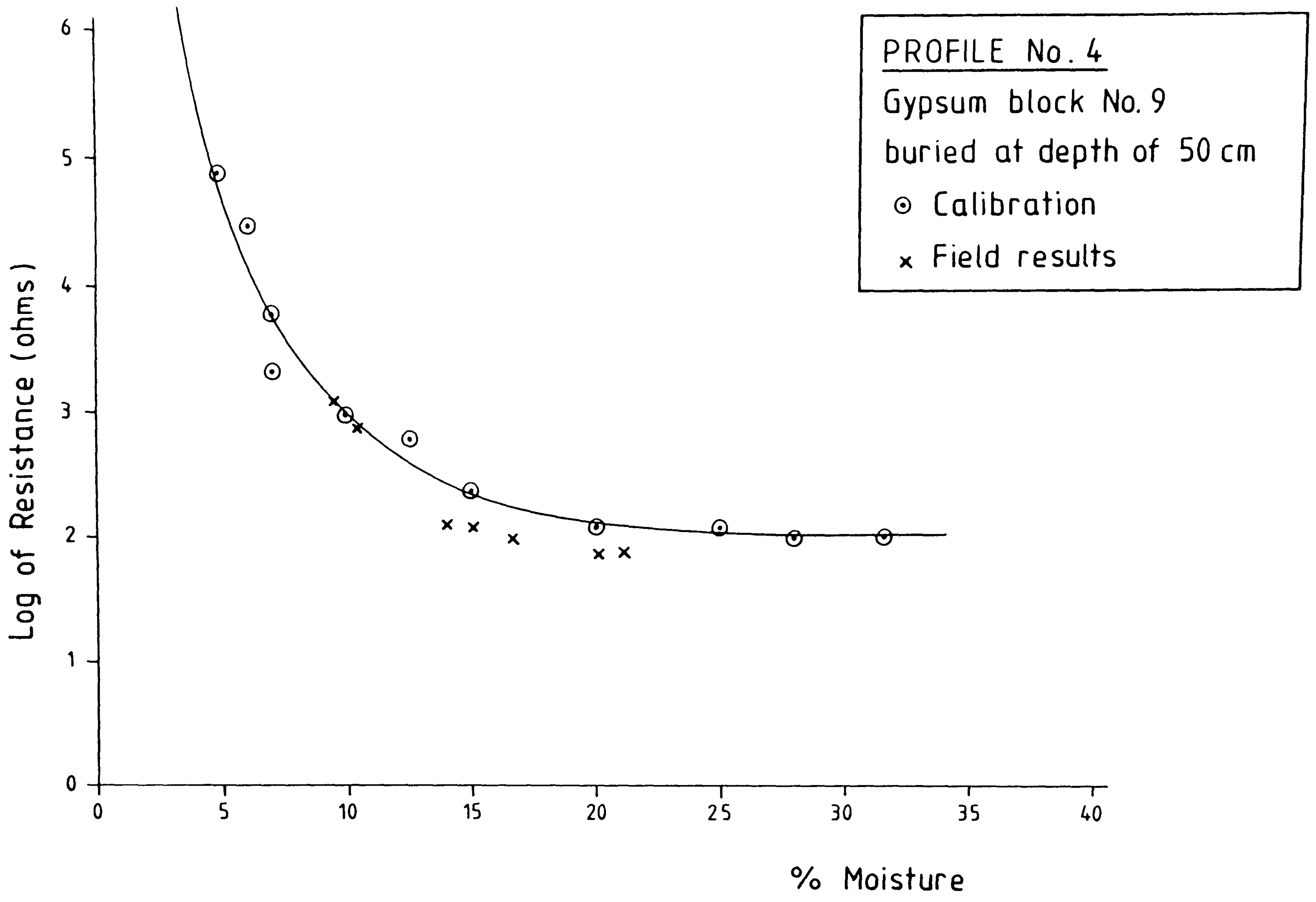
PROFILE No. 4
Gypsum block No. 9
buried at depth of 50 cm
⊙ Calibration
× Field results
Log of Resistance (ohms)
0
1
2
3
4
5
6
0
5
10
15
20
25
30
35
40
% Moisture

Figure 6·25

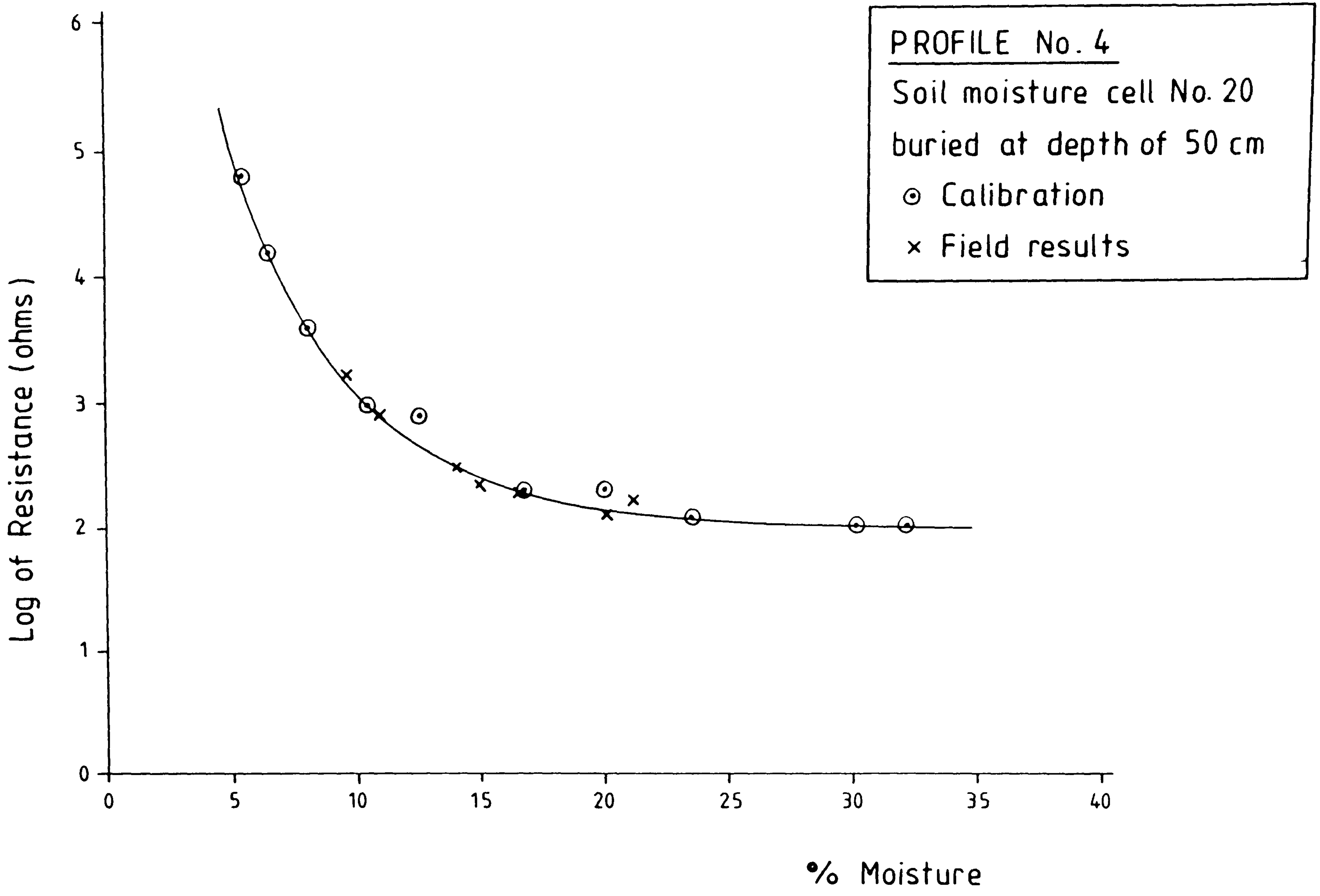
PROFILE No. 4
Soil moisture cell No. 20
buried at depth of 50 cm
⊙ Calibration
× Field results
Log of Resistance (ohms)
0
1
2
3
4
5
6
0
5
10
15
20
25
30
35
40
% Moisture

Figure 6·26

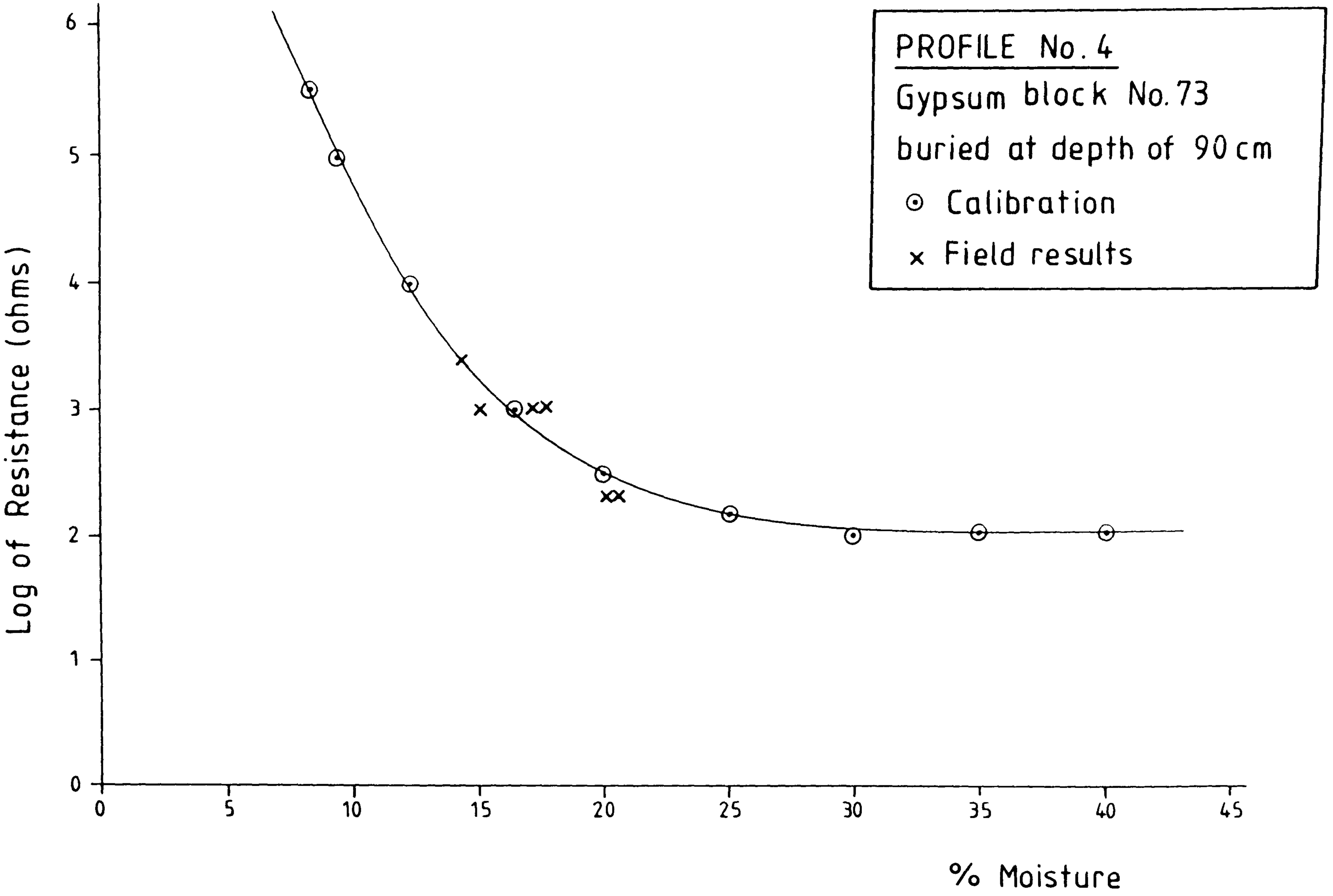
PROFILE No. 4
Gypsum block No. 73
buried at depth of 90 cm
⊙ Calibration
× Field results
Log of Resistance (ohms)
0
1
2
3
4
5
6
0
5
10
15
20
25
30
35
40
45
% Moisture

Figure 6·27

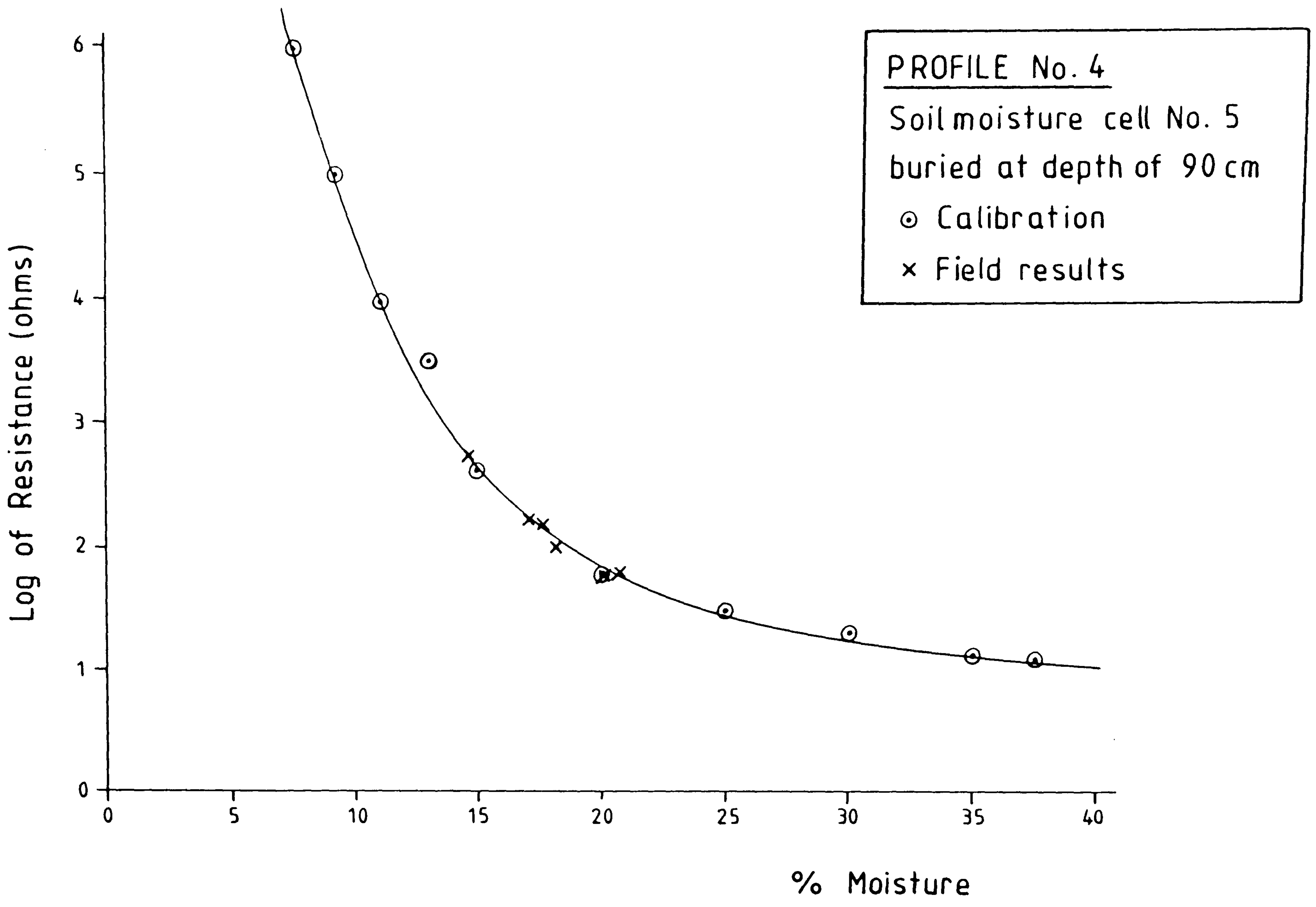
PROFILE No. 4
Soil moisture cell No. 5
buried at depth of 90 cm
⊙ Calibration
× Field results
Log of Resistance (ohms)
0
1
2
3
4
5
6
0
5
10
15
20
25
30
35
40
% Moisture

Figure 6·28

(b) that soil moisture cells tend to become sensitive at somewhat higher soil moisture levels than do gypsum blocks in the same soil (see Figs. 6.13 and 6.14, and Figs. 6.19 and 6.20)

(c) that in soils wetter than the start of instrument sensitivity, neither the blocks nor the cells produce accurate data. This sensitivity point - which varies with soil type and with the individual measuring instrument - can be at any soil moisture content from 40% to 15%

(d) that in the insensitive ranges of both types of instrument, the gypsum blocks tend to give lower than accurate readings, whilst the blocks tend to over-read the soil resistance values

(e) that in the one saline profile (no. 3), the gypsum blocks lost weight and became so fragile that they disintegrated and could not be excavated for reweighing after the field trials. In the other profiles, the gypsum blocks did not lose weight or suffer from any solubility effects whatsoever

(f) that the soil moisture cells proved to be robust throughout the trials

(g) that the grain size distribution of the soils in which the blocks and cells were installed did appear to affect their calibration curves and their field accuracies and sensitivities. In the very sandy upper layers of profile No. 1 neither blocks nor cells were sensitive at moisture contents above 15% (Figs. 6.7 and 6.8). In the nearly as sandy upper layers of profile No. 4, moisture contents above 25% made both types of instrument insensitive (Figs. 6.23 and 6.24). Whereas in the less sandy materials in the upper layers of profiles 2 and 3 (see Figs. 6.14 and 6.18) the soil moisture cells were sensitive to soil moisture contents of 25% and more. This is analogous to the situation encountered with the tensiometers and will be commented on in Chapter 7.

What was somewhat surprising was that the results found in the saline environment of profile No. 3 were analogous to those in profile No. 2. Laboratory tests carried out prior to the field trials with the same soil moisture cell calibrated with waters of various salinity (Figs. 6.29) had indicated that saline water would markedly reduce the measured resistances and adversely affect instrument sensitivity. That this did not appear to happen in profile No. 3 (other than the slight fall off in the sensitivity value in the wetter lower levels of profile No. 3 where instruments were insensitive at moisture contents above the

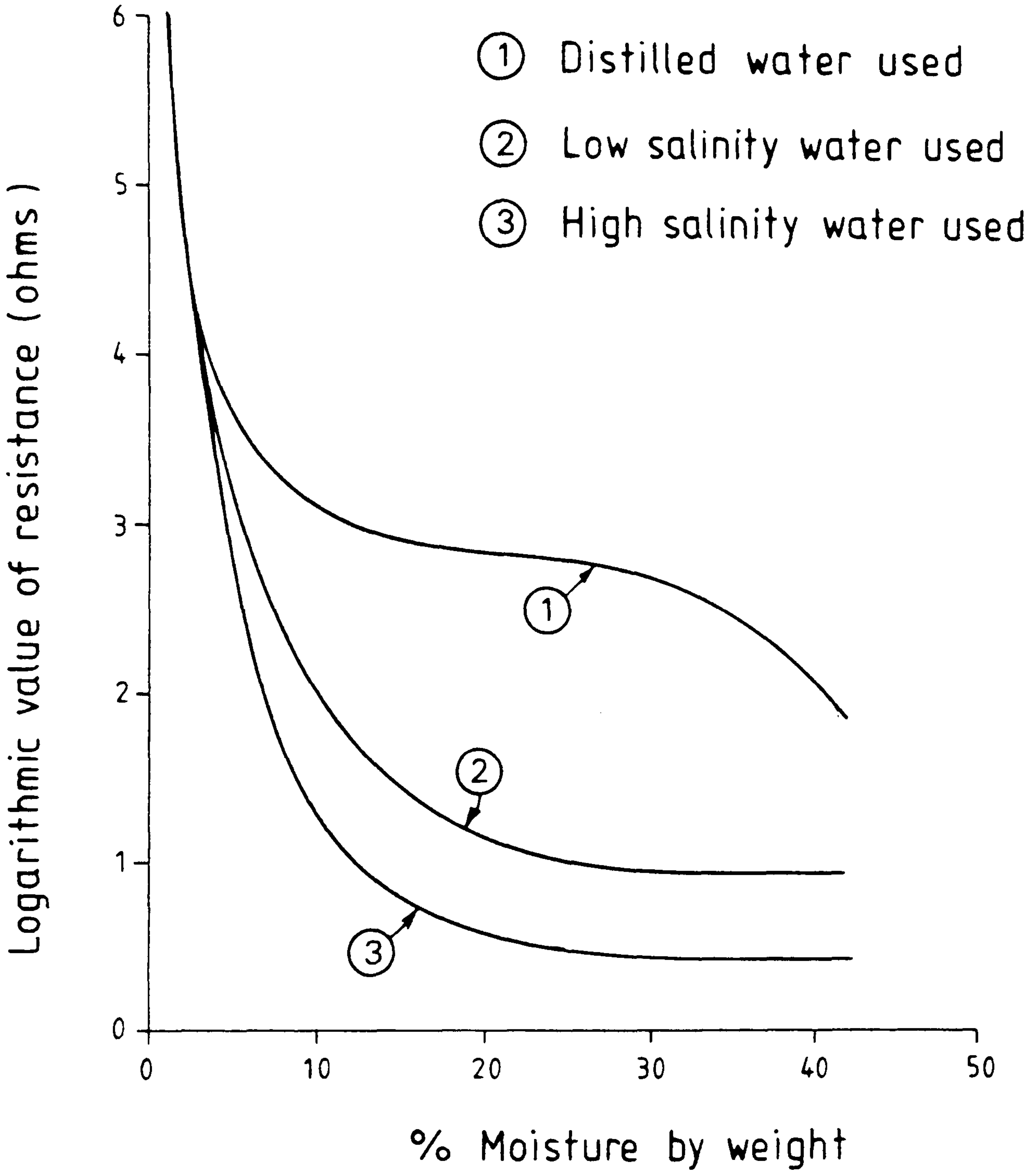

Figure 6·29 Effects of salt contents on composite soil moisture blocks (Blown Dune Sand experiment)

20% level) is probably due to the extreme dryness of this profile. Had higher moisture states existed, it is likely that effects such as those shown in Fig. 6.28 would have been noted.

6.4 Comparison with Tensiometers

Most workers have tended to see gypsum blocks and soil moisture cells as complementary to tensiometers, i.e. able to extend the tensiometer range but incapable of providing accurate data in the wetter soil states where a tensiometer would operate.

Bouyoucos himself (Ref. 6.6) always rejected this view and claimed that his blocks and cells were as accurate as tensiometers even in wet soils, and indeed stated that

> "the nylon device '(i.e. the type of soil moisture cell used in the Al-Hasa work)' begins to function satisfactorily at almost as high a moisture content as does the tensiometer. .... The nylon device, therefore, is as sensitive as the tensiometer in measuring soil moisture near the saturation range". (Ref. 6.6, pp 141, 142).

In the Al-Hasa work and the earlier sand box laboratory trials, it was possible to evaluate this particular claim and to show (Table 6.1) that, whilst Bouyoucos' claim is certainly true (no tensiometer in the sand box trials

TABLE 6.1

Sensitivity of Soil Moisture Cells in Wetter Soils

Profile	Depth (cm)	Moisture Content at which cells start to become sensitive	Suction Equivalent to this moisture content (pF)
No. 1	25	15%	0.8
1	75	20%	0.95
1	90	17.5%	1.20
No. 2	20	45%	about 0.2
2	50	32%	2.3 (wet soil above perched water table)
No. 3	15	30%	1.1
3	50	45%	1.35
3	90	22%	3.0 (wet soil)
No. 4	18	25%	0.5
4	50	30%	0.5
4	90	40%	about 0.2

actually produced readings below a pF value of 1.2), the point at which soil moisture cell sensitivity commences does seem to vary with the soil in which it is installed. In profile No. 1 (allowing for any variations in manufacture between the individual cells), a pF of about 1 has to exist before the soil moisture cell starts to react. In profile No. 4 (which has a lower sand content), a pF of only about 0.5 is sufficient to bring the soil moisture cells to their sensitive states. The data from profile No. 2 is unfortunately too limited for factual comment (since one of the two cells installed here was in soil just above the permanent perched ground water table), whilst that from profile No. 3 shows that in the saline sandy loams, a pF in excess of 1.3 has to exist before the soil moisture cells act as sensitive measuring instruments.

The situation is thus similar to that noted with the tensiometers and due allowance would have to be made for the interaction of soil moisture cells and the soils in which they are to be installed. Further comment on this is made in Chapter 7.

6.5 The Applicability of Gypsum Blocks and Soil Moisture Cells at Al-Hasa

Enough work was carried out at prove that whilst gypsum blocks are not durable in saline soils and not particularly sensitive, modern soil moisture cells are effective and can read to pF values below the local field capabity value (100 cm of water head or a pF of 2.0). Thus their use at Al-Hasa would be appropriate, since effective irrigation (see Chapter 2) best takes place at a suction level of about 100cm of water head.

From a field work viewpoint, the soil moisture cells are not a problem and require no maintenance. Calibrating the cells, prior to field installation, is, actually, less demanding than is the process needed for the tensiometers, and - of course - the cells are more robust than are tensiometers, are not prone to be accidentally damaged by agricultural activities, and do give electrical readings. This last point offers the greatest potential, since - on the more modern irrigation schemes - it would be possible to connect the soil moisture cells to a central processing unit, which could activate the irrigation systems when the soil moisture content fell below the required field capacity level.

The added advantage of a much greater measuring range than that possessed by tensiometers also allows for use with those crops which grow at much lower soil moisture states.

This investigation of soil moisture cells was designed as minor to the tensiometer studies, since local information was that soil moisture cells had never been used in the Kingdom of Saudi Arabia, where laboratory trials had shown that they would not be effective. In fact, this advice was obviously incorrect, and probably arose from inadequate care in calibrating the soil moisture cells in the proper way.

In retrospect it is unfortunate that the local advice was taken and that a much greater emphasis was not given to soil moisture cell studies.

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CHAPTER SEVEN

Soil Particle Size Distribution Effects on Tensiometers and Soil Moisture Cells

CHAPTER SEVEN

Soil Particle Size Distribution Effects on Tensiometers and Soil Moisture Cells

7.1 Introduction

It is not uncommon for laboratory derived suction/water content curves to differ from those obtained by field studies. (Refs. 7.1 and 7.2). Natural soils have internal structures, root and worm channels, and other features which are difficult to replicate in the generally disturbed samples that have to be used in laboratory studies. Even where such internal features are absent, it can be difficult to ensure that laboratory samples are packed to their field densities before being experimented upon, and when one adds the obvious possibility of errors in both field and laboratory practice and of human failure in ensuring that readings are taken and noted accurately, it is not surprising that discrepancies can occur between laboratory and field results.

This position was recognised throughout the laboratory and field studies and all possible care was taken to make the laboratory work as representative of field reality as was possible. Great efforts were taken to test all laboratory samples at their field density values, the field densities themselves were measured and remeasured until consistent values were achieved for each soil horizon of interest, every experiment was repeated in triplicate to ensure consistent results, and all field instrument readings were checked (wherever possible) by an independent observer.

Thus it was anticipated that a close match would be achieved between the field and the laboratory results.

In fact, both in the preliminary sand box work and in the field testing of the tensiometers, quite obvious discrepanies occurred and appear to be related to the soil grain size into which the tensiometers were placed. This is most obviously displayed in the results given on Fig. 5.37, where it does appear that tensiometers are most accurate in loamy soils with up to 55% of combined silt and clay, and much more likely to over-reach in sandier soils.

A similar, but much less well defined, phenomenom appears to have occurred with the soil moisture blocks, whose sensitivities do appear to be governed by the nature of the soils in which they are installed. In the less sandy soils in profile No. 4 soil moisture cells became sensitive at much lower soil suction values than was the case in the sandier soils of profile No. 1.

Both the situations could - of course - be explained as the result of combinations of experimental errors, and this could be arithmetically accepted, since the observed discrepancies are not enormous, and are well within the feasible range of overall experimental error.

Whilst this explanation can be proposed, it is extremely difficult to accept that experimental error could be so biased in the sandier soils of one profile as to give field results that are in excess of those predicted in the laboratory, whilst in a profile with loamier soils, a different error bias could occur and give field results that closely match those obtained in the laboratory.

It appears more logical to note that both the tensiometers and the soil moisture cells work by their porous tips and surfaces coming into effective contact with the surrounding soils, and that any failure to achieve this must lead to discrepancies. Obviously the pore size distributions in the tensiometer tips and the soil moisture cell exteriors are fixed by their manufacture, and equally obviously the pore sizes in natural soils vary very considerably and need not match those of the tensiometer tips or the moisture cell surfaces.

7.2 Despite the above agrument, it has to be accepted that in a system in equilibrium, the balance of internal and external forces is fixed and that it is not possible - for example - for an accurate tensiometer to read a suction that is in excess of the suction in the surrounding soil. Newtonian physics clearly state that in a system in moisture equilibrium, the pressure (and so also the suction) at a point is the same in all directions around that point and uniform throughout the system as a whole.

If only one material is involved in the system, this is easy to understand, but when a tensiometer or a soil moisture cell is inserted into a uniform soil system (of whatever grain size distribution) then two quite different materials are involved - i.e. the soil itself and the porous material that has been inserted. This is analogous to the natural condition where two dissimilar soils are in contact, and, in such conditions at equilibrium, the two materials will be at the same suction but have different soil moisture contents, because of their distinctly different suction/water content characteristics (Ref. 7.3).

When a tensiometer is inserted into a porous soil, this is the situation that should occur and is the basis on which tensiometers and soil moisture cells have been accepted as valid methods of measuring soil moisture state.

Thus basic theory clearly indicates that the tensiometers and the soil moisture cells should not have given any discrepancies that were caused by the difference in pore size between the instruments and that of the soils around them.

7.3 However, it does appear that such discrepancies have been encountered and it is unfortunate that more work was not directed towards investigating these.

In the light of the limited evidence available, it is postulated that the phenomenon is due to contact effects between the instruments and the soils, and that as soil grain sizes (and so soil pore diameters) increase their contact between instruments and soils is progressively reduced and instrumental readings become less and less diagnostic of the soils in which they are installed.

No reference to this effect has been discovered in the published literature and the author hopes to make it a personal field of study, particularly since issues of practical importance are involved. Instrumental discrepancies of 70% to 90% (see Fig. 5.37) obviously are not merely of theoretical interest, when the existance of the Al-Hasa oasis is actually threatened if its water usage cannot be rationalised.

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CHAPTER EIGHT

The Value of Psychrometers

CHAPTER EIGHT

8.1 The Value of Psychrometers

Tensiometers, gypsum blocks and soil moisture cells are, in some ways, examples of an older technology, and the scientific literature today tends to emphasise the development of newer soil moisture measuring systems. To avoid the criticism that only past technology was being considered for the Al-Hasa situation, it was thus decided to evaluate the usefulness of the dew-point psychrometers, one of the most modern of soil suction measuring methods.

These psychrometers depend on the long proven relationship between soil water potential and relative humidity, if soil moisture and water vapour are, in fact, in equilibrium in the pores of the soil being examined (Ref. 8.1). This opens a way to measuring soil matrix potential by instead measuring the relative humidity in the soil pores by a thermocouple device.

Commercially available psychrometers consist of a tiny thermocouple (Fig. 8.1) with closely adjacent measuring and reference junctions. Essentially, using these instruments consists of moistening the reference junction . This sets

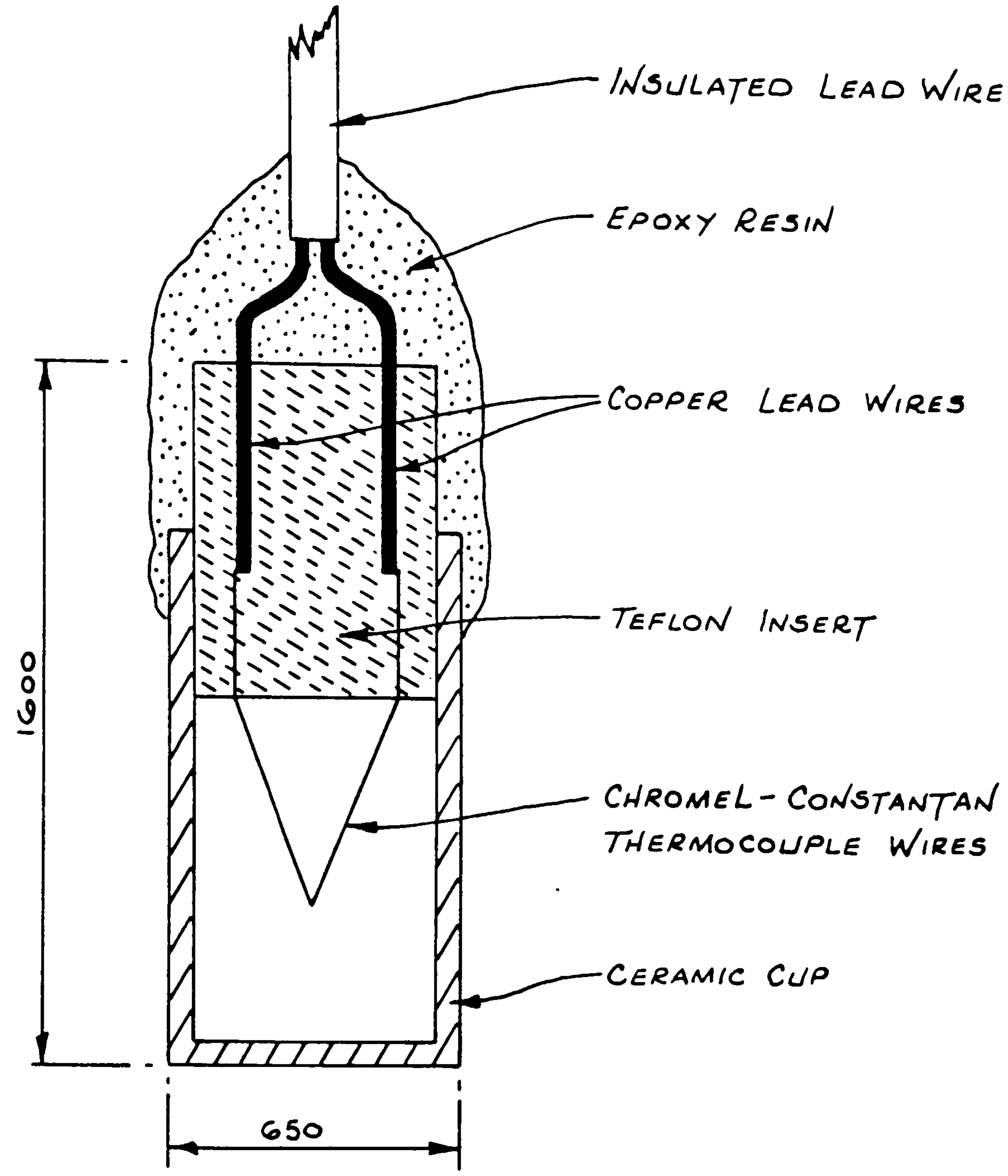
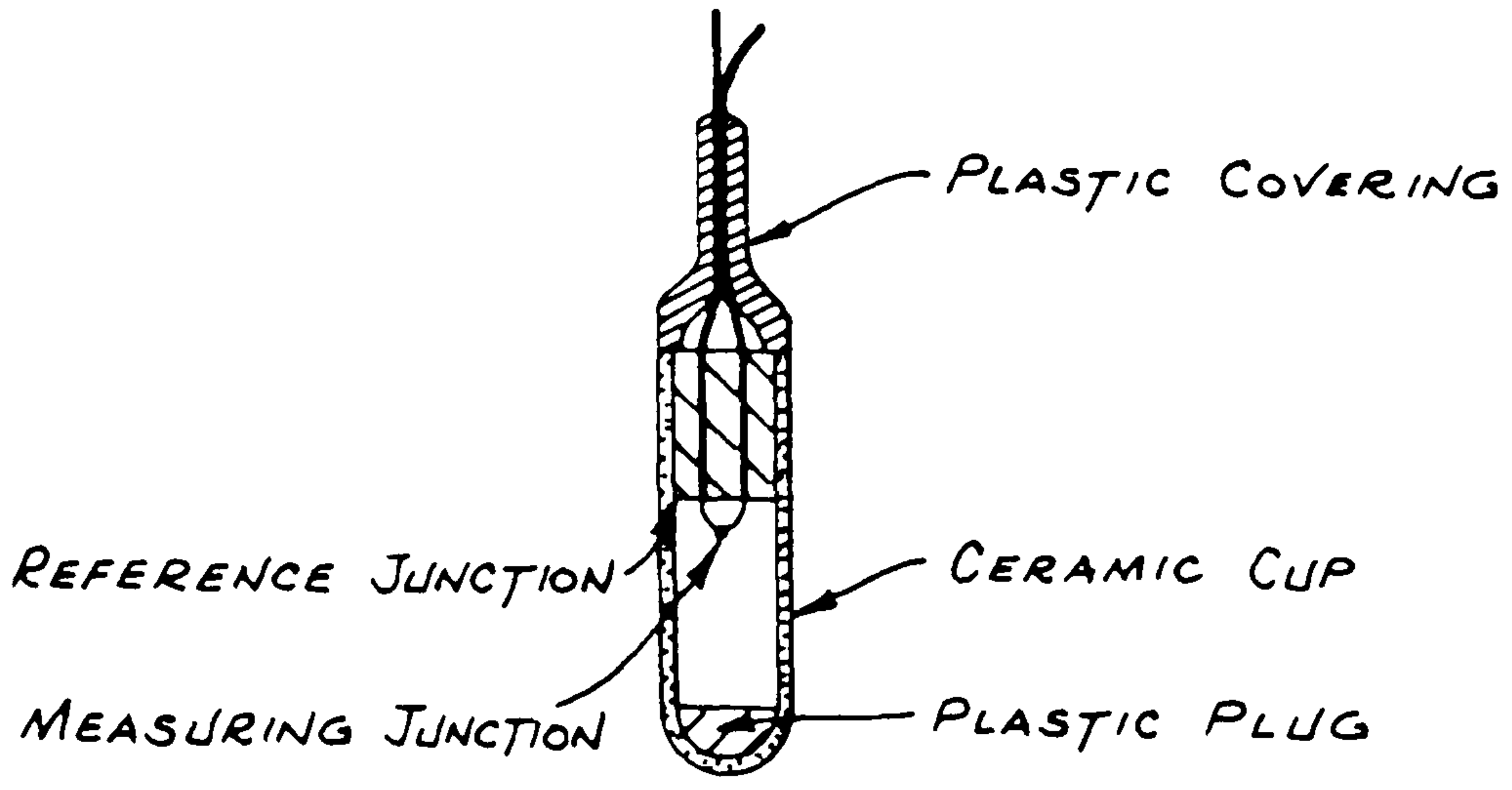
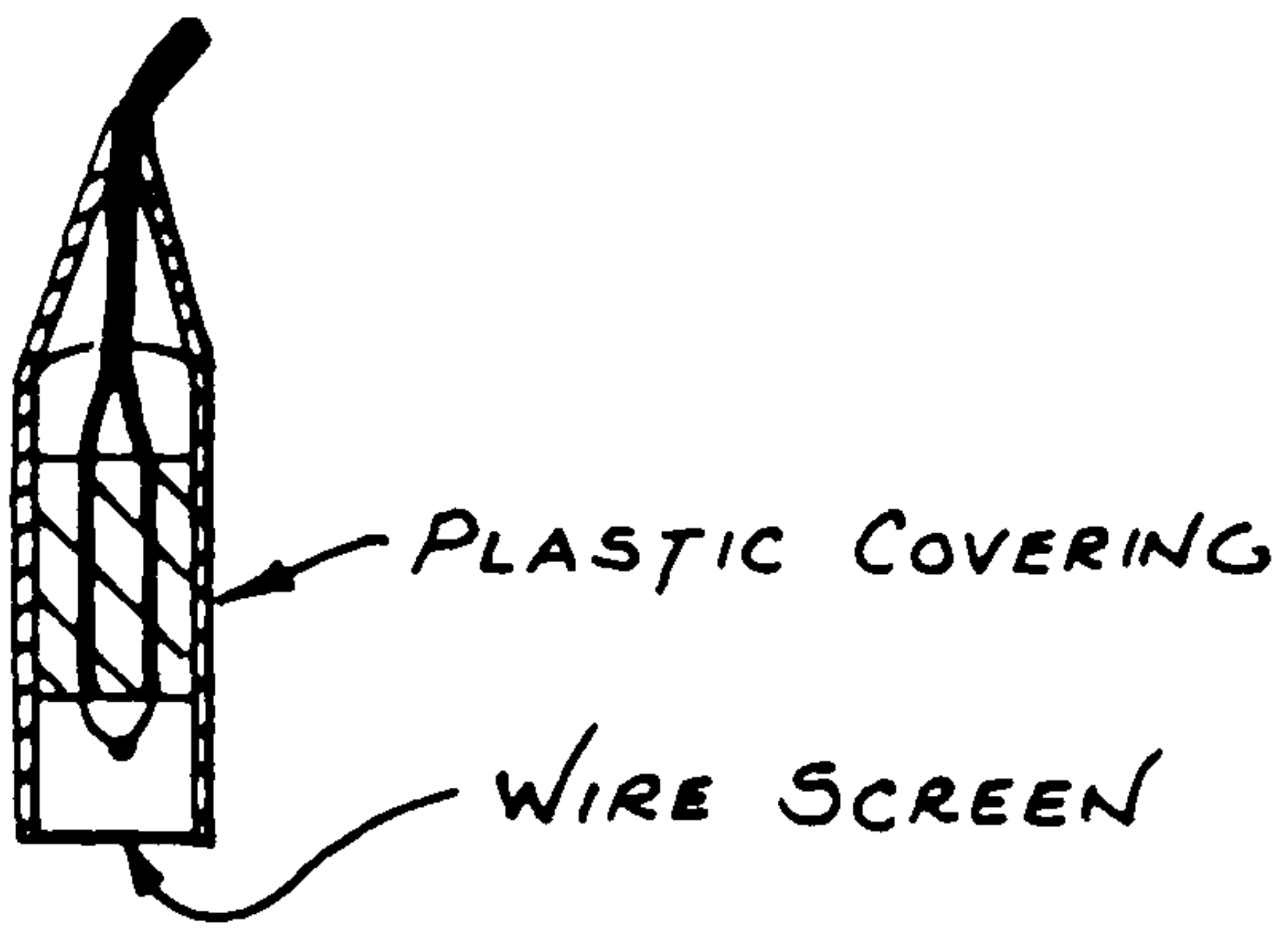


Figure 8·1 Cross section of the ceramic cup thermocouple psychrometer used by Wiebe and others (1970) up an electrical voltage proportional to the difference between the wet bulb and dry bulb temperatures of the soil pore vapour that is being sampled. Then if one knows the ambient temperature, and if the psychrometer calibration is accurate, the relative humidity and the soil matrix suction are given by the instrument's thermocouple voltage reading.

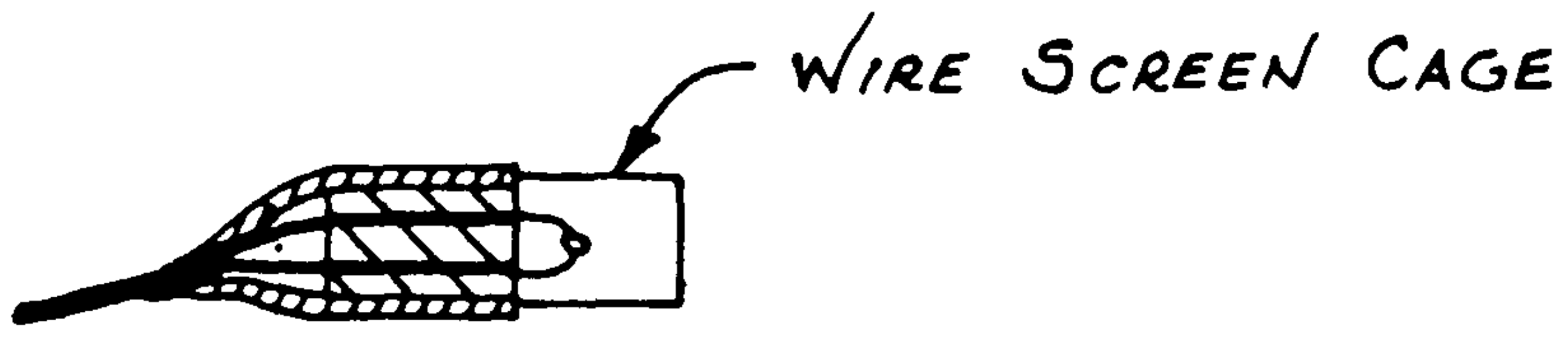
Although simple in theory, the practice is more complex largely because the voltages that are generated are so small (micro volts) that an expensive and fragile voltmeter has to be used. In this work, the Wescor type HR-33T meter (which costs £2,410.00) was used. The actual thermocouple probes are cheap and simple, and can be home made from chrome and constantan wire. (Ref. 6.2). The basic rule with the probes is to make them as small as possible to cause a minimum of thermal and vapour disturbance in the tested soil. A protective covering around the probe is essential to prevent mechanical damage, and various types (Fig. 8.2) were built. The ceramic cup types were found to be very robust but - as noted by earlier workers (Ref. 8.3) were somewhat insensitive, since the ceramic casing does impede vapour movements into the surrounding soil. The screen type casing is obviously easier to damage by careless handling, but is much more sensitive since its greater open area allows faster equilibrium of vapour pressure into the surrounding soil and a better temperature equilibrium. The compromise casing used in their work was the end-window



(A) CERAMIC COVER



(B) END WINDOW SCREEN COVER



(C) SCREEN CAGE COVER

Figure 8·2 Protective covers for psychrometers screen type, which proved acceptably robust and capable of giving equilibrium readings within 15 minutes, as the psychrometer was calibrated to vapour pressure equilibrium over a 0.3 mKCl solution 25^{o}C.

In field use, a small (2 to 10 mA) current is passed through the psychrometer for 60 seconds. This cools the measuring junction by the Peltier Effect (Ref. 8.4) to the dew point and deposits the necessary drop of water on the junction. Once this is achieved, the necessary micro voltage reading can be taken.

Two practical factors limit the usefulness of dew-point psychrometers:

(a) the limit on cooling that the Peltier Effect can give. Soils have to have at least 95% of their maximum possible pore relative humidities and - in suction terms - this indicates that the upper limit of a psychrometer's operating range will be about a pF of 4.9 (82,640 cm of negative water head). Obviously this upper limit would be no disadvantage in Al-Hasa, where interest is in much smaller suction values

and

(b) the sensitivity of the micro voltmeter equipment. In many soils, a suction of 1,033 cm of water is equivalent only to a voltage of about 0.5 μV. The smallness of this voltage obviously forces the use of expensive micro volt meters, but these are accurate only to a sensitivity of ± 0.1 μV, so errors are inevitable at low suctions and this would appear to persist until the soil becomes quite dry (to a pF of about 3.3 or more). This lower limit to the usefulness of psychrometers was of much greater concern in the Al-Hasa conditions, but it was felt worthwhile to evaluate the psychrometers in the laboratory soil columns and in the field, since no use of psychrometers in the Kingdom of Saudi Arabia had earlier been attempted, and the instruments could have particular useful advantages.

This decision to evaluate psychrometers was taken despite earlier work by Daniel and his co-workers (Ref. 8.4), who had found errors of 35% in quite wet sandy soils. An example of the insensitivity of psychrometers quoted by Daniel et al was when 3 well calibrated psychrometers, set in a wet silty sand (whose suction was proven by tensiometers to be 500 cm of water) revealed results that ranged from a suction of 0 to 723 cms of equivalent water suction.

8.2 Calibration of the Psychrometers

As with all soil suction/soil moisture measuring equipment, calibration before any experimental or field usage is crucial.

In the case of the psychrometers this proved to be a rather tedious process that required very accurate laboratory technique. A test tube was lined with filter papers, which were then wetted with 5 or 6 drops of a standard salt solution (0.3 M KCl solution). The probe was inserted and the test tube corked. The hole through the cork (to allow the electrical wires to connect to the micro voltmeter) was then sealed with vacuum grease and the test tube placed in a constant temperature bath (at 25°C) for two hours to ensure temperature equilibrium. Then readings could be taken to check those on the manufacturer's calibration curves. Because soil temperatures do vary, it was also necessary to repeat the calibration at other fixed temperatures to build up a temperature correction curve (Fig. 8.3).

This calibration exercise proved that the manufacturer's calibration curve was reasonably accurate (Fig. 8.4).

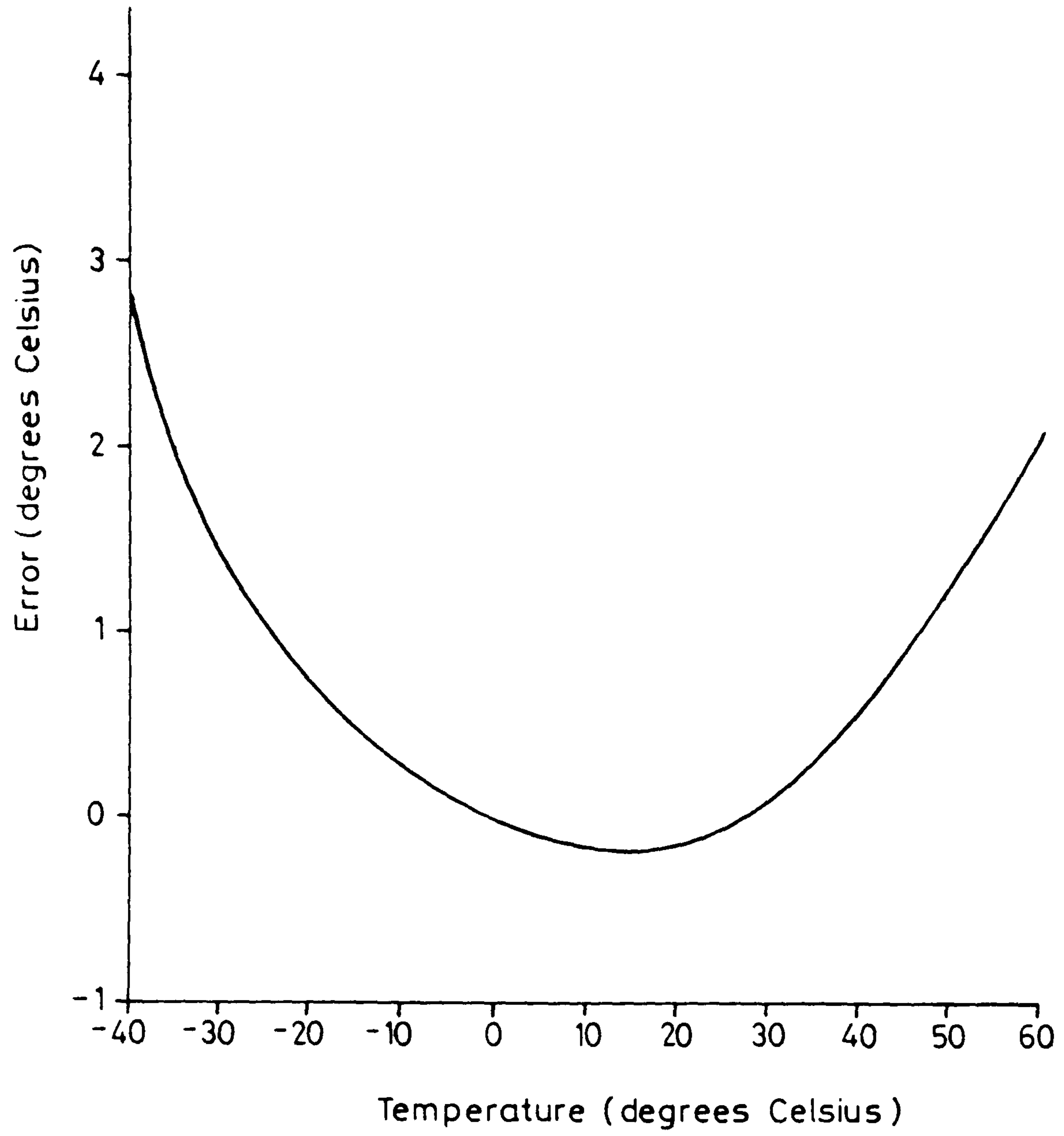


Figure 8·3 Temperature correction curve

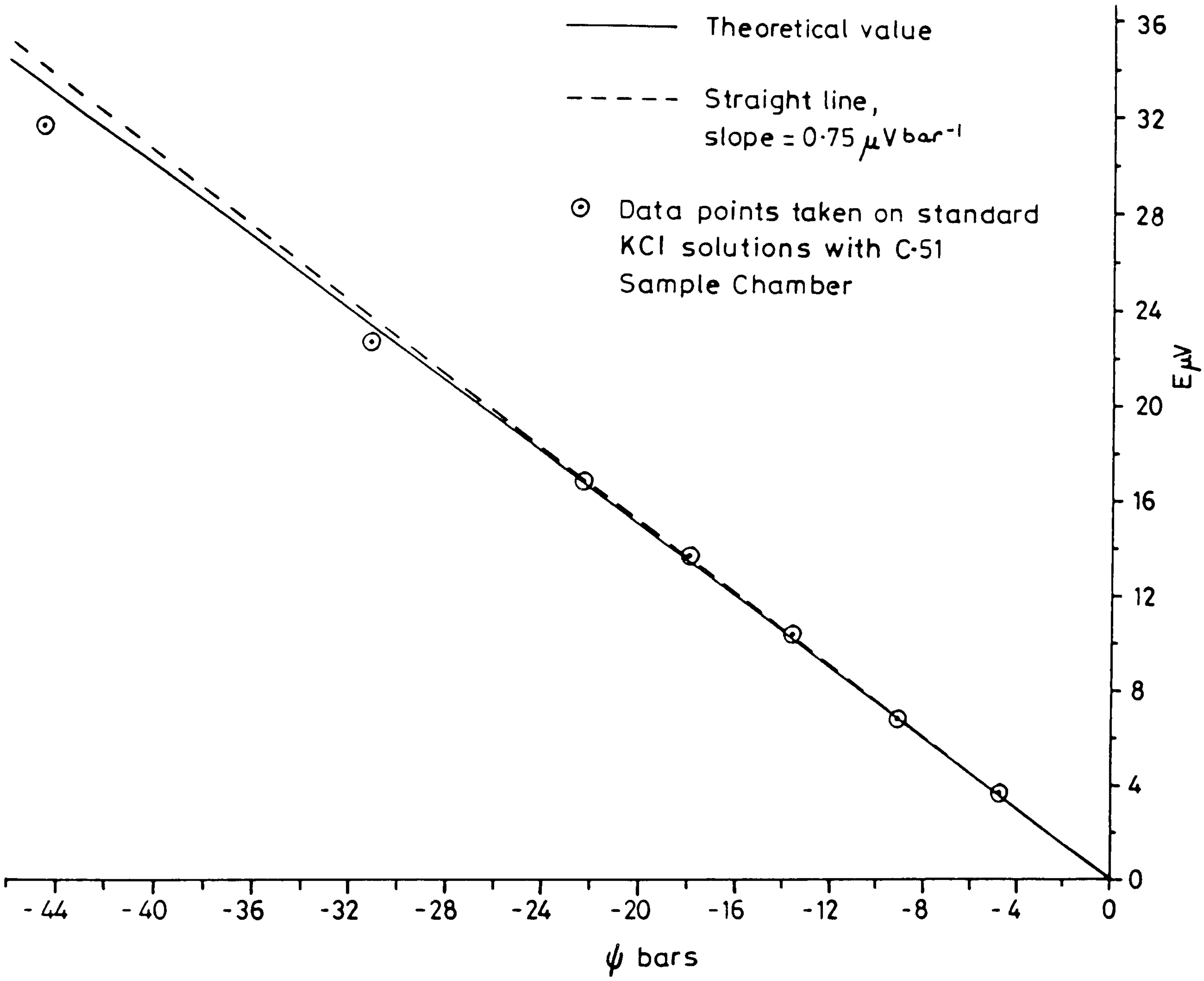


Figure 8·4 Theoretical VS. Actual Instrument Output

8.3 Operational Usage of Psychrometers

Initially the psychrometers were used in soil columns of the two soil types (see Table 5.2) utilised in the sand box trials for the tensiometer studies. The soils were packed to their known field densities, and thus to the same densities as had been used in the tensiometer work, and it proved possible to obtain suction/water content curves very similar to those given by the filter paper method, but only above suction values equivalent to 2,300 cm of water head. (Fig. 8.5). These columns (of 300 cm diameter uPVC tubing) were dried by passing warm air flows above their upper surfaces.

Comparative accuracies of psychrometers and tensiometers at low suction readings were also obtained in these column studies and confirmed earlier findings (Ref. 8.4) that the psychrometers give grossly inaccurate results in wet sandy soils (Table 8.1).

Quite apparently, psychrometers in these laboratory trials failed to meet the accuracy, sensitivity, simplicity and cheapness requirements needed for Al-Hasa. Thus it was decided to include only one psychrometer in each of the four instrumented soil profiles and to place that instrument in the top soil levels, where soil dryness would be greatest and where possibly the psychrometer would produce valid and

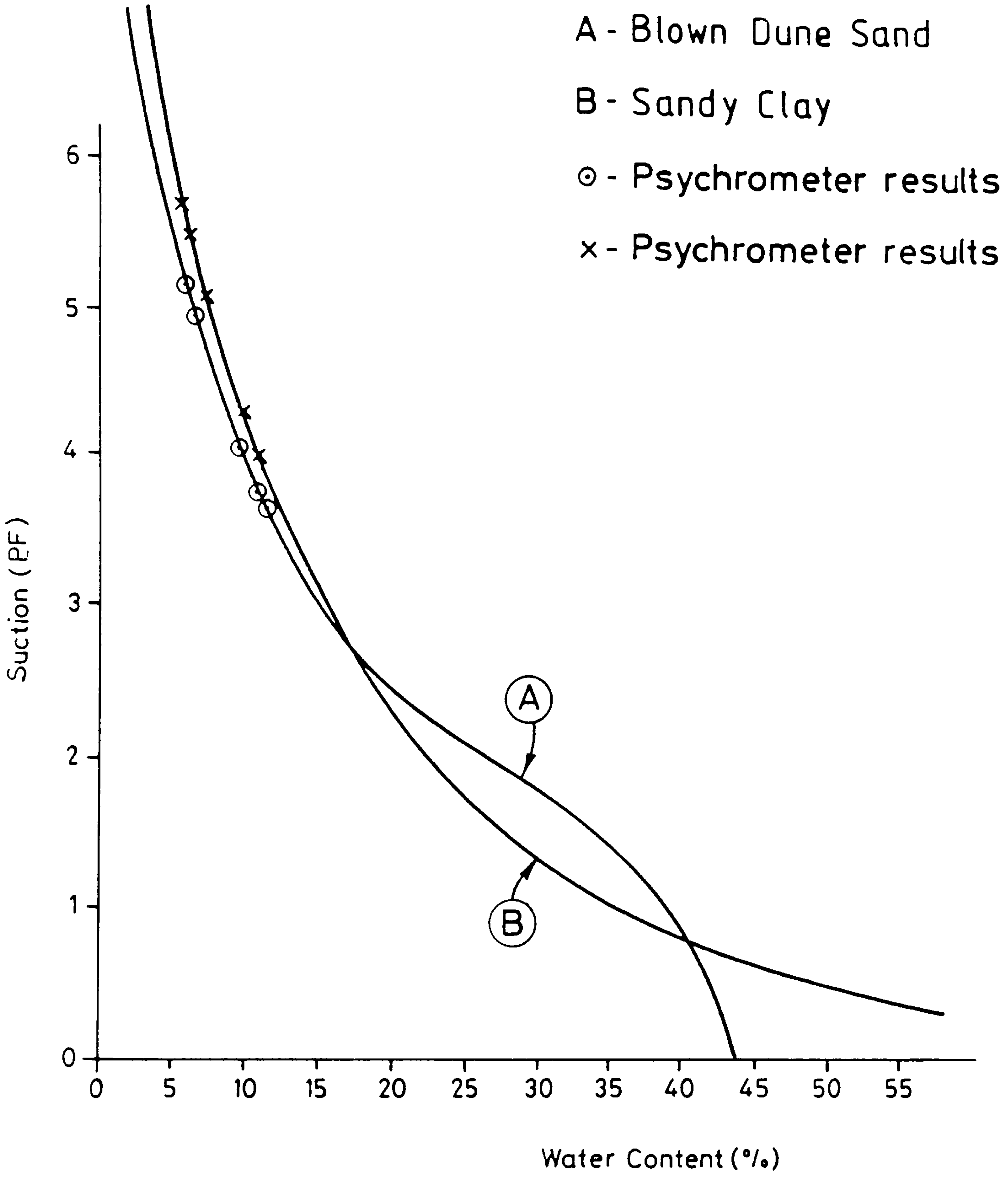


Figure 8·5 Comparative accuracy of psychrometer filter paper results

TABLE 8.1

Comparisons between Psychrometer and Tensiometer Results in Soil Columns

Known Suctions from Tensiometers (cm of H_2O)	Psychrometer Readings (cm of H_2O)
424.37 (dune sand column)	3 64,10
590.80 (" " ")	7 31,20
670.00 (Sandy clay column)	15 5,80
361.81 (" " ")	4 38,40

sensitive results.

In fact, the psychrometers in profiles 1, 2 and 4 never gave valid readings throughout the field trial period, since - as all 3 profiles were being irrigated - the soils were invariably too wet for the instruments to function.

In the unirrigated profile No. 3, however, at 15 cm depth, the psychrometer did give a constant suction/water content reading (see Fig. 8.6) which falls very accurately on the curve produced by the filter-paper laboratory based work. This obviously is because the top soil in this profile was dry enough for the lower limit of psychrometer operation to be passed. Despite this apparent success, it was, however, obvious that the psychrometer was relatively insensitive and always gave the same output reading, in contrast to the other instruments in this part of profile No. 3, which showed variations on the soil dried out over the period of field monitoring (see Table 5.8).

This insensitivity was probably due to the relatively small output electrical currents (3 μV) and to the coarseness of the dial markings on the micro voltmeter.

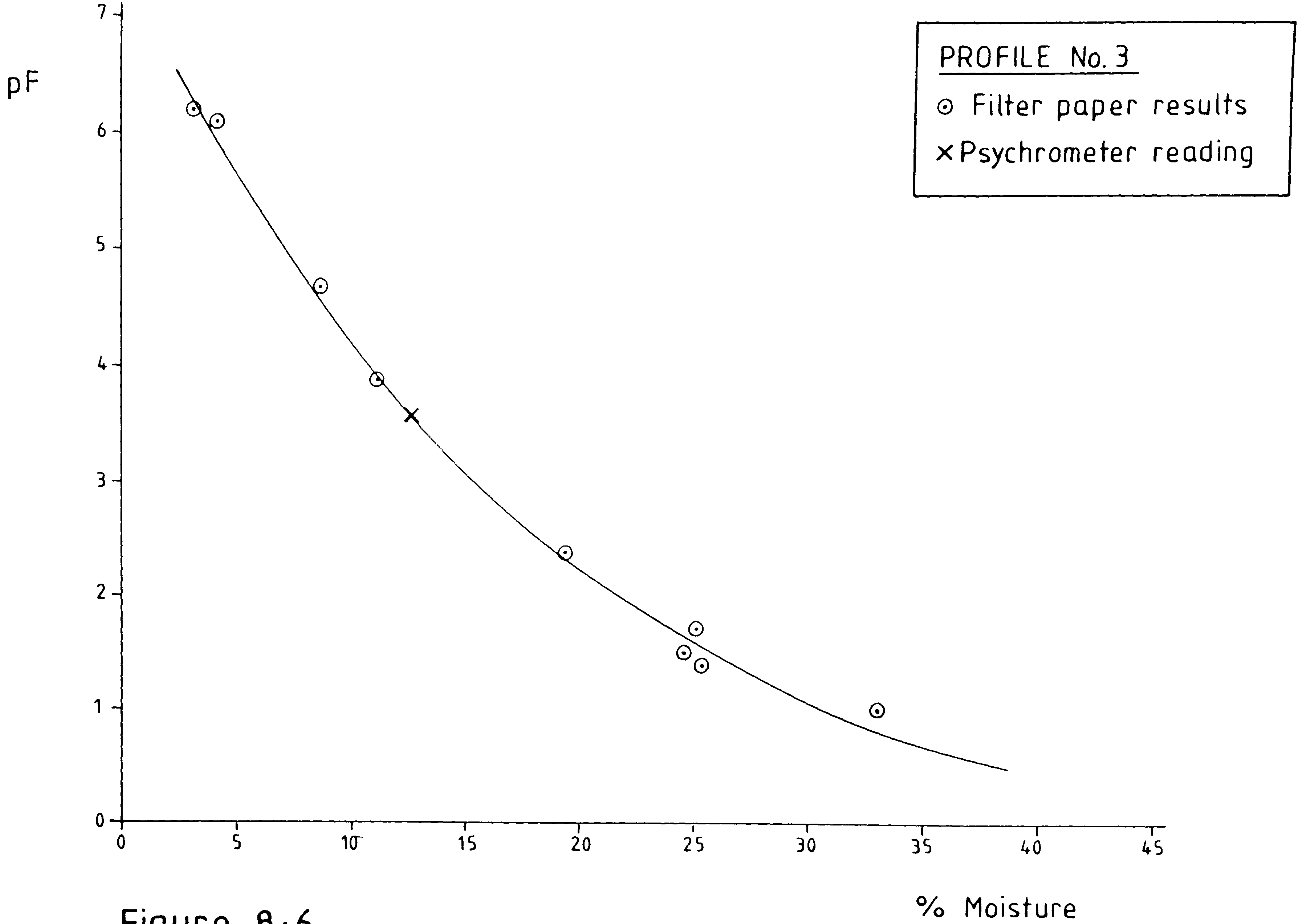

pF
7
6
5
4
3
2
1
0
0
5
10
15
20
25
30
35
40
45
% Moisture
PROFILE No. 3
⊙ Filter paper results
× Psychrometer reading

Figure 8·6

8.4 Summary

The psychrometer micro voltmeter was expensive and fragile, and the calibration of the psychrometer probes called for a much higher laboratory expertise than did the calibrations of the other instrument types.

If the psychrometers had proved to be accurate and sensitive in field conditions, then the above criticisms would not have been given such prominence, but the psychrometers proved to be almost entirely useless, until the soils were much drier than could be accepted under the Al-Hasa agricultural conditions.

Thus the inevitable conclusion is that psychrometer type devices have no place to play in irrigation control in Saudi Arabian conditions, until such time as instrumental improvements leads to a cheap and robust micro voltmeter that is capable of measuring voltages of 0.2 μV or less to a high order of accuracy.

In the current state of instrument development, it is difficult to envisage practical situations where psychrometers offer any advantage.

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CHAPTER NINE

The Significance of the Near Surface Perched Ground Water Table

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The Significance of the Near Surface Perched Ground Water Table

9.1 A hardpan layer occurs all over the oasis, and so reduces drainage that a near surface salty (5,000 mg/litre salt concentrations) groundwater exists wherever adequate drains have not been constructed. Generally these conditions occur in the central portions of the farms, and are usually the result of the farmers unwillingness to dig deep drains.

This near surface groundwater can reduce the surface soil's dryness, if enough upward soil moisture movement occurs.

The upward movement of soil moisture has been fully described by workers such as Hillel (Ref. 9.1), and is controlled by two discrete factors -

(a) the potential causing the flow, which in this case is the difference in moisture content between the dry surface layers and the saturated soils at the perched water table

and

(b) the ability of the soils in the profile to convey soil moisture. In a partly dry soil this ability is described by the soils' unsaturated hydraulic conductivity.

These two factors change in different ways as a soil profile dries out. Soil suction increases rapidly as the soils dry, whilst conversely hydraulic conductivity declines (Fig. 9.1). Thus to quantify the amount of upward migration of moisture requires the use of a modification of the Darcy Formula; i.e.

$$V = K(\theta)\left[\frac{d\psi}{dz} - 1\right]$$

where V = the flux or the upward rate of moisture movement (cm^3/day through each cm^2 of soil surface)

$K(\theta)$ = the change in hydraulic conductivity as the soil's moisture state varies

and $\frac{d\psi}{dz}$ = the change in soil suction (ψ) with height (Z) above the water table

From the viewpoint of improving irrigation efficiency at Al-Hasa by giving farmers instruments for measuring the moisture conditions of their soils, such upward moisture migration can have two adverse effects:-

(a) if tensiometers are being used, the soil around them will be moistened by the upward moving salty water, and so it will appear that less irrigation is needed

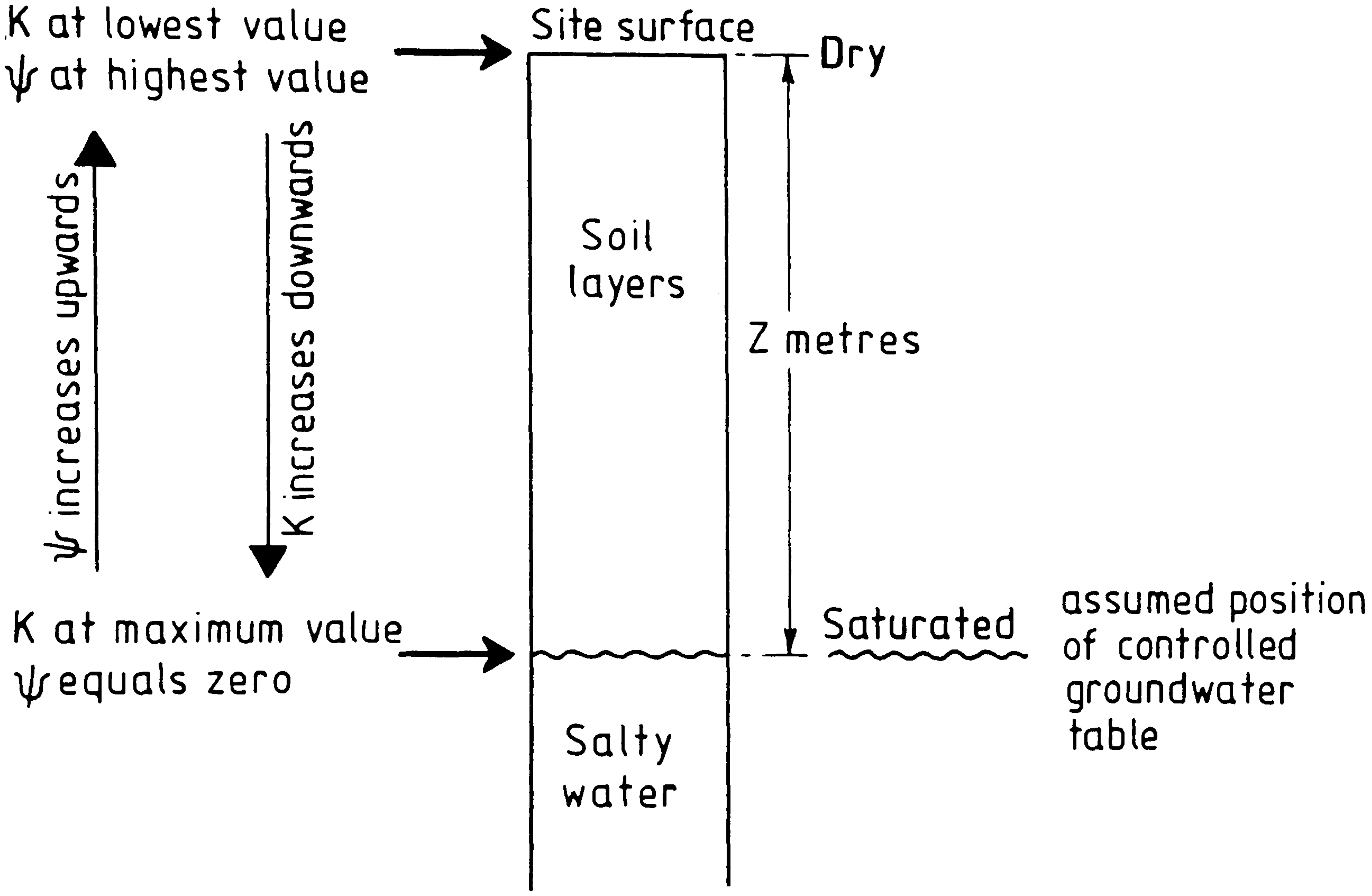


Figure 9·1 Factors which affect upward migration of soil water than is actually the case. The salty water will, of course, add additional salts to the soil and so increase its salt toxicity, and reducing the amount of fresh irrigation water will make this toxicity more of a problem

(b) if soil moisture cells are being used, these will lose their sensitivity as they are exposed to salty moisture (Ref. 9.2), and so will be less effective than expected.

Given these possibilities, it seemed worthwhile to determine how much water could rise up an Al-Hasa soil column in the summer months and to predict how much extra salt this could add to the soil surface and the plant root zones.

9.2 Predicting the Amount and Rates of Upward Moisture Movement

Whilst a number of mathematical models exist to solve the Darcy Formula given above, perhaps the most accurate is the computer model devised by Bloeman (Ref. 9.3) and applied by Sharrock (Ref. 9.4) and other workers to land reclamation schemes.

The basic information needed to use the Bloeman model is (for each soil layer in the profile) an accurate particle size analysis

an accurate suction/water content curve

an accurate hydraulic conductivity/water content curve

The first two already were defined for the work reported in Chapter 5, the last was determined by Ehlers' method (Ref. 9.5).

In this, the soil in question is packed (at its dry field density) into an aluminium tube (38 mm diam. and 100 mm long), then fully saturated and placed on an electronic laboratory balance. The end of the tube is heated with a stream of warm air and weighings noted against times until, (after about 10 minutes) the cumulative weight loss against the square root of time is linear (Fig. 9.2). The sample is then reweighed, extruded, cut into radial slices and the moisture content of each slice determined. This allows the moisture content changes with distance away from the open heated end of the tube to be established (Fig. 9.3), and from a smoothed graph of this the diffusivity ($D(\theta)$) is determined from

$$D(\theta) = \frac{1}{2t} \times \frac{dx}{d\theta} \int_{\theta x}^{\theta i} x \, . \, dx$$

(Ref. 9.6)

The actual variation in hydraulic conductivity with moisture level (i.e. $K(\theta)$) can then be found from the relationship -

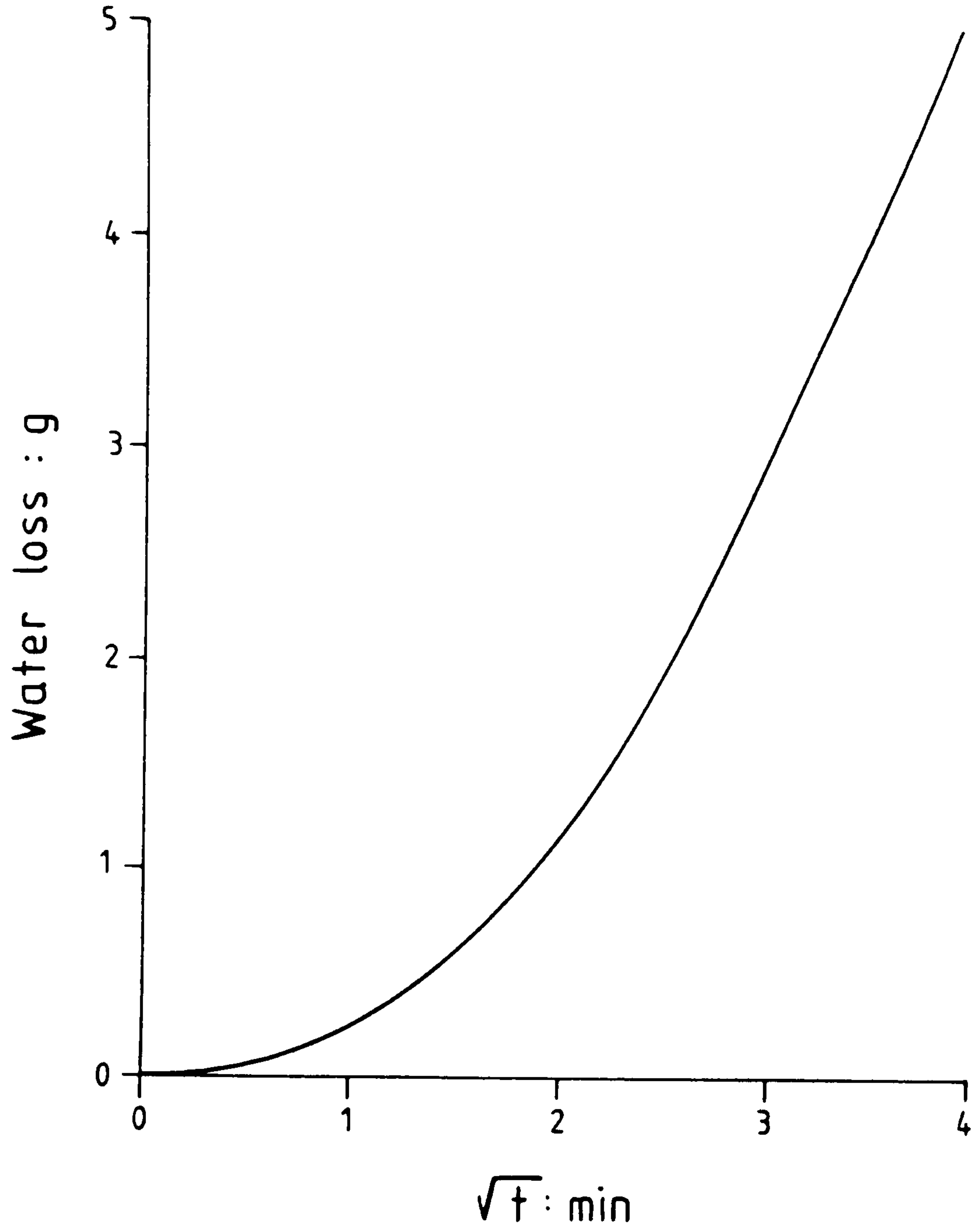


Figure 9·2 Variation of weight loss with time

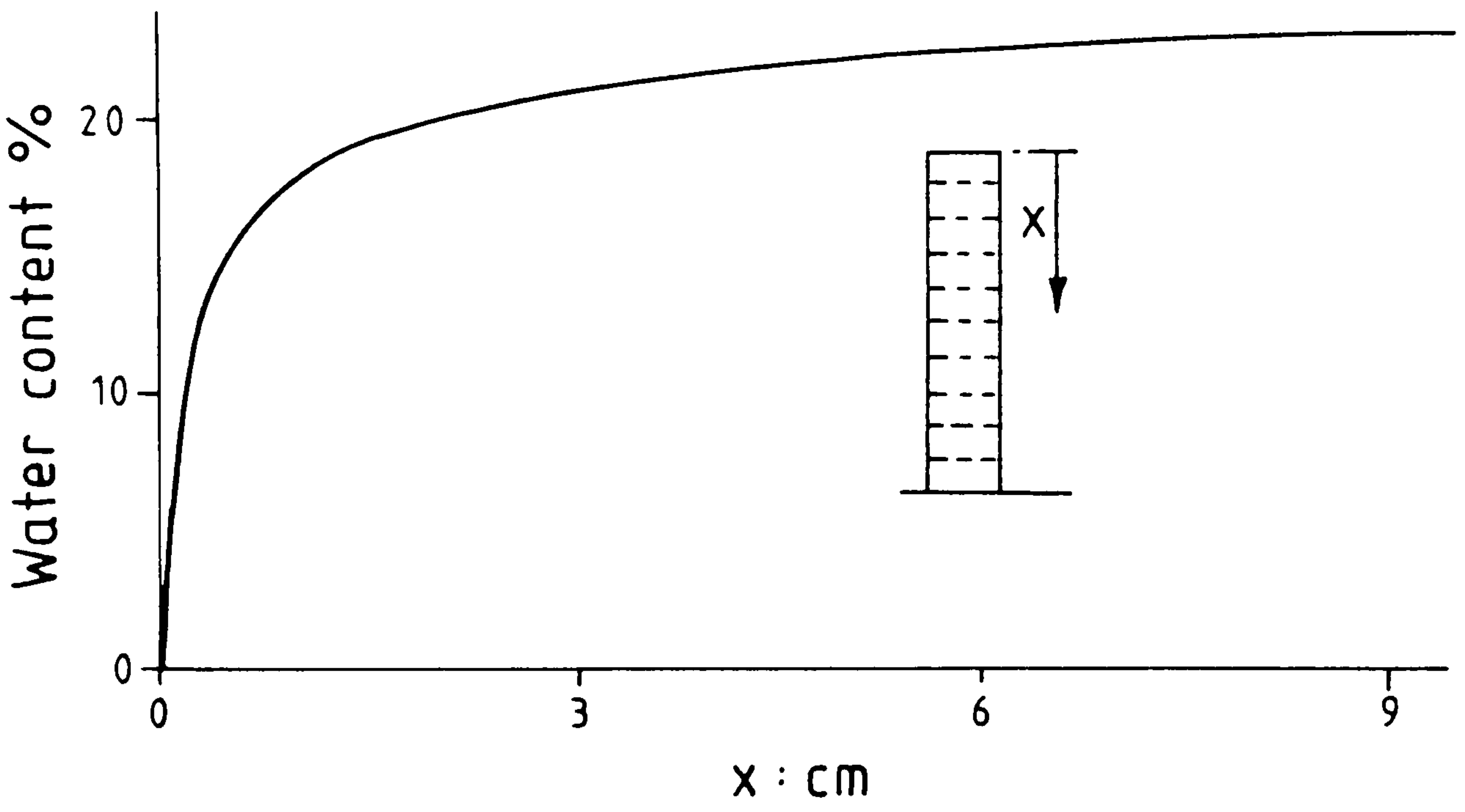


Figure 9·3 Variation of water content with distance

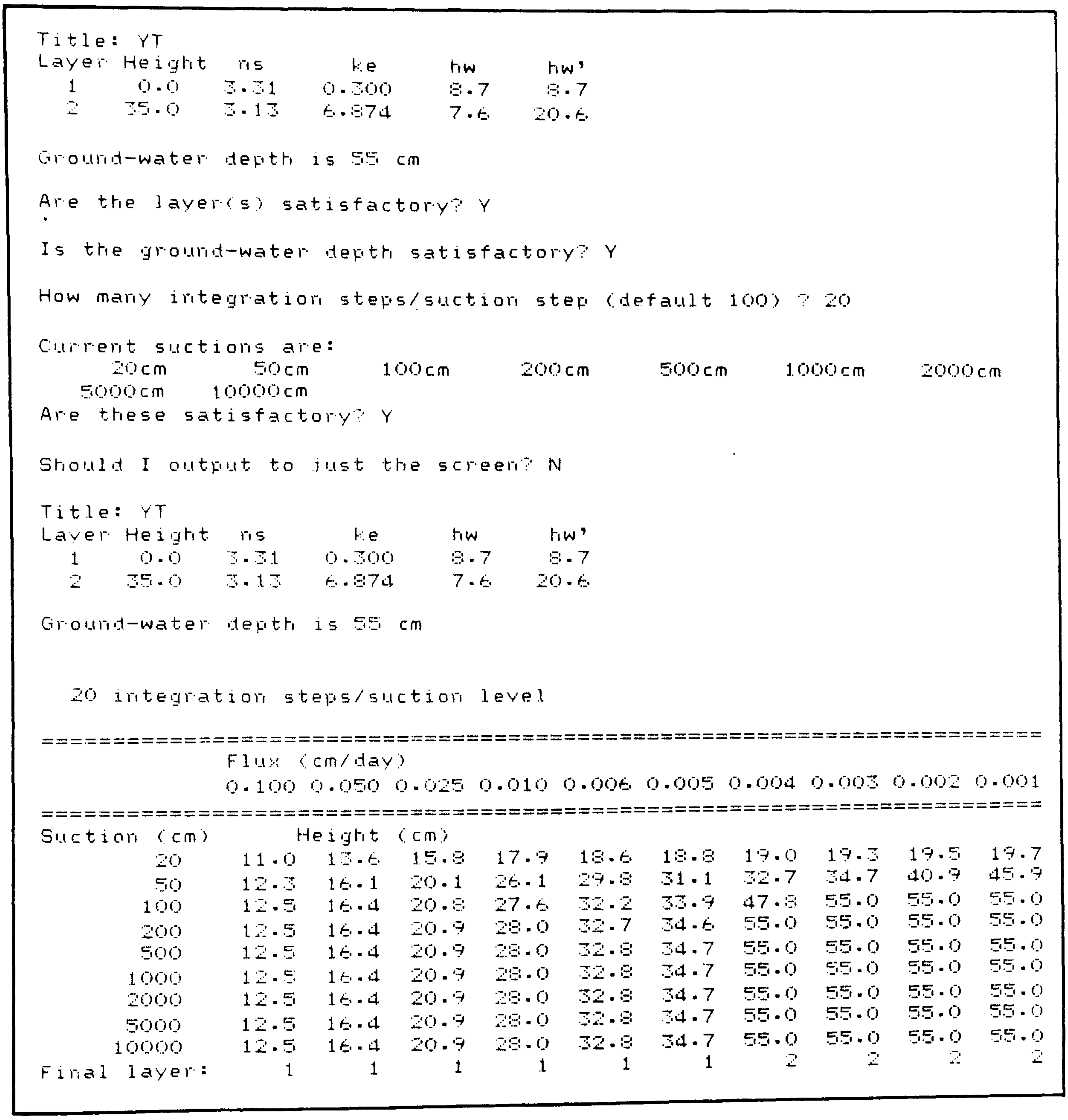
$$K\theta = D(\theta)\left(\frac{d\theta}{d\psi}\right)$$

The last term ($\frac{d\theta}{d\psi}$) is derived from the filter paper suction/ water content curve.

Once the three items of basic information are available, the computer model can be used. The actual inputs are the parameters "f", "n", "ha", "ks", "ke", "hw" and "ns" and are all derived from the three already noted items of basic information.

The computer print-out obtained is of the type shown in Fig. 9.4 and this shows that a flux of 0.005 cm^3/day will rise through each cm^2 of soil surface if the surface soil suction is equal to 1000 cm of water head. Usually it is preferable to plot Fig. 9.4 graphically to obtain Fig. 9.5, as this allows detailed evaluation of changes in the plant root zone (here taken to be the top 20 cm of soil).

Knowing that a flux of 0.004 $cm^3/day/cm^2$ reaches the base of the root zone is useful, since it shows that moisture equivalent to 36 mm of water depth rises to the plant root zones over a 2 hectare farm in the six summer months alone (soil suctions from April to September tend to be at 1000 cm of water head over the oasis). This is a very significant water addition when it is realised that the annual rainfall at Al-Hasa is only 62.8 mm.



```
Title: YT
Layer Height  ns       ke      hw      hw'
  1     0.0   3.31   0.300    8.7     8.7
  2    35.0   3.13   6.874    7.6    20.6

Ground-water depth is 55 cm

Are the layer(s) satisfactory? Y

Is the ground-water depth satisfactory? Y

How many integration steps/suction step (default 100) ? 20

Current suctions are:
     20cm        50cm       100cm       200cm       500cm      1000cm      2000cm
   5000cm    10000cm
Are these satisfactory? Y

Should I output to just the screen? N

Title: YT
Layer Height  ns       ke      hw      hw'
  1     0.0   3.31   0.300    8.7     8.7
  2    35.0   3.13   6.874    7.6    20.6

Ground-water depth is 55 cm


   20 integration steps/suction level

=========================================================================
                 Flux (cm/day)
                 0.100 0.050 0.025 0.010 0.006 0.005 0.004 0.003 0.002 0.001
=========================================================================
Suction (cm)        Height (cm)
          20      11.0   13.6   15.8   17.9   18.6   18.8   19.0   19.3   19.5   19.7
          50      12.3   16.1   20.1   26.1   29.8   31.1   32.7   34.7   40.9   45.9
         100      12.5   16.4   20.8   27.6   32.2   33.9   47.8   55.0   55.0   55.0
         200      12.5   16.4   20.9   28.0   32.7   34.6   55.0   55.0   55.0   55.0
         500      12.5   16.4   20.9   28.0   32.8   34.7   55.0   55.0   55.0   55.0
        1000      12.5   16.4   20.9   28.0   32.8   34.7   55.0   55.0   55.0   55.0
        2000      12.5   16.4   20.9   28.0   32.8   34.7   55.0   55.0   55.0   55.0
        5000      12.5   16.4   20.9   28.0   32.8   34.7   55.0   55.0   55.0   55.0
       10000      12.5   16.4   20.9   28.0   32.8   34.7   55.0   55.0   55.0   55.0
Final layer:         1      1      1      1      1      1      2      2      2      2
```

Figure 9·4

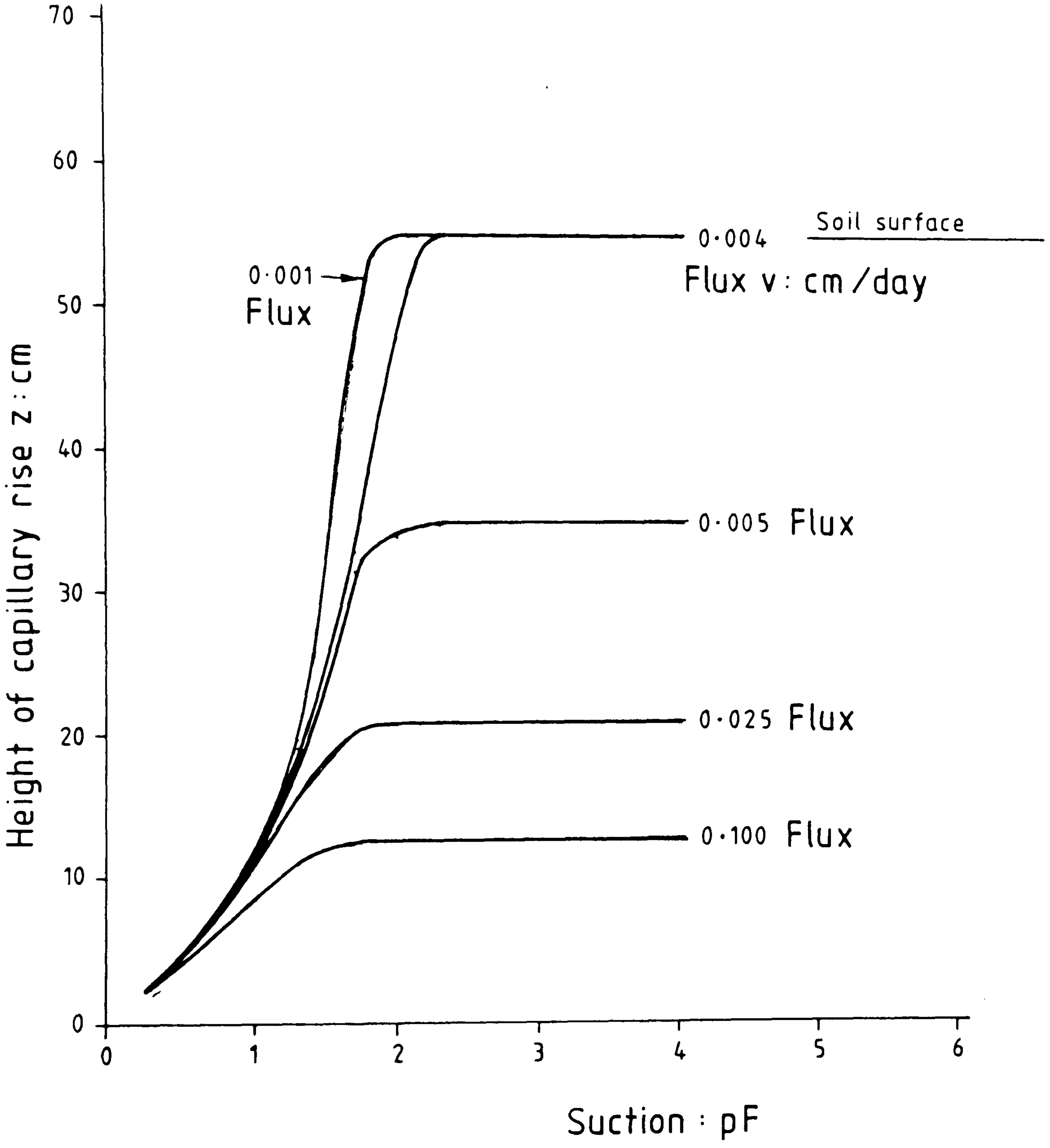


Figure 9·5 Variation of capillary rise with suction

More importantly, the fluxes that have been calculated can be manipulated (Ref. 9.6) via the equation

$$\text{Conc} = \frac{c \times \rho \times d \times (\text{Vbase} - \text{Vtop})}{\rho\,\text{soil} \times dh}$$

to allow estimates of the concentration of salts ("conc") carried up to the root zone by the moisture movements. In this equation, "c" is the salt concentration in the packed groundwater; "ρ" is the density of the soil water; "d" is the length of time (days) during which a suction of 1000 cm of head persists; and "Vbase - Vtop/dh" is the difference in the amount of flux reaching the base of the root zone from that reaching the soil surface and can be read off. (Fig. 9.6). The denominator term is the field density of the soil ("ρ soil").

Inserting the known values for all those terms reveals that 3.16 mg/kg of additional salt contamination is added to the less well drained areas of the oasis every summer.

The calculations, above have been carried out using the soil and groundwater data from Profile No. 2, where a near surface groundwater exists because the drainage works have not been effective or well constructed.

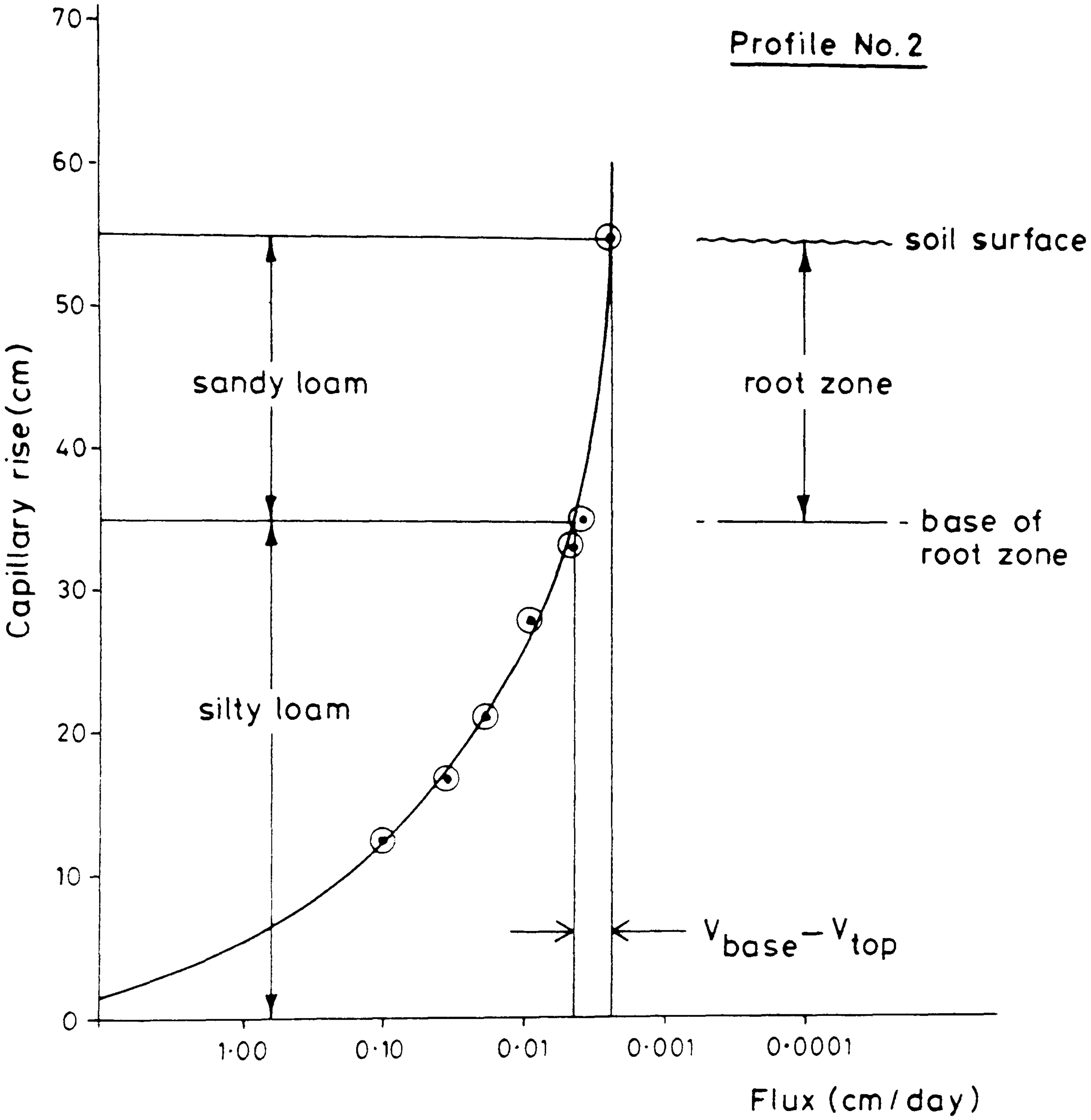


Figure 9·6 VARIATION OF FLUX WITH HEIGHT

(At a suction of 1000 cm H_2O)

9.3 Consequences of the Shallow Perched Groundwater

The calculations that indicate that capillary upward flow from the perched water table will add water equivalent to 36 mm of infiltrated rain fall and so increase the salt concentration of the top soil layers by 3.16 mg/kg, assuming that a surface suction (pF) of 3.0 will persist for the six summer months of each year. This - in fact - could be an underestimate since the surface instruments in the un-irrigated profile No. 3 reach pF values of between 3.6 and 4.4. Since field monitoring did not continue throughout the 1987 summer this point cannot be factually resolved.

However, it does appear that the calculations could be underestimates, and that higher upward movements of groundwater and greater additions of salt to the surface soils could occur.

This explains the increasing prevelance of salty "sabkah" patches throughout the oasis and indicates the crucial importance of improving the drainage throughout all the oasis's farms. As Fig. 9.1 clearly shows, the depth ("Z") down to the groundwater is a crucial control on upward moisture movement and any increase in the depth down to the perched groundwater markedly reduces the amount of groundwater (and its dissolved salts) that can rise to the root zone and the ground level.

Drainage improvements do, however, take time to implement and the local farmers will have to be persuaded that the effort of digging deep drains is worth while. Thus no rapid improvement in the areas of poorer drainage seems likely.

In the period when drainage is still poor in some areas, tensiometers and soil moisture cells will be less effective in improving irrigation efficiency than really is wanted. Although the tensiometers will be accurate in measuring soil moisture conditions, they will not reveal that the land is gradually becoming saltier and saltier and that extra irrigation water should actually be applied to wash the salts down below the plant root zones.

The situation with soil moisture cells is rather worse. These instruments appear (see Chapters 5 and 6) somewhat superior to tensiometers in terms of sensitivity, measuring range and robustness but will become less sensitive as they are exposed to an increasingly salty and moist environment. Thus their use in areas of poor drainage and near surface perched groundwaters is less effective than expected.

In practical terms, the best solution is to install field monitoring devices (tensiometers or soil moisture cells) only in those fields where the groundwater never rises to within 1 m of the ground level.

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CHAPTER TEN

Conclusions

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Conclusions

Al-Hasa is a long established agricultural community that is totally dependent on a single water source, and - at present - the efficiency of the use of this water source is poor.

Studies by other workers have revealed that the greatest opportunity for improving water use efficiency lies with the oasis's individual farmers.

The basic theme of this thesis is that if the farmers are each provided with the means of checking the moisture contents of their own fields, and if they have the various crop water consumption studies explained to them, then a marked increase in irrigation efficiency will be possible.

Studies both in laboratory and field conditions have revealed that very simple tensiometers can be acceptably accurate and sensitive. Calibration of tensiometers (and of their vacuum gauges) is however crucial if the farmer's equipment is to be accurate. The use of commercially available tensiometers is not recommended, since many of these appear to be inaccurate when supplied.

these appear to be inaccurate when supplied.

A simple and cheap facility to construct tensiometers and to calibrate and check these is recommended and should be established.

Soil moisture cells and gypsum blocks were also evaluated in laboratory and field conditions. This showed that the traditional gypsum blocks are relatively insensitive and are also subject to chemical attack from saline soil water. In contrast, composite soil moisture cells did prove to be both very accurate and very sensitive and were indeed every bit as accurate as tensiometers, even in very wet soils. These soil moisture cells appear to be excellent soil moisture measuring devices for the larger commercial farms, since the electrical signals given by the cells can be used to activate automated irrigation systems.

Studies of the more modern soil science equipment - i.e. suction transducers and psychrometers - revealed that these expensive items of equipment are not suitable for irrigation control use in Saudi Arabia, either because they are too sensitive to temperature variations or because they cannot give valid readings at the important soil moisture level (i.e. at a pF of 2.0).

Laboratory studies, to help evaluate the field equipment, proved interesting and, in particular, showed that the widely used pressure plate apparatus is less accurate than normally believed. The evidence in this thesis is that pressure plate tests should be replaced by the simpler and more accurate filter paper analytical technique.

The most interesting feature of the research was that the field readings from both tensiometers and soil moisture cell are affected by the nature of the soil into which these instruments are placed. Further work is needed to determine the cause of this phenomenon, which has so far not been reported in scientific works.

The overall conclusion of the research is that enough water exists at Al-Hasa to provide the required irrigation water, provided that the efficiency of use by the individual farmers is increased. This can be done by supplying the smaller farmers with simple tensiometers and by providing soil moisture cells to the larger commercial farms. In both cases, proper calibration of the equipment is crucial before any field use.

APPENDIX 1

Technical Terms Used in this Thesis

Air Entry Value (With respect to porous tips and plates)

The suction level that has to be reached before air at atmospheric pressure can commence leaking through the fine pores of the tips or plates. Until this suction level is reached, the tips and plates are effectively impermeable to air entry.

Aquifer

A geological rock layer or layers that can both store and transmit ground water. Confined and unconfined varieties exist, but those detailed in this thesis are all of the confined (artesian) type.

Crop Water Consumptive Use

The amount of water needed by plants for the processes of transpiration and growth, plus that water vapour lost by evaporation from adjacent soil. Normally consumptive use values are expressed in water depths per unit of time (e.g. mm/day or m^3/ha. per year).

Flow in Soils

The flow of water in saturated or unsaturated soils is a laminar flow effect expressed by the Darcy Equation. The simplest form of this equation is

$$V = k.i$$

where V = the flow velocity

K = the hydraulic conductivity

i = the hydraulic gradient on overall potential

Other forms of the Darcy Equation (e.g. see Chapter 9) are also used.

Field Capacity

Field capacity is that state of soil moisture that occurs after a totally saturated soil is allowed to drain under gravity for 24 hours. Whilst the actual pF value at which field capacity takes place varies with soil moisture retention capacity, in Al-Hasa experience indicates that this stage is equivalent to a pF of 2.0.

Wilting Point

The soil moisture level which is inadequate to allow plants to live. Normally this occurs at a pF of 3.3 (i.e. at a suction equal to about 2000 cm of water head).

Soil Suction Concepts

The actual direction and amount of moisture movement in a soil is now known to be due to the interaction of various potentials, or energy states, to which the water can be exposed.

The simplest is the gravity potential, by which is meant the energy the water has to do work because of its height above a chosen datum. This depth of water gives a positive pressure, whose size can be calculated from

$$p = \rho g h$$

where ρ = the water's density

g = the gravitational constant

h = the depth of water above the datum

The presence of colloids and adhesive surfaces in a soil matrix also permit a *matric potential* or *soil suction* to develop. Such a potential is invariably negative in type and is the cause of upward capillary flow. Obviously matric potentials (for particular dessication of soils) are larger in the soils with smaller soil pores (e.g. soils with high clay and silt contents).

The final type of potential - *osmotic* or *solute potential* results from the presence of dissolved solutes which lower the free energy of the water and so allow a negative potential to develop. Such solute potentials occur in saline soils.

The total water potential, above any chosen datum in a soil profile, is the algebraic sum of the four other terms, i.e.

Total potential= Gravity potential + Pressure potential - Matric potential - Osmotic potential

and governs whether the soil water will move down the soil profile (this occurs if the above equation has a positive answer) or upwards against gravity (if the above equation gives a negative result).

Soil Suction Units

Suction is generally measured in centimetres of equivalent water head, and the other common terms (e.g. bars) can be converted to centimetres of water head by the simple expression

$P = \rho g h$, provided that the correct density (ρ) value is used.

pF is a logarithmic expression of centimetres of water head and a pF of 1 equals 10 cm of water head, a pF of 2 equals 100 cm of water head, etc.

A bar - i.e. one atmosphere equivalent - is taken as equal to 1012 cm of water head.

APPENDIX II

Equipment Used in this Research

Supplier	Equipment
Vinten Inst. Ltd., Jessamy Road, Weybridge, Surrey, England	Ceramic plates Ceramic cups and tips P.V.C. tubes Perspex tubes
E.L.E. Hemel Hempstead, Hertfordshire, England	Tensiometers Soil Moisture Cells Gypsum blocks Psychrometers Microvoltmeters Wheatstone Bridge Vacuum gauges Pressure plates Moisture content tins Filter papers Neutron Probe
Geotechnical Instruments Ltd., Hatton, Warwick, England	Piezometers Bourdon gauges Vacuum gauges Pressure gauges Neutron Probes Pressure Transducers
Wykeham Farrance Inc., Weston Road, Slough, England	Air compressors Pressure regulators Pressure plates Vacuum gauges Pressure gauges Pressure transducers Neutron Probes
Soil Tech. Ltd., Langton Building,	Tensiometers Soil moisture cells

Denmark Street, Maidenhead, Berkshire, England	Psychrometers Microvoltmeters Neutron Probes Wheatstone Bridge Aluminium tubes Pressure plates Kaolin clay All types of Augers Soil moisture tins
Griffin & George, Bishop Meadow Road, Loughborough, Leicestershire, England	Hot air blower Filter papers Pressure gauges Vacuum gauges Microvoltmeter Wheatstone Bridges Air pumps Soil conductivity meters Augers Chemical components
Various hardware suppliers	PVC tubes and fittings for construction of tensiometers