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GEOLOGICAL AND NATURAL HISTORY SURVEY
3817 Mineral Point Road
Madison, Wisconsin 53705

M.E. Ostrom, State Geologist and Director

DEVELOPMENT OF A FIELD PROCEDURE FOR PREDICTING MOVEMENT OF LIQUID WASTES IN SOILS. Report No. 1.

by

J. Bouma and F.D. Hole, and D.I. Hillel

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DEVELOPMENT OF A FIELD PROCEDURE FOR PREDICTING MOVEMENT OF LIQUID WASTES IN SOILS

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By

J. Bouma, F. D. Hole and D. I. Hillel

Soil Survey Division (203 Soils Building)

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Development of field procedures for predicting movement of liquid wastes in soils

Contents

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C. F. Hanson, Director of the Geological and Natural History Survey, and State Geologist, The University of Wisconsin Extension;

E. D. Cann, Research Director, Wisconsin Department of Natural Resources;

J. E. Kerrigan, Assistant Director, Water Resources Center, The University of Wisconsin;

R. J. Muckenhirn, Chairman, Department of Soil Science, The University of Wisconsin;

M. T. Beatty, Professor of Soil Science, The University of Wisconsin;

J. Cain, Acting Chief, Water Planning Section, Wisconsin Department of Natural Resources;

J. S. Drake, Foreman, Experimental Farms, College of Agriculture and Life Sciences, The University of Wisconsin;

W. R. Gardner, Professor of Soil Science, The University of Wisconsin;

L. V. Hilliker, Acting Southern District Director for Forestry and Recreation, Nevin Fish Hatchery;

V. W. Matthias, Director, Experimental Farms, College of Agriculture and Life Sciences, The University of Wisconsin.

C. J. Milfred, Assistant Professor of Soil Science, Geological and Natural History Survey, The University of Wisconsin Extension;

A. E. Peterson, Professor of Soil Science, The University of Wisconsin;

D. A. Stephenson, Assistant Professor of Geology, The University of Wisconsin;

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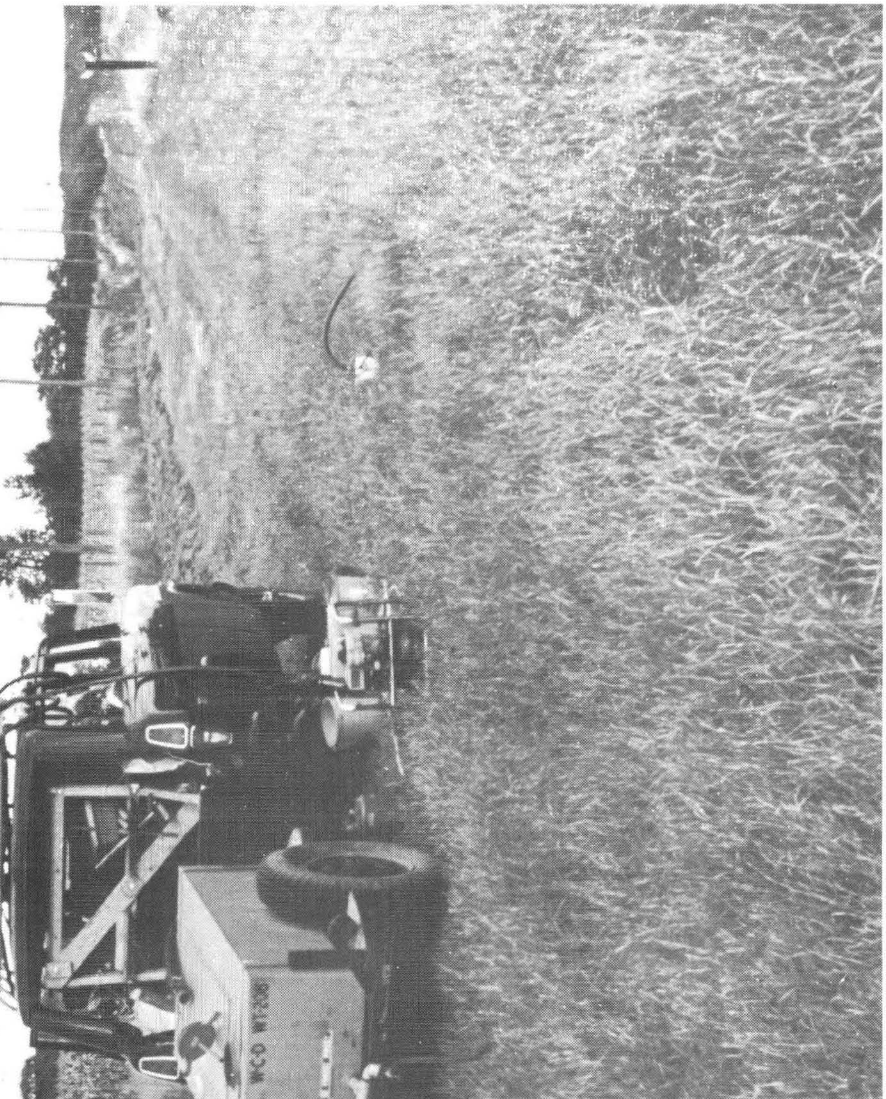


Summary

The increasingly pressing problem of liquid waste disposal is nationwide in scope. The success or failure of systems designed to infiltrate such wastes into the soil depends upon the hydraulic regime, which, in turn, is strongly affected by the soil's intrinsic hydraulic properties. Accordingly, site selection and predictions of the performance of projected sewage disposal systems should be based on knowledge of pertinent soil parameters. This study is an attempt to measure and evaluate such parameters in the state of Wisconsin.

During the past six months, alternative methods for measuring hydraulic conductivity and seepage rates have been evaluated and compared. The most promising methods were adapted to the purposes of the study and employed at different sites having different soil properties throughout Wisconsin. It appears that the Bouwer Double-Tube Method is superior to the State Percolation Test, in that it yields more dependable, consistent and physically interpretable data. Measurements of unsaturated conductivity were also carried out successfully in the field, in anticipation of the unsaturated flow regimes which will undoubtedly result form surface clogging of soils by the infiltrating effluent. Since the hydraulic properties of the soil can be expected to vary during the annual cycle, it would seem desirable to monitor these variations periodically. Toward this end, an attempt is being made to adapt morphological techniques to the evaluation of soil hydraulic properties.

Data are presented on the comparison of conductivity measurements (obtained in situ as well as in the laboratory under both saturated and unsaturated conditions) with State Percolation Tests. In addition, basic physical and morphological data are given for the following soils:

St-Charles-Batavia silt loam (location: Charmany farm, Madison)

Plano silt loam (location: Mandt farm, Madison)

Oshkosh clay, both virgin and cultivated (location: OMRO, Wisconsin)

Tama silt loam, both virgin and cultivated (location: Platteville, Wisconsin)

Sparta loamy sand (location: Arena, Wisconsin)

These data were not heretofore available for the soil types included in this study.

1. Introduction

Disposal of liquid wastes in recognized as an increasing problem throughout the nation. The considerable capacity of many soils to absorb and permit microbial break-down of such wastes above a water table is taken advantage of by means of various systems such as spray irrigation of waste waters, waste stabilization ponds and septic tank effluent distribution fields. In 1963, according to the Federal Council for Science and Technology, fifteen percent of the U.S. population depended upon waste disposal by dispersion in the soil, and installation of individual sewage systems took place at the annual rate of 300,000 on 75,000 acres of land. The problem is accordingly of greater magnitude today. Care must be taken to select for such purposes only those soils that are capable of absorbing the wastes above the water table, and holding them until noxious materials have been decomposed to harmless components such as CO_2, H_2O and N_2. The state of the soil system needs to be checked periodically (Preul, 1964; Hansel, 1968) to make certain that the rate of introduction of wastes does not exceed the capacity of the soil system to break them down before they have reached the water table or surface bodies of water.

There are two concerns in the disposal of domestic sewage by soil absorption. These are (1) health of the public and (2) surface water fertilization. Sewage spilling onto the ground or into surface waters is a vehicle of infection. Of considerable public interest is the relationship of waste discharge from septic tank-soil absorption systems to eutrophication of lakes. This investigation will contribute to public health and water pollution administration _via_ our increased knowledge of waste movement through soils.

Reflecting a national trend to better control pollution of our waters, all Wisconsin Counties are now required by state law to regulate the installation of on-site sewage absorption systems in shoreland areas. Many counties are adopting sanitary ordinances which apply county-wide. Where soil maps are available, counties are using them increasingly as a basis for implementing these ordinances (Cain and Beatty, 1965). In the absence of soil maps, greater reliance is placed on on-site investigation. This increased emphasis on regulation of on-site sewage absorption systems makes it very important that soil map interpretations be sound and on-site evaluations be as accurate as possible. This may well involve a scientific reëvaluation of current soil percolation tests required of land developers by state boards of health. The purpose of the reevaluation is to determine margins of error and amplitudes of safety factor. Comparisons of results of mandatory percolation tests as now conducted with data obtainable by newly developed sophisticated apparatus has not been made systematically. This should be done in a research program in which advanced methods would be adapted for routine field use and in which the growing body of theory about water movement in soil will be applied to problems of liquid waste disposal in particular soil profiles and watersheds.

Accurate information on the rates of movement of water, both clean and polluted, into and in soil (infiltration rate; hydraulic conductivity) is prerequisite to adequate solution of the problem of liquid waste disposal. New methods are available for the determination of hydraulic conductivity of soil at saturation (Bouwer, 1961, 1962, 1964, 1966, 1967) and at various moisture contents in the unsaturated range (Hillel and Gardner, 1969, 1970) but these methods have not been widely applied in the field to major soils of the nation.

Comparison of measurements by the new, precise methods with test data obtained by conventional field and laboratory percolation and infiltration precedures is essential to (1) improvement in interpretation of the conventional test data and (2) development of more adequate field procedures for predicting movement of liquid wastes in soils. Specifically, the results of the widely used percolation test examplified by that required by the State Division of Health (Wisconsin State Department of Health and Social Services, 1969) should now be compared with results of advanced methods, including the Bouwer hydraulic conductivity field test, the laboratory percolation test on undisturbed soil cores taken horizontally and vertically, and the infiltration tests of crust-capped soil columns. The variety of soils in Wisconsin is sufficient to represent many conditions elsewhere in the country.

This effort was begun by the Principal Investigator in 1968, by Dr. Johannes Bouma and the Principal Investigator in 1969. The work holds the promise of advancing our understanding of the behavior of liquids in our principal soils, and for development of new practical procedures for testing soils in this regard. Results of the proposed work in Wisconsin are expected to be applicable in other areas and to contribute to the solution of the national problem of liquid waste disposal.

Fundamental studies of the properties, processes and classification of the soils selected for investigation are necessary to properly interpret data on infiltration and hydraulic conductivity and to apply this knowledge to other areas not directly tested.

2. Methods of characterizing percolation properties of soils

2.1. General

A number of alternative methods have been proposed to characterize the percolation properties of soils and to help in predicting the expectable behavior of sewage disposal systems in different locations. Perhaps the simplest method is to impound water over the surface or inside a boring and to observe the rate of infiltration of the water into the soil. This is the principle of the method known in Wisconsin as the State Percolation Test, and specified by law as the standard criterion for the installation of septic tanks.

Unfortunately, such infiltration tests, though they are simple and easy to perform, cannot be expected to yield reliable information on the hydraulic behavior of the soil. The results of any such test depend on the initial conditions (e.g., soil moisture content and tension) and on the boundary conditions (e.g., the size, and depths of the impounded area, the depths of the soil and the water table) which prevail at the time and site of the test. Hence the results of such tests are often arbitrary even when the method of performance is highly standardized (which, in any event, isn't often the case).

Inherently superior and more reliable are methods which measure intrinsic physical properties of the soil. Such measurements should be essentially independent of the way they are measured (provided the method is physically sound) and therefore more reproducible and characteristic. The most pertinent soil physical property to measure in connection with seepage systems is the hydraulic conductivity, which is defined as the rate of flow through a unit cross-sectional area of soil per unit hydraulic head gradient.

Numerous techniques are now available for measuring hydraulic conductivity, both in the laboratory and in the field. In principle, field methods are to be preferred, since they can give values more nearly pertinent to the actual behavior of the soil in situ, while laboratory methods necessarily entail some disturbance of the soil sample as it is removed, transported, and subjected to the testing procedure.

The most convenient field methods for measurement of hydraulic conductivity apply to the soil below the groundwater table which is always in the saturated state. However, in most locations where sewage disposal systems are likely to be planned the water table is fairly deep, and we are concerned with the hydraulic properties of the soil above the water table.

Under such conditions, hydraulic conductivity can be measured either in the saturated or in the unsaturated soil condition. For the conductivity at saturation, a convenient method is the one of Bouwer, to be described subsequently. However, the information obtained may not apply for predictive purposes where the percolating water tends to clog the surface of the soil or form a crust over it (due to deposition suspended mineral and organic matter, and/or to physicochemical and biochemical processes). Under such conditions, the seepage process can be expected to take place in a primarily unsaturated soil. Evaluation of the unsaturated hydraulic conductivity is in general more difficult, since it depends on the suction of soil-water,--a property which is difficult to control and even to measure in practice. Recently, however, a method has been proposed (Hillel and Gardner, 1970) which offers a simple way to evaluate the unsaturated conductivity characteristics of a soil in situ.

2.2. State percolation test

Soil percolation tests closely resembling the current State Percolation Test, have been used since their introduction by Henry Ryon ca. 1926, McGauhey *et al.*, 1963. The test estimates the suitability of a certain site for a septic tank system. A detailed description of the Wisconsin test is to be found in the Register of the State Board of Health of Wisconsin, November, 1969 Chapter H. 62.20: Private domestic sewage treatment and disposal systems. This chapter is reproduced here.

(c) *Vacuum-breaker.* If the water supply inlet cannot be raised above the maximum possible water level, an approved type of vacuum-breaker shall be installed between the control valve and the fixture in such manner that no back-siphonage is possible under any degree of vacuum in the water lines and with water in the fixture at the maximum possible water level. For positive protection each such fixture shall have a vacuum-breaker installed 4 inches above the maximum water level.

(d) *Maximum water level.* The maximum possible water level referred to heretofore shall be construed as the height to which water can rise in a fixture, tank or vat before it flows freely into the open atmosphere above the fixture rim or through adequate size openings so designed as not to be obstructed by debris or waste matter.

(e) *Impure liquids.* Fixture contents against which back-siphonage protection shall be maintained include all pollutional material, sewage, waste water, processing liquids, chemicals, and all water and other liquids which can be polluted at some time or other.

(5) SPECIAL EQUIPMENT PROTECTION. All water supply equipment and appliances serving special fixtures shall conform with the intent and purposes of this section. Any unusual use for water, as for air-conditioning equipment, hydraulic elevators, presses, fountains, etc., shall be given special consideration in relation to possible pollution of the pure water supply system.

(6) IMPROPER LOCATION OF SEWERS AND DRAINS. Sewers and drains shall never pass directly over water tanks or any place where drinking water, ice, or food is prepared, handled, or stored.

(7) DUAL WATER SUPPLIES. The maintenance of a pressure system of water supply whose purity is questionable, such as cistern water, in the same building in which a pure water supply exists is discouraged, especially if the water is piped throughout the building and not confined to a certain section for special uses or processing. The piping containing such impure water supply shall be painted red and properly labeled at intervals. Under no circumstances shall the two supplies be cross-connected or provision made for their cross-connection. No cross-connection shall be made between piping connected to a public water supply system and piping of a private water supply system. See H 62.22 (40).

H 62.20 Private domestic sewage treatment and disposal systems. (1) APPROVALS AND LIMITATIONS. (a) *Allowable use.* Septic tank and effluent absorption systems or other treatment tank and effluent disposal systems as may be approved by the department may be constructed when no public sewerage system is available to the property to be served or likely to become available within a reasonable time. All domestic wastes shall enter the septic or treatment tank unless otherwise specifically exempted by the department or this section.

(b) *Public sewer connection.* Private domestic sewage treatment and disposal systems shall be discontinued when public sewers become available to the building served. The building sewer shall be disconnected from the private system and be connected to the public sewer. All abandoned septic tanks and seepage pits shall have the contents removed and shall be immediately filled with sand, gravel or similar material.

(c) *Plans and specifications.* 1. Public buildings. Complete plans and specifications shall be submitted to the department and written approval received before letting contracts or commencing work for all private domestic sewage treatment and disposal systems, and for the addition to or replacement of existing systems for all public buildings. Included as public buildings but not limited by enumeration herewith are:

a. Theaters and assembly halls
b. Schools and other places of instruction
c. Apartment buildings, hotels and places of detention
d. Factories, office and mercantile buildings
e. Mobile home parks, camp grounds and camping resorts
f. Parks

2. Local approval. The approval by county or other local governmental agency shall not exempt the requirements for state approval for the installation of sewage treatment and disposal systems serving public buildings.

3. Submission of plans and specifications. All plans and specifications shall be submitted in triplicate and shall include the following:

a. Detailed plan of the proposed septic tank or treatment tank and effluent disposal system showing building location with all lateral distances indicated, including distance from building served to system, from system to well, lot line, lake, stream or other watercourse.
b. Legal description of the property on which the system is to be installed.
c. Soil boring and percolation test data.
d. Ground slope and lot size.
e. Complete data relative to the expected use and occupancy of the building to be served.

4. Availability of plans. There shall be maintained at the project site one set of plans bearing the department's stamp of approval.

(d) *Specific limitations.* 1. Cesspools. Cesspools are prohibited.

2. Revised plans. Approved plans and specifications shall not be revised except with the written approval of the department.

3. Industrial wastes. When industrial wastes are intended to be disposed of by soil absorption, the department shall be consulted as to requirements.

4. Clear water. The discharge of surface, rain and other clear water into a private domestic sewage disposal system is prohibited.

(2) SOIL TESTS AND SITE REQUIREMENTS. (a) *Soil tests supervision.* Soil boring and percolation tests shall be made by or under the direction and control of a master plumber, or master plumber restricted licensed in Wisconsin to install private sewage disposal systems or an engineer, architect, surveyor or sanitarian registered in Wisconsin. Certification of the tests shall be signed by the person providing supervision and control on blank forms furnished by the department.

(b) *Percolation and boring tests.* The size and design of each proposed soil absorption system shall be determined from the results of soil percolation tests and soil borings conducted in accordance with this section. At least 3 percolation tests shall be conducted with the holes located uniformly over the area and to the depth of the proposed absorption system. At least 3 soil borings shall be dug to a depth at least 3 feet below the bottom of the proposed system. The borings shall be distributed uniformly in the area of the proposed system.

(c) *Septic tank location.* No tank shall be located within 5 feet of any building or its appendage, 2 feet of any lot line, 10 feet of any cistern, 25 feet from any well, reservoir, swimming pool or the high water mark of any lake, stream, pond or flowage. Where practicable, greater distances should be maintained.

(d) *Soil absorption site.* 1. Location. All soil absorption disposal systems should be located at a point lower than the surface grade of any nearby water well. The soil absorption system shall be located not less than 25 feet from any building, dwelling or cistern, 50 feet from any water well, reservoir or swimming pool, 5 feet of any lot line, 25 feet of any water service or 50 feet of the high water mark of any lake, stream or other watercourse. Where possible, greater distances should be maintained.

2. Percolation rate—trench or bed. A subsurface soil absorption system of the trench or bed type shall not be installed where the average percolation rate of the 3 tests for the site is slower than 60 minutes for water to fall one inch.

3. Percolation rate—seepage pit. For a seepage pit, percolation tests shall be made in each vertical stratum penetrated below the inlet pipe. Soil strata in which the percolation rates are slower than 30 minutes per inch shall not be included in computing the absorption area. The average of the results shall be used to determine the absorption area.

4. Flood plain. A soil absorption system shall not be installed in a flood plain.

5. Slope. The soil absorption system shall be constructed on that portion of the lot which does not exceed the slope here specified for the class. In addition, the soil absorption system shall be located at least 20 feet from the top of the slope.

Class	Minutes Required for Water to Fall One Inch: Shallow Absorption Systems	Minutes Required for Water to Fall One Inch: Deep Absorption Systems	Slope
1	Under 3	Under 2	20%
2	3 to 45	2 to 30	15%
3	45 to 60	30 to 60	10%

6. Filled area. A soil absorption system shall not be installed in a filled area unless written approval is received from the department.

7. Ground water and bedrock. There shall be at least 3 feet of soil between the bottom of the soil absorption system and high ground water or bedrock.

(3) PERCOLATION TEST PROCEDURE. (a) *Type of hole.* The hole shall be dug or bored. It shall have vertical sides and have a horizontal dimension of 4 to 12 inches.

(b) *Preparation of hole.* The bottom and sides of the hole shall be carefully scratched with a sharp pointed instrument to expose the natural soil interface. All loose material shall be removed from the

bottom of the hole which shall then be covered with 2 inches of coarse sand or gravel when necessary to prevent scouring.

(c) *Test procedure, sandy soils.* For tests in sandy soils containing little or no clay, the hole shall be carefully filled with clear water to a minimum depth of 12 inches over the gravel and the time for this amount of water to seep away shall be determined. The procedure shall be repeated and if the water from the second filling of the hole at least 12 inches above the gravel seeps away in 10 minutes or less, the test may proceed immediately as follows: Water shall be added to a point not more than 6 inches above the gravel. Thereupon, from a fixed reference point, water levels shall be measured at 10-minute intervals for a period of one hour. If 6 inches of water seeps away in less than 10 minutes, a shorter interval between measurements shall be used, but in no case shall the water depth exceed 6 inches. The final water level drop shall be used to calculate the percolation rate. Soils not meeting the above requirements shall be tested as in subsection (d) below.

(d) *Test procedure, other soils.* The hole shall be carefully filled with clear water and a minimum water depth of 12 inches shall be maintained above the gravel for a 4-hour period by refilling whenever necessary or by use of an automatic siphon. Water remaining in the hole after 4 hours shall not be removed. The soil shall be allowed to swell not less than 16 hours or more than 30 hours. Immediately following the soil swelling period, the percolation rate measurements shall be made as follows: Any soil which has sloughed into the hole shall be removed and water shall be adjusted to 6 inches over the gravel. Thereupon, from a fixed reference point, the water level shall be measured at 30-minute intervals for a period of 4 hours unless 2 successive water level drops do not vary by more than $\frac{1}{16}$ of an inch. The hole shall be filled with clear water to a point not more than 6 inches above the gravel whenever it becomes nearly empty. Adjustment of the water level shall not be made during the last 3 measurement periods except to the limits of the last measured water level drop. When the first 6 inches of water seeps away in less than 30 minutes, the time interval between measurements shall be 10 minutes and the test run for one hour. The water depth shall not exceed 6 inches at any time during the measurement period. The drop that occurs during the final measurement period shall be used in calculating the percolation rate.

(e) *Verification.* 1. Physical characteristics. Depth to high ground water and bedrock, ground slope and percolation test results shall be subject to verification by the department. Verification of high ground water shall include, but not be limited to, a morphological study of soil conditions with particular reference to soil color and sequence of horizons.

2. Filling. Where the natural soil condition has been altered by filling or other attempts to improve wet areas, verification may require observation of high ground water levels under saturated soil conditions.

Note: Detailed soil maps are of value for determining estimated percolation rates and other soil characteristics.

(4) TREATMENT TANKS. (a) *Design.* 1. General requirements. a. Septic tanks shall be fabricated or constructed of welded steel, monolithic concrete or other materials approved by the department.

All tanks shall be watertight and fabricated so as to constitute an individual structure.

b. The design of prefabricated septic tanks shall be approved by the department.

c. Plans for site-constructed concrete tanks shall be approved by the department prior to construction.

d. The liquid depth shall not be less than 3 feet nor more than an average of 6 feet. The total depth shall be at least 8 inches greater than the liquid depth.

e. Rectangular tanks shall have a minimum width of 36 inches and shall be constructed with the longest dimensions parallel to the direction of flow.

f. Cylindrical tanks shall have an inside diameter of not less than 48 inches.

g. Each prefabricated tank shall be clearly marked to show liquid capacity and the name and address or registered trademark of the manufacturer. The markings shall be inscribed into or embossed on the outside wall of the tank immediately above the outlet opening. Each site-constructed concrete tank shall be clearly marked at the outlet opening to show the liquid capacity. The marking shall be inscribed into or embossed on the outside wall of the tank immediately above the outlet opening.

h. Precast concrete tanks shall have a minimum wall thickness of 2 inches.

2. Materials and joints. a. The concrete used in constructing a precast or site-constructed tank shall be a mix to withstand a compressive load of at least 3,000 pounds per square inch. All concrete tanks shall be designed to withstand the pressures to which they are subjected.

b. The floor and sidewalls of site-constructed concrete tanks shall be monolithic except a construction joint will be permitted in the lower 12 inches of the sidewall of the tank. The construction joint shall have a key way in the lower section of the joint. The width of the key way shall be approximately 30% of the thickness of the sidewall with a depth equal to the width. A continuous water stop or baffle at least 6 inches in width shall be set vertically in the joint, embedded one-half its width in the concrete below the joint with the remaining width in the concrete above the joint. The water stop or baffle shall be copper, neoprene, rubber or polyvinylchloride designed for this specific purpose.

c. Joints between the septic tank and its cover and between the septic tank cover and manhole riser shall be tongue and groove or shiplap type and sealed watertight using neat cement, cement or bituminous compound.

d. Steel tanks shall be fabricated of new, hot rolled commercial steel. The tanks, including cover with rim, inlet and outlet collars and manhole extension collars shall be fabricated with welded joints in such manner as to provide structural stability and watertightness. Steel tanks shall be coated, inside and outside, in compliance with the U. S. Department of Commerce Commercial Standard 177.

DOUBLE - TUBE

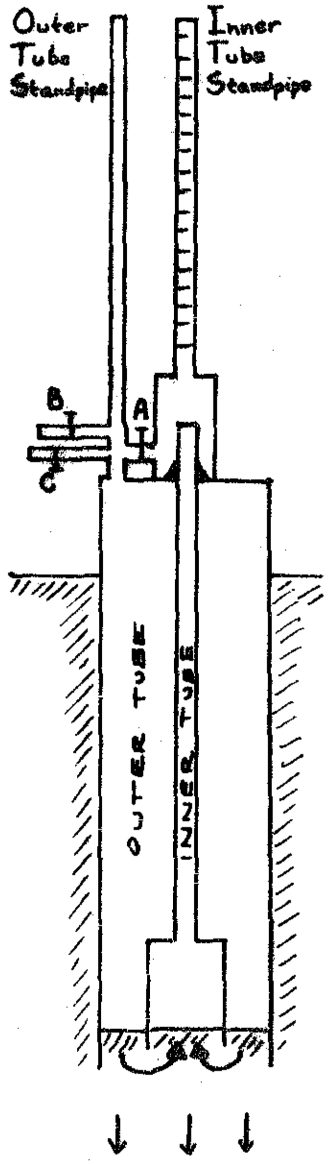


FIG 2.3.1.

MANDT - 2 55 CM
BOUWER - DOUBLE TUBE MEASUREMENT

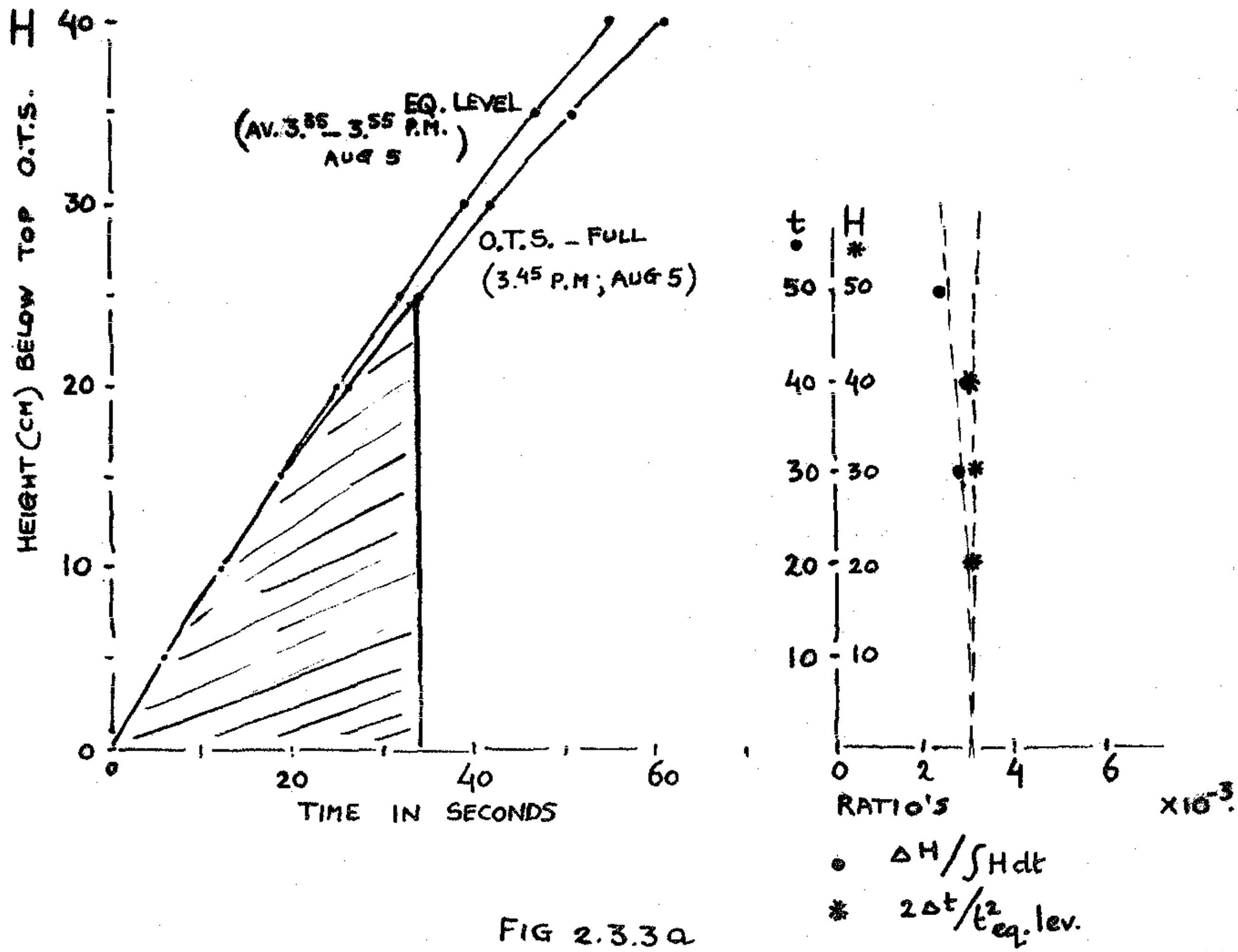


FIG 2.3.3 a

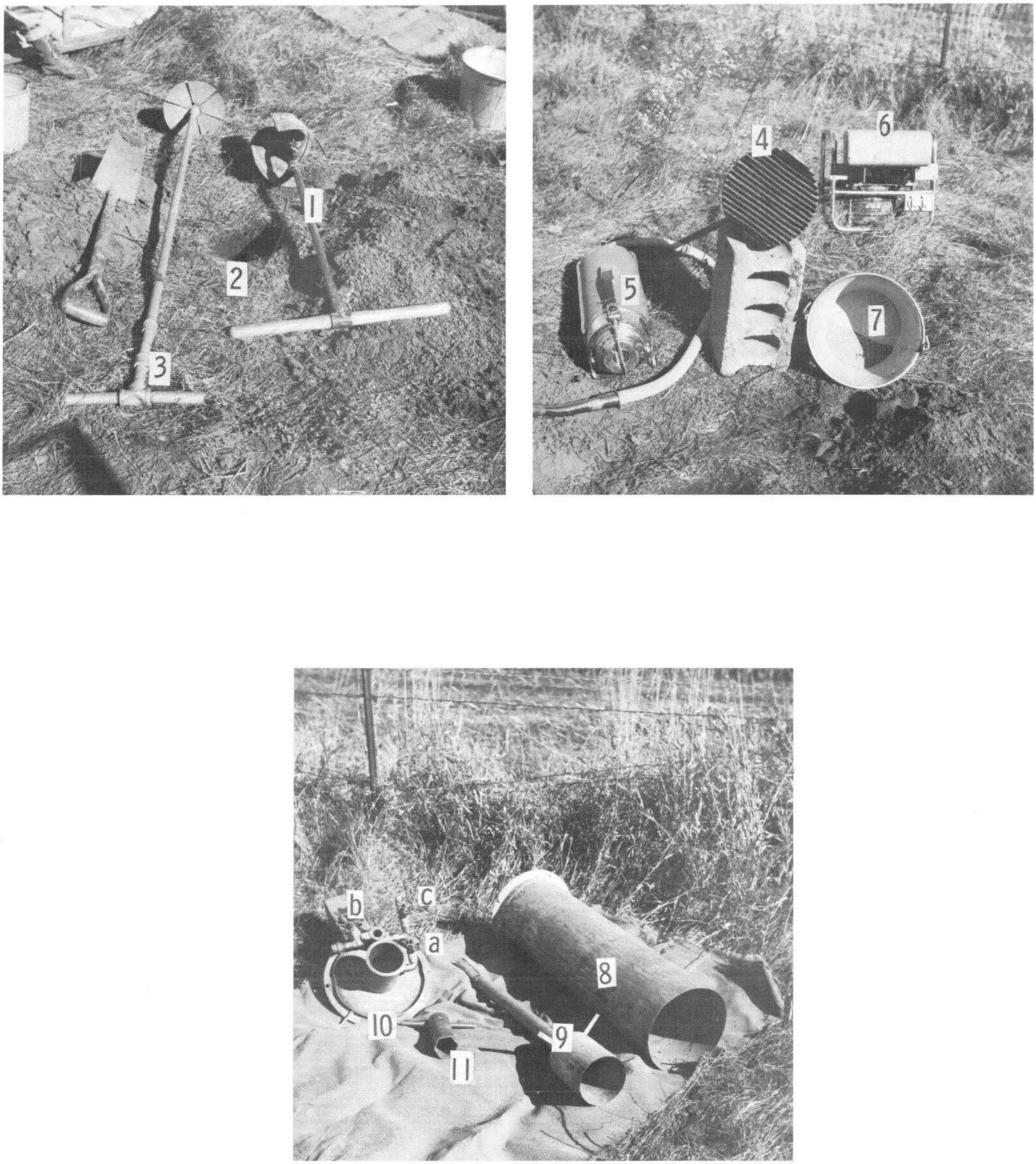
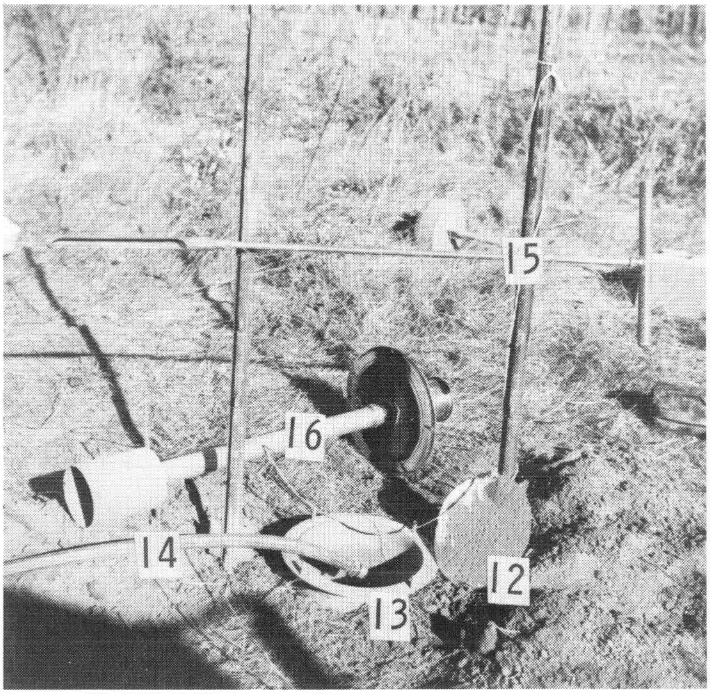


FIG. 2.3.2 Measurement of the hydraulic conductivity with the Bouwer Double-tube apparatus.


15
16
14
12
13


a
17


a
b
18

2.3. In situ measurement of saturated hydraulic conductivity: The Bouwer double-tube method.

This method is a standard procedure for measuring hydraulic conductivity of saturated soil, well above the groundwater table (Boersma, 1965, in: Methods of Soil Analysis, Part 1, p. 234). With the Double tube method, two concentric tubes are inserted into an auger hole and covered by a lid with a standpipe for each tube. (fig. 2.3.1.) Water levels are maintained at the top of the standpipes to create a zone of positive water pressures in the soil below the bottom of the hole. The hydraulic conductivity (K) of this zone is evaluated from the reduction in the rate of flow from the inner tube into the soil when the water pressure inside the inner tube is allowed to become less than that in the outer tube. This is done by stopping the water supply to the inner tube (closing valve a) and measuring the rate of fall of the water level in the standpipe on the inner tube while keeping the standpipe on the outer tube full to the top. This rate of fall is less than that obtained in a subsequent measurement in which the water level in the outer tube standpipe is allowed to fall at the same rate (by manipulating valve b) as that in the inner tube standpipe. The difference between the two rates of fall is the basis of the calculation of K.

Procedure:

The different stages of the method will now be explained in more detail with reference to the numbers on the included pictures. (fig. 2.3.2) A large auger, with a diameter of 10 inches (1) is used to make a cylindrical hole (2) to the desired depth. A bottom scraper (3) is used to obtain a flat surface at the bottom. Loose soil is removed from the hole. Before using the hole cleaner (4) the outer tube (8) is forced down into the hole. It is often necessary to widen the hole locally to make this possible. This is done with a scraper, not pictured here. When the outer tube is found to fit well it is temporarily removed again. The hole cleaner (4) is gently forced into the soil at the bottom of the hole. If the soil is dry, premoistening of it may be necessary. The thin metal fins of the hole cleaner should penetrate about 2 cm into the soil. Next, the hole cleaner is pulled out of the hole with an upward cork-screw movement that prevents smearing the soil surface, as would happen if the cleaner were turned without being pulled up at the same time. The detached mass of soil is up-ended for observation of the natural broken surface of soil held between the fins. A corresponding natural broken soil surface is left at the bottom of the hole.

The outer tube (8) is forced down as evenly as possible about 5 cm into the soil at the bottom of the hole (13). This may require careful blows of a sledge hammer on a wooden cross-piece. Control of the distance is by measurement from a fixed horizontal reference rod (15). With a vacuum cleaner (5), powered by a portable electric generator (6), loose soil fragments are removed from the bottom of the hole. This bottom surface is then covered with a thin (1 cm) layer of coarse sand (7) on top of which a baffle is laid (12), with attached strings looped over the top of the tube. The outer tube is slowly filled with water (14). The energy breaker and sand layer protect the natural soil surface from erosion by the turbulent water. Then the inner tube (9) and the top plate (10) which has two basal standpipes leading to the inner tube and outer tube, respectively, and three valves (a, b and c)* are assembled into one fixed unit (16). A special wrench (11) is used to tighten a ring with washer inside the inner well of the top plate (10). This binds the inner tube to its standpipe.

* The functions of the three valves are explained as follows. Starting with the valves closed, they can be manipulated in the course of the experiment to control the flow of water. Opening valve c allows water to flow into the outer tube basal standpipe which is situated between valve c and valve b. Opening valve a admits water into the inner tube basal standpipe. Opening valve b bleeds water from the outer tube standpipe, which can be isolated from the water supply by closing valve c, and from inner tube standpipe by closing valve a.

The distance of the bottom of the inner tube from the top plate should be so spaced that the bottom of the inner tube will be only a few cm above the sand when the assembly (16) is set into and attached to the outer tube. The hose (14) is then attached adjacent to valve c on the top plate (1). When the outer tube is brim full and water starts streaming between the loose top plate and the upper rim of the outer tube, the bolts are tightly screwed, closing down on the gasket. This procedure flushes out air, avoiding its entrapment on the under side of the top plate. Valve a is now opened to admit water to the inner tube basal standpipe. Then the connection between the top plate and the inner tube is loosened again. The inner tube slides downwards to the soil surface. The sliding distance should not exceed a few cm in order to avoid turbulence that might disturb the soil surface. The inner tube is pushed down about 2 cm into the soil. In the meantime water is continuously entering the system in such a quantity as to keep both tubes filled all the time. Overflow water that spills onto the top plate from the outer tube basal standpipe (near valve b) is drained off the top plate through a brass tube and hose extension into a bucket nearby. The depth of penetration of the inner tube is accurately measured using the reference level (15). Next, the plastic standpipes for the inner and outer tubes are fastened to the two openings in the top plate. For slow infiltrations, a smaller inner tube standpipe (ITS) is used (R = 0.6 cm); for larger infiltrations a larger one is used (R = 1.85 cm). Valve c is then opened enough to ensure a slight overflow at the top of the standpipes.

Two types of readings are made, usually starting one hour after application of the water: 1. The outer tube standpipe (OTS) - full measurement (17). Valve a is kept closed, as is, of course, valve b. 2. The equal-level measurement (18). Valve a is closed and valve b is opened, but with obstruction by the fingers at the open end of the pipe, in such a way as to synchronize the drop of the water level in the OTS with that in the ITS. Eight stop watches are started simultaneously at the beginning of a reading. One watch at a time is stopped as the water level in the ITS reaches a mark on the tube. The marks are spaced 5 cm apart over a total distance of 60 cm. Elapsed time is recorded in tenths of a second. The readings over a distance of 40 cm should yield a difference of at least 6 seconds between two measurements; that is, between one OTS-full measurement and the average value of the preceeding and the next equal-level measurements. If the time difference is less than 6 seconds, measurement should be extended to, say, 60 cm and readings made within the lower 40 cm interval thereof. The measurements are repeated at regular time intervals until the ratio $\Delta t/t^2$ eq. level becomes constant (Bouwer, 1962).

A constant ratio may occur after a period varying from one to four hours. The constant ratio is supposed to indicate sufficient saturation of the soil below the tubes. The intervals between successive measurements should be approximately ten times as long as the time required for each separate reading, or 15 minutes (Baumgart, 1967), whichever is the shorter, to allow reëstablishment of equilibrium. The two final curves obtained (fig. 2.3.3.a) differ because of flow of water from the outer tube into the inner, during the OTS-full measurement.

K is calculated according to the equation:

$$K = (R_v^2/F_f \cdot R_c) \cdot (\Delta H/\int Hdt)$$

where: H = difference in hydraulic head H between both curves at any time t.

Hdt = surface below OTS curve (to be determined graphically)

Ff = flow factor, to be read from tables, expressing the influences of the dimensions of the system and the depth D to a layer

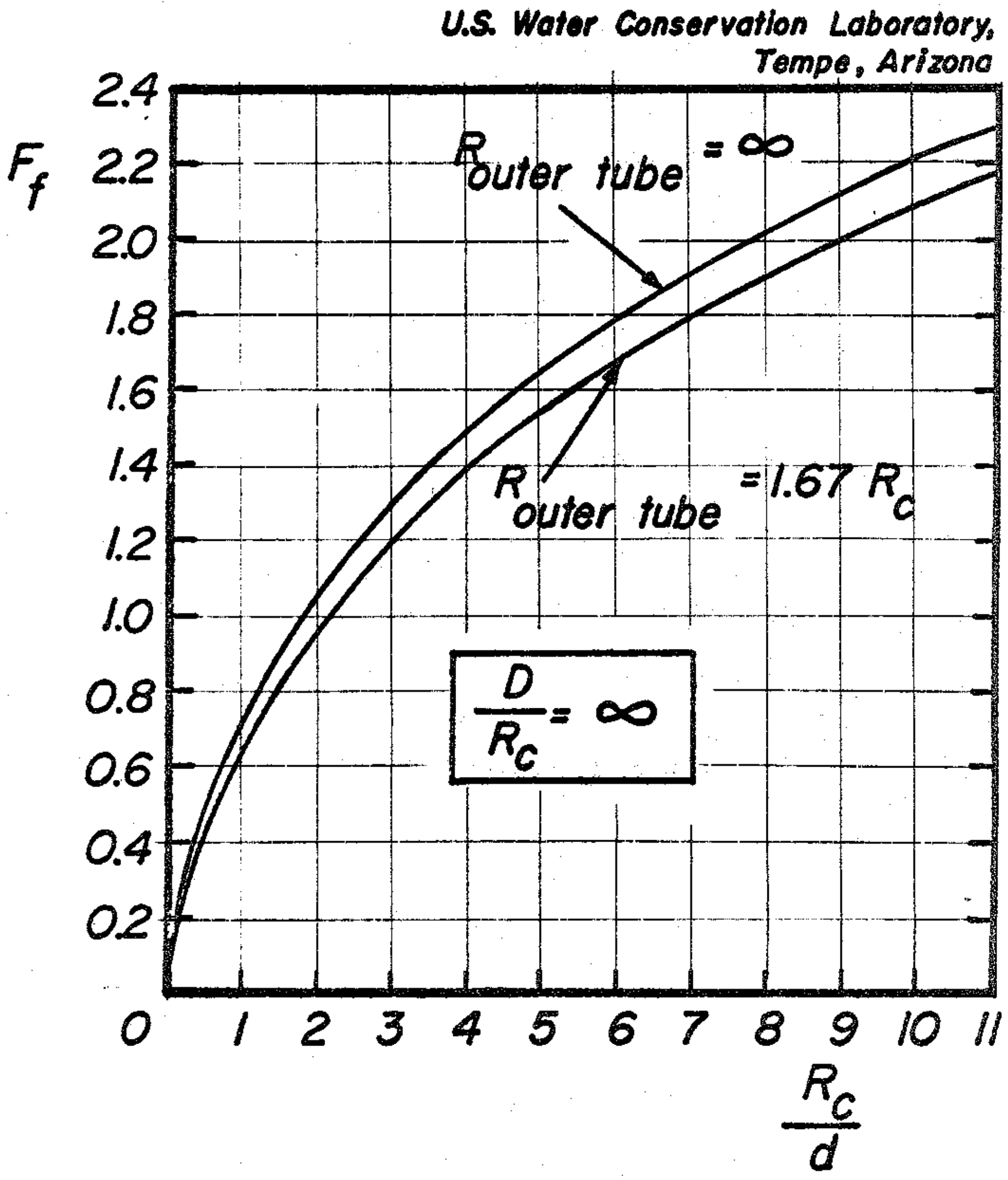


Figure 4. Graph showing F_f as a function of R_c/d for two outer-tube sizes.

FIG 2.33 b

CALCULATION SHEET FIELD DATA

DOUBLE TUBE TEST

Date: Aug 5, 1969
Location: Mandt farm - Madison
Code no.: Mndt 2
Operators: BOUMA HOLE
Time water started: 12.00
Temp. Water: 20 °C

Soil Type:
Depth hole: 55 CM
Horizon: B2
Tube radii:
O.T.= 25.0 cm
I.T.= 14.4 cm
Rv = 0.6 cm

Measurements.
A= 140.0 cm
C= 48.6 cm
I.T.= 94.0 cm
O.T.= 90.0 cm
d= 2.6 cm

t	1.45	1.55	2.05	2.15	2.25	2.35	2.45	2.55	3.05	3.15	3.25	3.35
H	OTS-c	Eq-lev.	OTS-c	Eq-lev.	OTS-c	Eq-lev.	OTS-c	Eq-lev.	OTS-c	Eq-level	OTS-c	Eq-lev.
0												
5	3.9	4.4	4.3	4.6	4.2	4.7	4.2	5.2	5.4	5.6	6.2	6.2
10	7.7	7.9	8.8	9.0	8.9	10.0	9.2	9.8	10.4	11.0	11.8	12.2
15	12.0	11.6	13.0	13.0	13.4	14.7	13.8	15.0	16.2	16.8	18.2	18.4
20	16.6	15.5	18.2	17.7	18.6	20.0	19.0	20.4	22.0	23.0	24.8	25.6
25	20.8	20.0	23.9	23.0	24.0	26.0	24.5	26.0	28.4	28.9	32.5	32.2
30	25.8	24.2	28.8	27.6	29.8	31.6	30.0	31.8	35.2	35.2	39.8	39.4
35	31.7	28.8	34.4	33.0	35.9	37.4	37.0	37.6	42.6	42.0	48.4	47.0
40	37.0	34.2	41.2	38.6	42.6	44.2	45.0	44.4	50.0	49.4	58.0	55.0

H		
0	6.0	
5	12.4	6.2
10	19.0	12.0
15	26.2	18.2
20	33.8	25.0
25	41.8	31.9
30	50.8	39.2
35	61.0	47.0
40		55.1
t	3.45	3.55

8

Ratio's $\Delta t / t^2_{eq.\,lev}$

1^{55} — 2^{15}	—	0.00305
2^{15} — 2^{35}	—	0.00070
2^{35} — 2^{55}	—	0.00032
2^{55} — 3^{15}	—	0.00014
3^{15} — 3^{35}	—	0.00020 } const.
3^{35} — 3^{55}	—	0.00020 }

CALCULATION SHEET DOUBLE TUBE METHOD

Measurement: Mnd 2 (aug 5)

K measurement based on:

OTS – 3.45 P.M

Eq. lev. 3^{35} + 3^{55} P.M.

H (cm)	OTS-full time:	Eq. level times:
5	6.0	6.2
10	12.4	12.1
15	19.0	18.3
20	26.2	25.3
25	33.8	32.0
30	41.8	39.3
35	50.8	47.0
40	61.0	55.0

Graphical evaluation:

	t	ΔH	$\int$ Hdt	Ratio
	30	1.0	352.5	2.84×10^{-3}
	40	1.8	610.0	2.95×10^{-3}
	50	2.2	975.0	2.25×10^{-3}
	Ratio	extrapol	to $t=0$ →	3.0×10^{-3}
	2 Δt	$t^2_{eq.\,level}$	ratio	
20	1.8	625	2.9×10^{-3}	
30	5.0	1544	3.2×10^{-3}	
40	12	3025	3.9×10^{-3}	
	Ratio	extrapol.	to $H=0$ ⇒	30×10^{-3}

Ratio extrapolated to H=0 :

Other values: d= 2.6 R_v = 0.6 R_c= 6.2 R_c/d = 2.38

F_f= 1.1

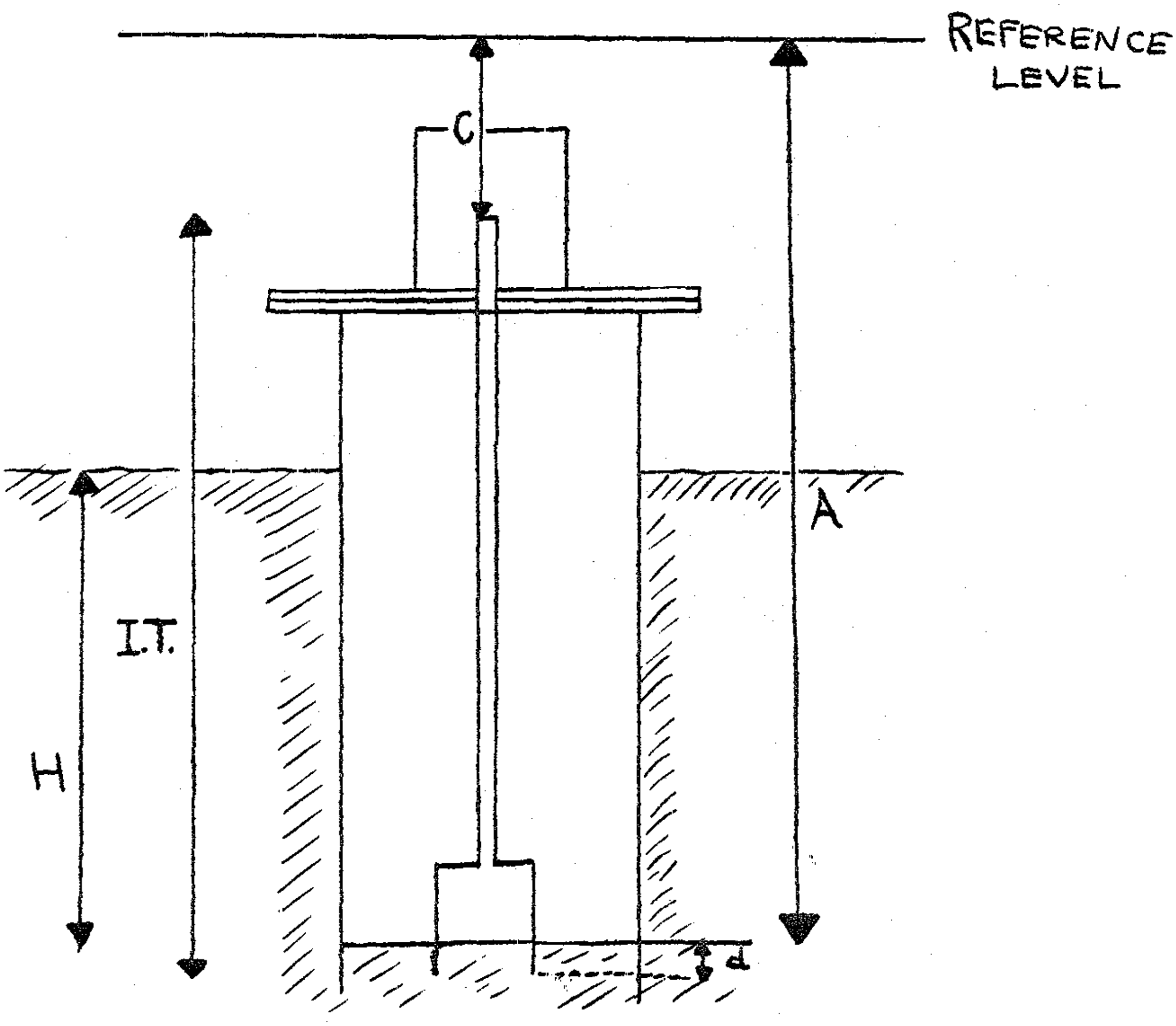
$$K = \frac{R_v^2}{F_f \cdot R_c} \cdot \frac{\Delta H}{\int Hdt} = 0.053 \times 60 \times 3 \times 10^{-3} =$$

13 cm/day

0.009 cm/min

CALCULATION SHEET

MEASUREMENT OF d



$d = I.T. + C - A$ cm

For $d = 2$ cm : $C = A - I.T + 2$ cm.

with a much smaller or higher permeability. When D is several times larger than the diameter of the inner tube (R_c) a general set of curves may be used to estimate F_f (see fig. 2.3.3b). The flow factor deviates usually only slightly from unity.

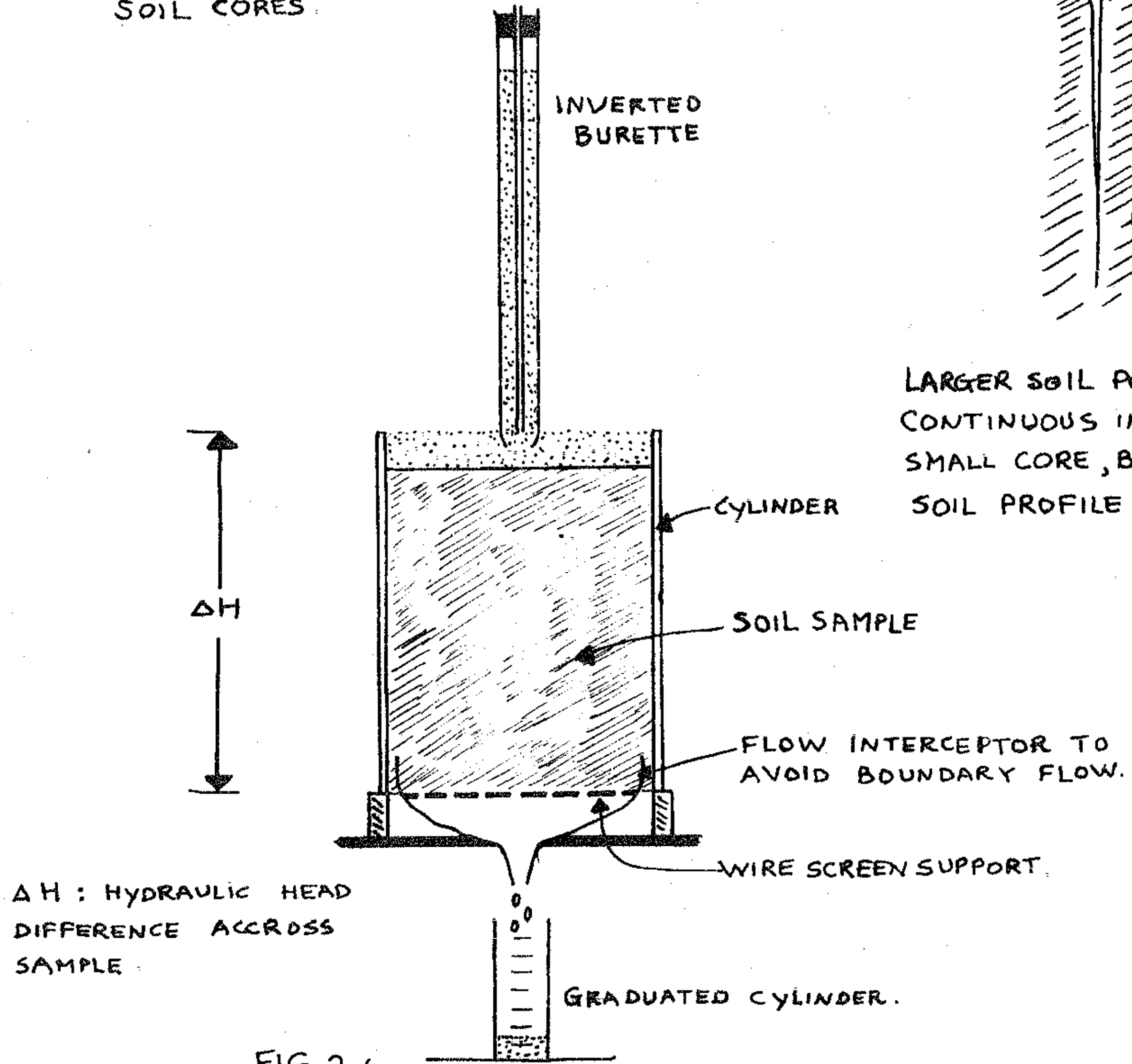
A more convenient method of calculation was suggested by Bouwer (1962) using the ratio: $2\Delta t/t^2$ eq. level instead of $\Delta H/\int Hdt$.

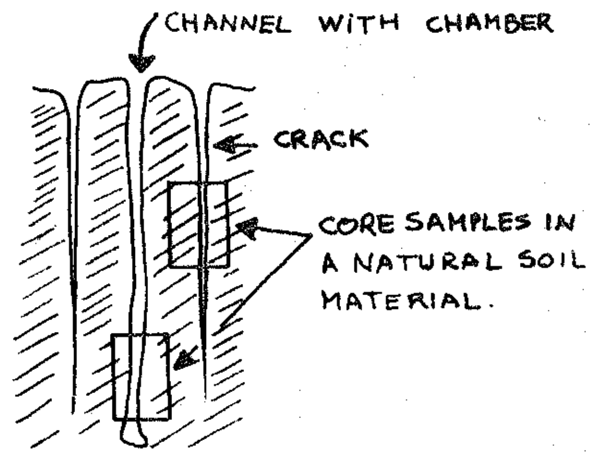
The ratios obtained for the final set of data are extrapolated to zero, to correct for the decrease in infiltration that occurs during the equal level reading, due to the gradual decrease of hydraulic head. (see example of field data sheet and calculation). Aside from K values, infiltration rates can also be calculated from the equal level curve, considering the inner tube as a buffered cylinder infiltrometer. These figures were calculated for our soils. (see data sheets sec. 3.1) The values are very high because of the high hydraulic pressure of at least 150 cm. These infiltration data therefore are only supplementary. A realistic infiltrometer would use much lower hydraulic pressures.

2.4. Measurement of saturated hydraulic conductivity with soil cores

Such measurements are generally based on the collection of representative, "undisturbed" cores of soil from the field. This is usually carried out by means of cylindrical core samplers, equipped with a cutting edge, and pushed or hammer driven into the soil. The ring containing the sample ("the retainer") is then taken into the laboratory, rigged into a permeameter and saturated. Measurement of the hydraulic conductivity can be carried out either by the constant head or falling head technique. Provision should be made to prevent, or at least minimize, boundary flow along the inner wall of the retainer.

MEASUREMENT OF SATURATED CONDUCTIVITY OF SOIL CORES.





LARGER SOIL PORES MAY BE CONTINUOUS IN A RELATIVELY SMALL CORE, BUT NOT IN THE SOIL PROFILE (SEE TEXT)

FIG 2.4

<u>Procedure</u>:

The measurement was performed according to the standard procedures described by Klute (1967) in Methods of Soil Analysis I (p. 210) with only a few modifications.

Undisturbed soil cores, with a surface area of 44 cm^2 and a height of 9 cm were collected in cylinders with a height of 10 cm and pushed into the soil to 9 cm depth. These cylinders are relatively large (cylinders of 100 cm^3 are in general use in Europe) and were chosen to minimize variation among individual samples. When the soil material in the profile was dry (with suctions higher than 0.5 bar) slight rewetting of the soil material in situ before sampling was found to reduce soil disturbance during sampling. For the same purpose the empty cylinders were immersed in water before sampling in order to reduce the resistance between the soil and the wall of the cylinder when pushed into the soil. The cylinders were pushed steadily into the soil at right angles to the soil surface. Pushing, whenever possible, was found to be preferable to hammering. Natural soil surfaces on both ends of the core were obtained by breaking both ends of the core (the upper end at about 1 cm below the edge of the cylindrical retainer). The cylinders were placed in a container and the water level was raised about 0.5 cm above the top of the core. At least 48 hours were allowed for saturation. Measurements were then made of hydraulic conductivity (see figure 2.4). Our apparatus had twelve units, permitting the measurement of twelve samples simultaneously, either in the laboratory or in the field. A constant hydraulic head of 1 cm was maintained on top of the sample, with the aid of an inverted burette (Mariotte) device. (see Figure 2.4.) To avoid boundary flow along the vertical inner walls of the cylinder during the measurement, water was not collected from the full bottom of the cylinder (44 cm^2) but from a slightly smaller area (38 cm^2). This was accomplished by gently pushing a truncated beer can with sharpened edges into the bottom of the core. In comparative experiments it was established that boundary flow in samples from the Mandt and Charmany sites was negligible. Nevertheless this device was used in all experiments to exclude any chance of boundary flow.

Hydraulic conductivity K was calculated according to:

$$K = (Q/A \cdot t) \cdot (L/\Delta H)$$

where Q = outflow (cm^3) A = cross sectional area of outflow (38 cm^2) t = duration of measurement L = length of the sample ΔH = hydraulic head difference across sample.

Measurements were made continuously until the rate of outflow became constant with time. Large worm and root channels caused a high conductivity in vertical cores. The same samples were also measured with these channels plugged by means of small rubber stoppers.

2.5. In situ measurement of unsaturated conductivity

2.5.1. Introduction

The infiltration of water into the soil is strongly reduced if a surface crust develops, closing relatively large pores present in the original soil surface. Such a reduced value would represent some unsaturated conductivity of the soil material. Under natural conditions of infiltration, exposed soil surfaces will rarely be without a crust. Impact of raindrops, slaking of soil fragments when wetted, and the sedimentation of particles from the water or liquid waste, in the upper part of the

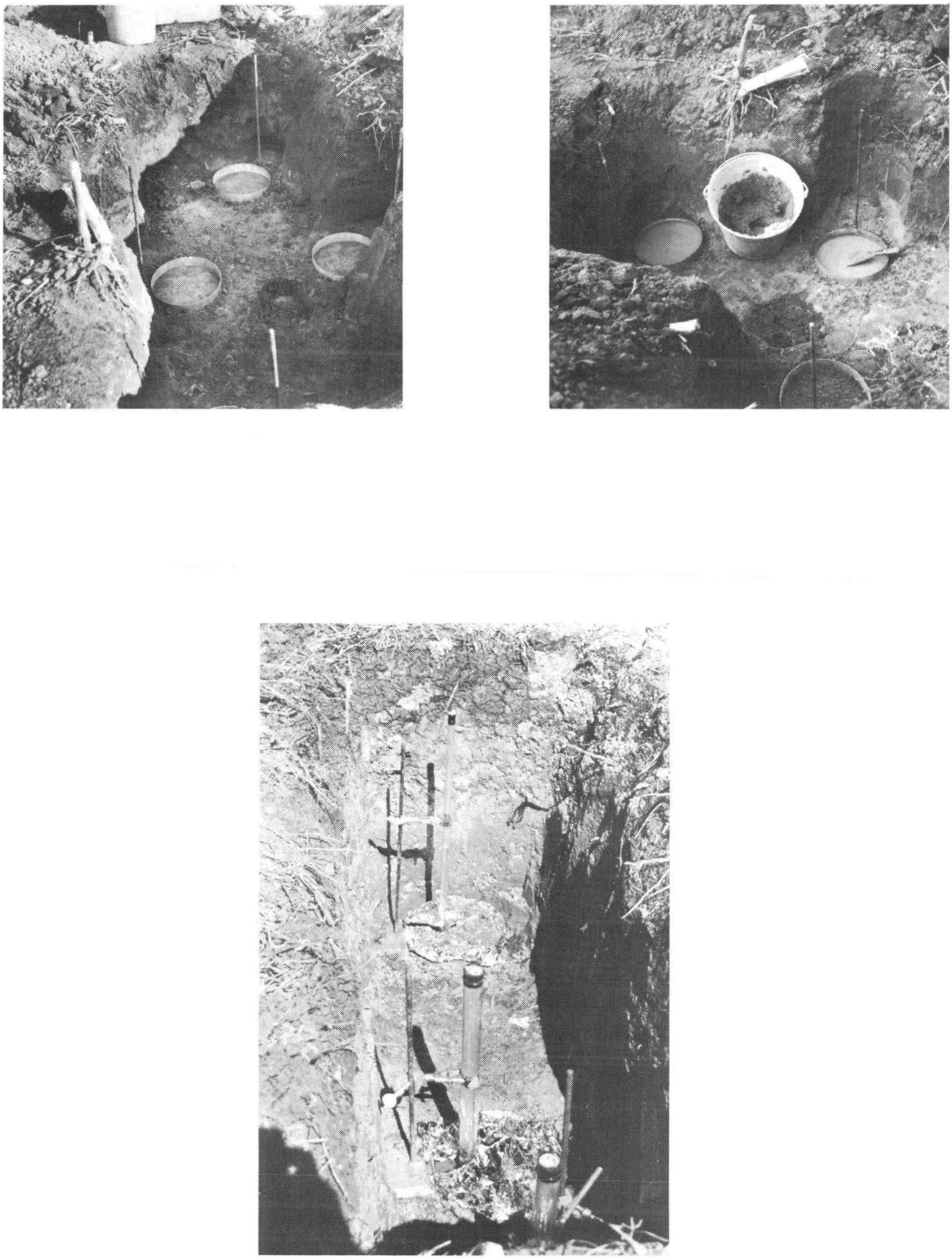


FIG. 2.5.2 In situ measurement of unsaturated conductivity (explanation in text).

soil, may all contribute to the formation of a superficial crust. This feature will govern the rate of infiltration of liquid into the soil material itself. Soil crusting is particularly likely to occur in sewage-disposal trenches. Digging of the trench in soil of relatively high moisture content may lead to puddling of the soil at the bottom of the trench. Soil fragments may slake when the sewage moves into the trench. Finally, solid particles and sludge from the sewage may clog the soil surface.

The method described by Hillel and Gardner (1970) for measuring the hydraulic transmission properties of a profile, as a function of water content or suction, involves a series of infiltration trials through capping plates (or crusts) of different hydraulic resistance. The effect of this resistance is to induce development of a suction at the surface of the infiltrating column. A measurement of the unsaturated (capillary) conductivity is obtained by allowing the process to proceed to the steady stage, when the flux becomes equal to the conductivity. The use of a series of plates of progressively lower resistance can give progressively higher K values corresponding to higher water contents, up to saturation. Such a series of tests can be carried out if the soil is initially fairly dry, either successively in the same location or concurrently on adjacent locations.

2.5.2. Procedure (see photographs on adjacent page)

A horizontal plane (at least 50 X 50 cm) was prepared at the required depth in the pedon, by using a putty knife and a carpenter's level. A large cylinder, with a height of 10 cm and a diameter of 25 cm, sharpened at the lower edge, was pushed into the horizontal soil surface to a depth of appr. 6 cm. The crust material was prepared and applied to the soil surface and spread out evenly to create a crust of uniform thickness. Special care was given to create a close contact with the walls of the cylinder. Crusts of this type were applied in several thicknesses. Another type of crust having a lower resistance, was created by crumbling friable soil in an even, thin layer on the horizontal surface. When water was poured over this, slaking occurred. This formed a continuous, though still porous crust with a concentrate in its upper surface of very fine particles that had been thrown into suspension by the turbulence of the water that was poured onto the crumbled soils. Thus a continuous seal was formed.

A shallow hydraulic head of about 2.5 cm was maintained over the crust surface by means of a Mariotte device. The rate of movement of the level in the burette was continuously observed, in order to record the gradual slowing of infiltration rate into the soil below the crust. After the infiltration rate had remained virtually constant for a period of at least 4 hours, it was assumed that a steady state of infiltration had been reached, and the experiment was stopped. This infiltration rate was in fact the unsaturated K-value at the actual moisture content, and suction, of the soil below the crust. During all measurements the cylinder was covered with aluminum foil to prevent significant evaporation of the water.

After the measurement, the water was removed from the crust and the soil below the crust was sampled in 5 cm increments with a small tube auger. The samples were immediately stored in air-tight moisture cans and transported to the laboratory, where their moisture content was determined. Separately from this, undisturbed cylindrical field samples measuring 2.5 cm in height and 7.5 cm in diameter were collected in cylinders from all investigated horizons for the determination of the relationship between suction and moisture content. The values were obtained by desorption of initially-saturated samples in a pressure chamber to suction values of 0.01, 0.03, 0.1, 0.3 and 1 bar. We found that the particular procedure followed to saturate the still moist or slightly moist field samples influenced the magnitude of the measured values considerably. Immediate saturation often induced very pronounced swelling, particularly in the silty clay loam soils. The moisture contents, after desorption to the different suctions, proved later to be relatively high. However, when the samples were wetted slowly to a moisture content corresponding to approximately 0.01 bar before full saturation, this swelling process proved to be less marked.

Following the relationship θ (moisture content) versus h (suction), each moisture content below the crust could be translated into a certain suction value. This procedure disregarded the hysteresis effect. When a relatively dry soil is moistened at a certain suction, the moisture content at equilibrium is generally lower than that after desorbing the similar, but initially saturated soil, to the same suction. The experimental conditions of the crust test will mostly involve the wetting process. We therefore plan to use tensiometers in the experiments of next season. There instruments will measure the tension below the crusts directly. The important relation between K and the suction can then be determined directly in the field.

2.6. Additional analytical measurements

Bulk density of natural cores, sampled in the field, and particle density were determined by methods described by G. R. Blake (in Black, 1965, p. 375 and 371). Particle size distribution analysis was done by the method of Day (1957). Soil reaction and available plant nutrients were determined in the State Soil Testing Laboratory of the Department of Soil Science, University of Wisconsin, Madison.

2.7. Morphological description of soil structure and its relation to conductivity

According to the Soil Survey Manual (SSM) (1951) p. 225, soil structure is defined as "the aggregation of primary soil particles, which are separated from adjoining aggregates by surfaces of weakness". When no peds (defined as individual natural soil aggregates) can be distinguished, a soil material is considered "structureless".

In a soil material, composed of peds, three characteristics are noted: the shape and the size of peds, and the grade of structure. Observations are made by studying natural soil surfaces both before disturbance (in situ) and afterward.

Shape. The classification of shapes of peds is rather general in the SSM, and new systems have been proposed (Jongerius, 1957, Brewer, 1964) where a much more detailed classification of shape is followed. While such very detailed systems may fit the needs of specific investigations, the very complexity of the detailed systems discourages general and uniform application.

Size. A classification of sizes is admittently arbitrary. The SSM classes, however, are sufficiently detailed for general use.

Grade. The description of "grade of structure" offers special difficulties. Grade is described in the SSM as "the degree of aggregation", noting essentially the difference between cohesion in peds and adhesion between peds. A high cohesion combined with a low adhesion yields a strong grade of structure, whereas low cohesion and high adhesion, on the contrary, yield a weak grade. Detailed field description of "grade of structure" is a rather complicated procedure involving.

1. Observation of a broken surface of an otherwise undisturbed soil mass that remains in situ.
2. "Disturbance" of a volume of soil, followed by an estimation of the amount of entire peds, broken peds and unaggregated soil material, present after the "disturbance".

Three grades are distinguished: weak, moderate and strong. In section 3.5 these concepts will be critically discussed, in evaluating the data obtained.

Water movement in soils occurs through pores. Types of pores, and their size and shape govern this physical process that results from a gradient of the hydraulic potential. Hydraulic conductivity of a porous body is strongly related to pore size (Childs, 1969). The amount of flow through a cylindrical pore with radius r is given by:

$$Q/t = g\rho\pi r^4/8\eta$$

where: t = time, g = accelleration of gravity, ρ = density of liquid,

η = viscosity of the liquid and ∅ = hydraulic potential.

The amount of flow through a plane slit of unit length and width D is given by:

$$Q/t = \frac{g\ D^3}{12\eta}\ \text{grad}\ \phi$$

Both formulae demonstrate the strong increase of flow with increasing pore size.

In a natural soil material planar voids occur between peds. The pictures in Appendix 6.1 demonstrate that more of these voids are present in a certain soil surface when the peds are small. Sizes and shapes of peds determine the morphology of the pores in between. The width of the pores will vary with moisture content, as a result of swelling and shrinkage. A qualitative comparison between measured K values and soil morphological features is presented in section 3.3.5. Investigations to establish more quantitative relationships based on the aforementioned equations and on morphometric data are in progress.

Procedure: Counting macro channels in the natural soil profile

Since 1960, counts have been made in the Netherlands of the amount and the sizes of vertical channels in soils. Slager (1964) summarizes these procedures. He introduced the term, "biopore" for thin cylindrical channels presumably formed by worms or roots. The use of the term biopores has caused some confusion, since it emphasizes genesis rather than pure pore morphology. We therefore prefer to follow Brewer (1964), who describes channels as "voids that are significantly larger than those which would result from normal packing of single grains, and have a generally cylindrical shape. They commonly have smooth walls, regular conformation and a relatively uniform cross sectional size and shape over significant proportions of their length. They may be transpedal or intrapedal".

Counting implies the following stages:

1. A horizontal soil surface is prepared at the desired depth; an area of 100 square inch (10 X 10" or 25 X 25 cm) is delineated with the point of a knife.
2. The soil surface within the rectangular area must be cleaned in order to obtain a fresh surface in which the channels can easily be observed. This is done with a large pocket knife; small volumes of soil are pryed loose with an abrupt movement of the knife. A natural surface of breakage is thus formed. Empty pores with a morphology in accordance with Brewer's description are counted during this procedure, that continues until the whole area has been observed. A chart, picturing the channel sizes to be distinguished (1-2 mm = fine; 2-4 mm = medium; > 4 mm = large) is continuously within observation during the measurement, so as to ensure a constant reference.

Each profile is thus characterized at 10 cm intervals. The figures obtained can be plotted in a graph, picturing the occurrence of channels at a function of depth in each profile (see tables in section 3.1)

The occurrence of channels is important for roots of crops that may penetrate certain layers through these channels that would have otherwise been unpenetrable (Bouma, 1969). Channels may strongly increase the vertical permeability of the soil, particularly in relatively small samples in which the channels are continuous. The Bouwer values are hardly influenced by the occurrence of large channels. We think this is fortunate since at very small suctions these relatively large voids will not contain water anymore. Thin crusts may render them useless as conduits of water, whereas the usually smaller planar voids between peds may still be filled with water. Another fact may prove to be important in our later experiments. Since channels will mostly be filled with air, they will play an important role in the aeration of the soil. Clogging of the sort caused by anaerobic processes in septic tank trenches can sometimes be alleviated by aeration.

Soil Structure diagrams

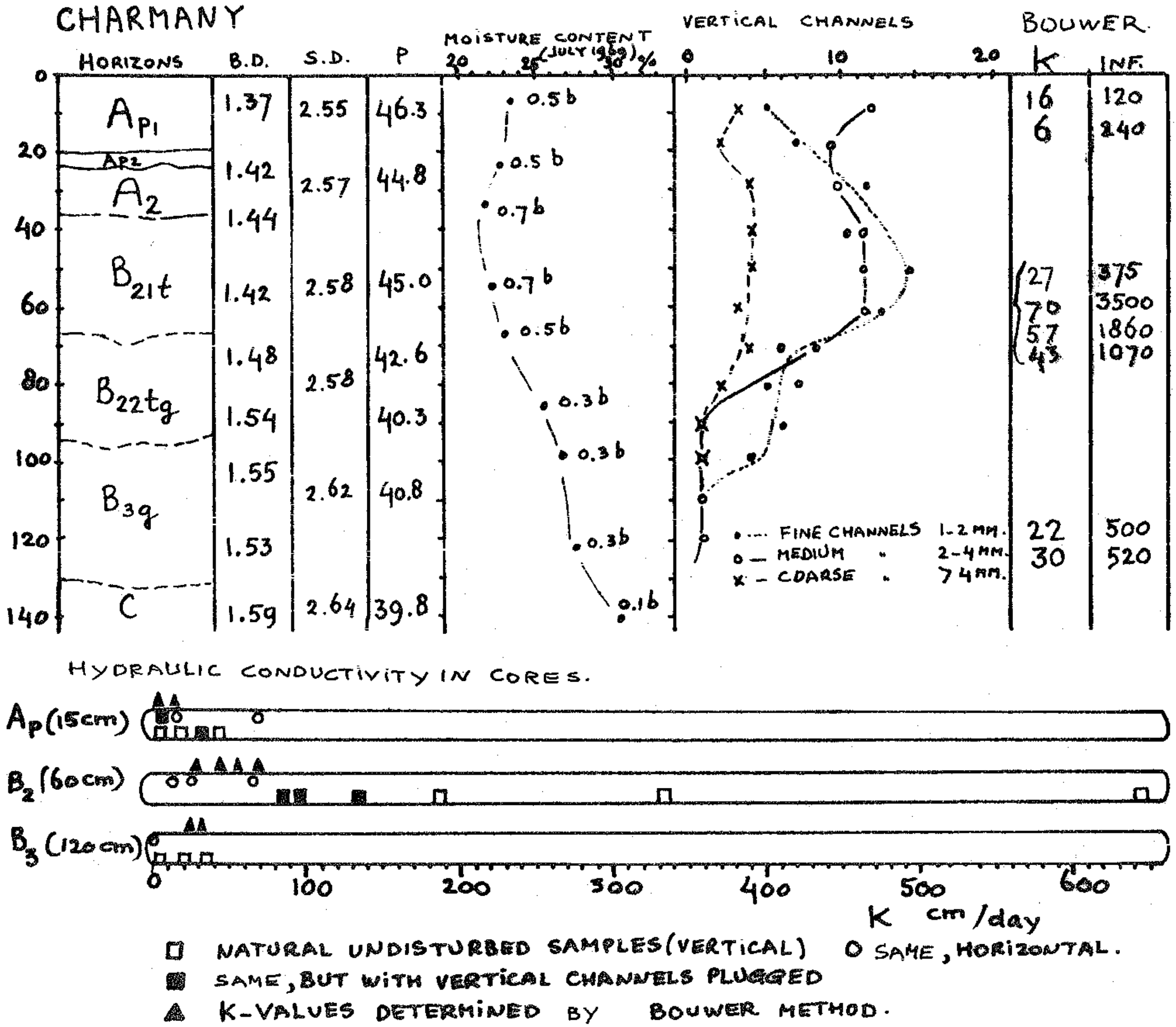
In the soil profile description, soil structure is characterized for each horizon separately by noting grade, size and type of peds. Dutch morphologists have emphasized the importance of the vertical succession of soil structural types in a profile. The practical soil physical consequences of the structure of any particular horizon are influenced by the structures of adjacent horizons. The entire array of structures of a soil profile may be reported schematically (see section 3.5). Jongerius pioneered this approach to soil structure but did not publish papers on the subject. In our drawings types and sizes of peds are shown; grades of structure are written in the code next to the drawings.

3. RESULTS AND DISCUSSION

3.1. Tables for each pedon with soil profile descriptions and results of measurements.

The following tables (3.1.1 - 3.1.7) present a summary of measurements made at the following locations, respectively: Charmany (Madison), Mandt (Madison), Omro 1 (cultivated area), Omro 2 (virgin area), Arena, Platteville 1 (cultivated area), and Platteville 2 (virgin area). The measurements include profile horizons, bulk densities, particle densities, porosities, moisture content, vertical channels, hydraulic conductivity, and infiltration values, all for different depths within the soil profile.

FIG 3.1.1.



B.D. = Bulk density (gm/cm^3) at field moisture content; S.D. = Particle density (gm/cm^3); P = Porosity (%); moisture content (%, gravimetric); vertical channels (no/100 in^2); K = hydraulic conductivity (cm/day), Inf. = infiltration rate of double tube (cm/day) • cores (vertical and horizontal) = hydraulic conductivity (cm/day) of undisturbed cores.

FIG 3.1.2.

MANDT

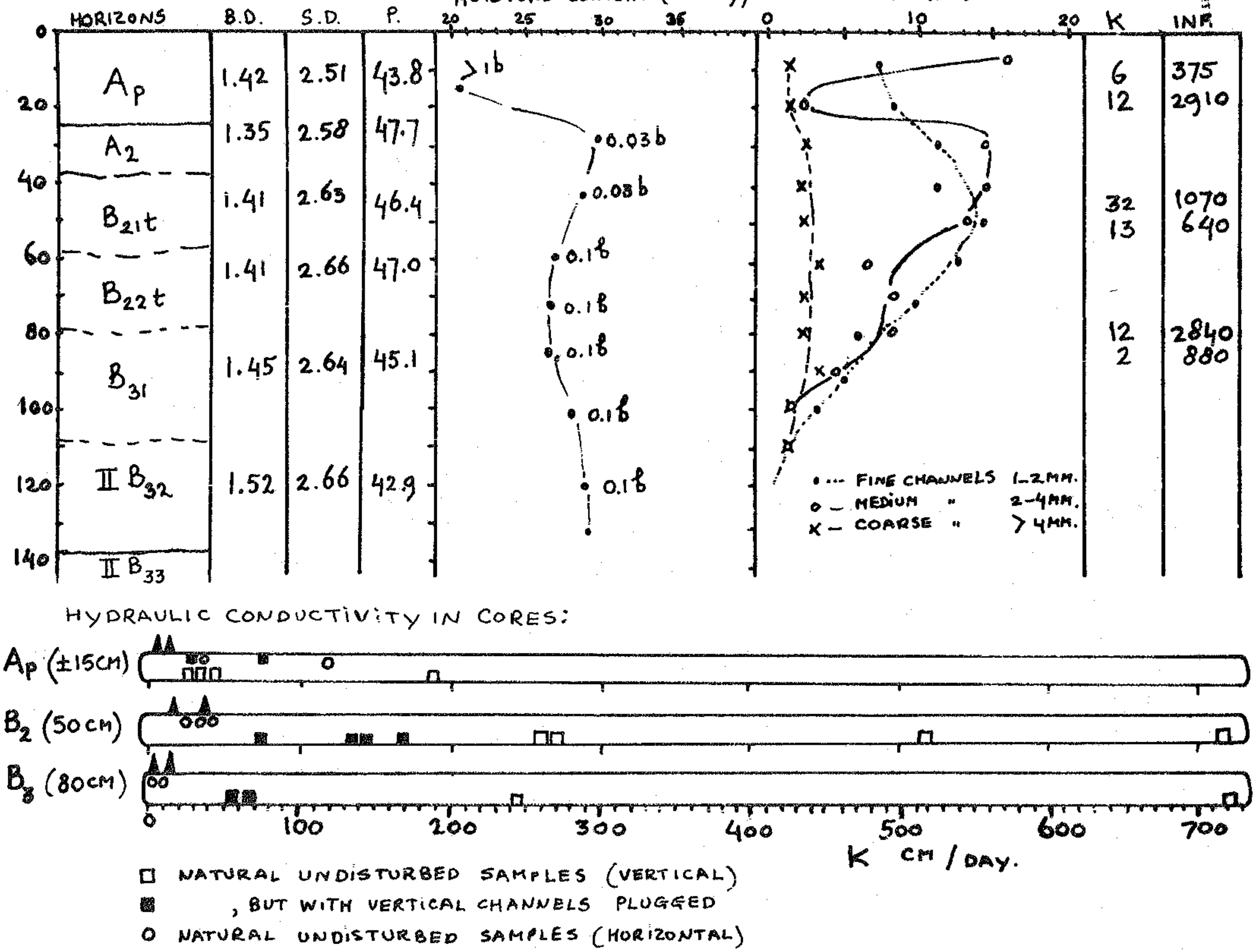
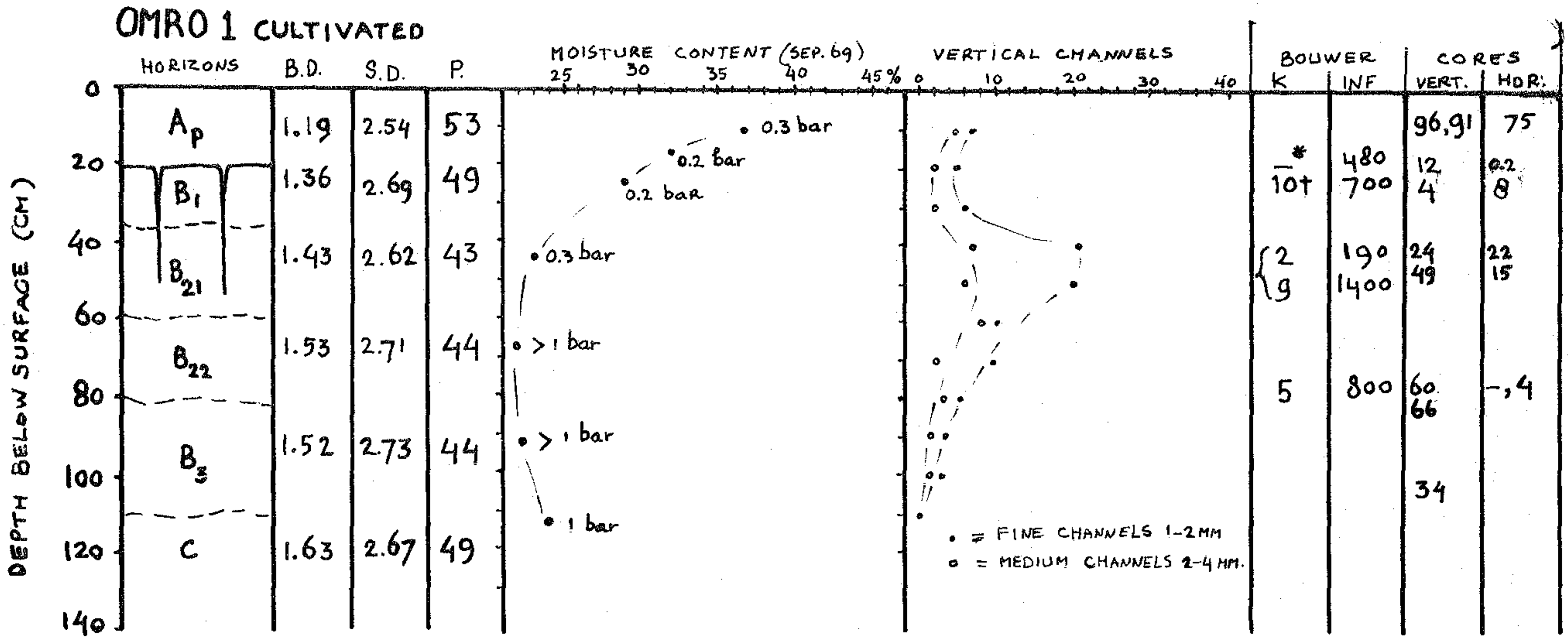


FIG 3.1.3



—* NO K-MEASUREMENT POSSIBLE DUE TO VERY LOW INFILTRATION.

† K ALONG CRACKS THAT EXTEND INTO THE B_2 (see text)

FIG 3.1.4

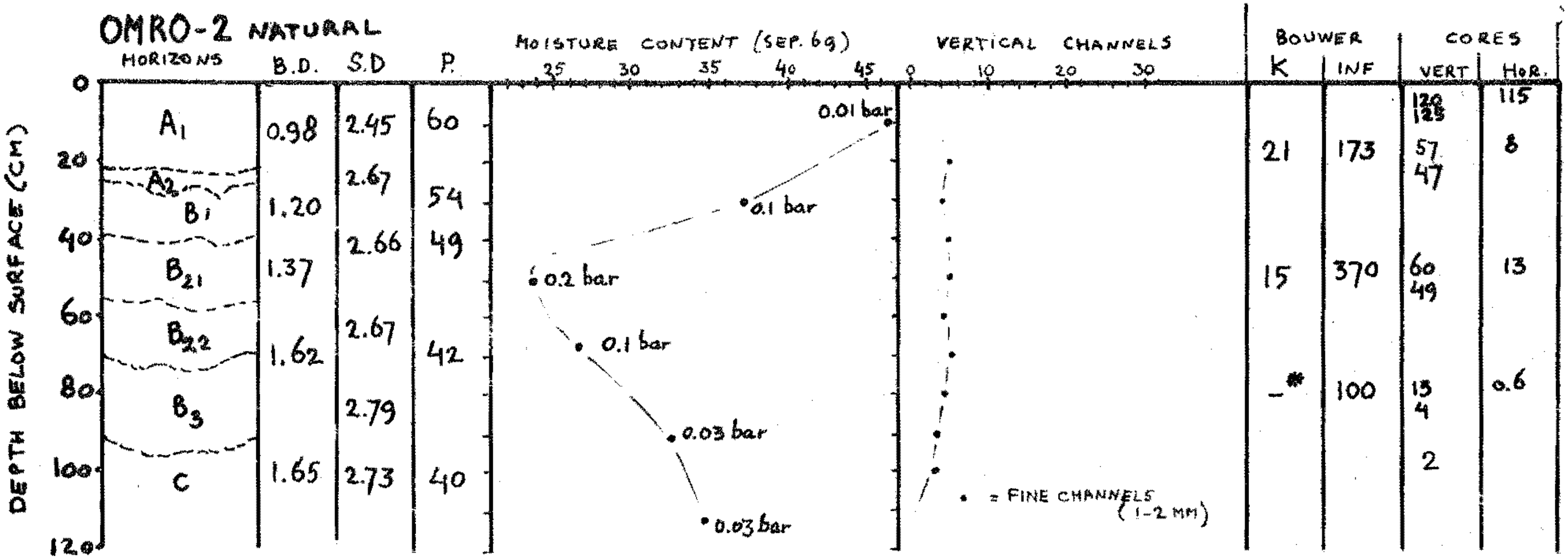
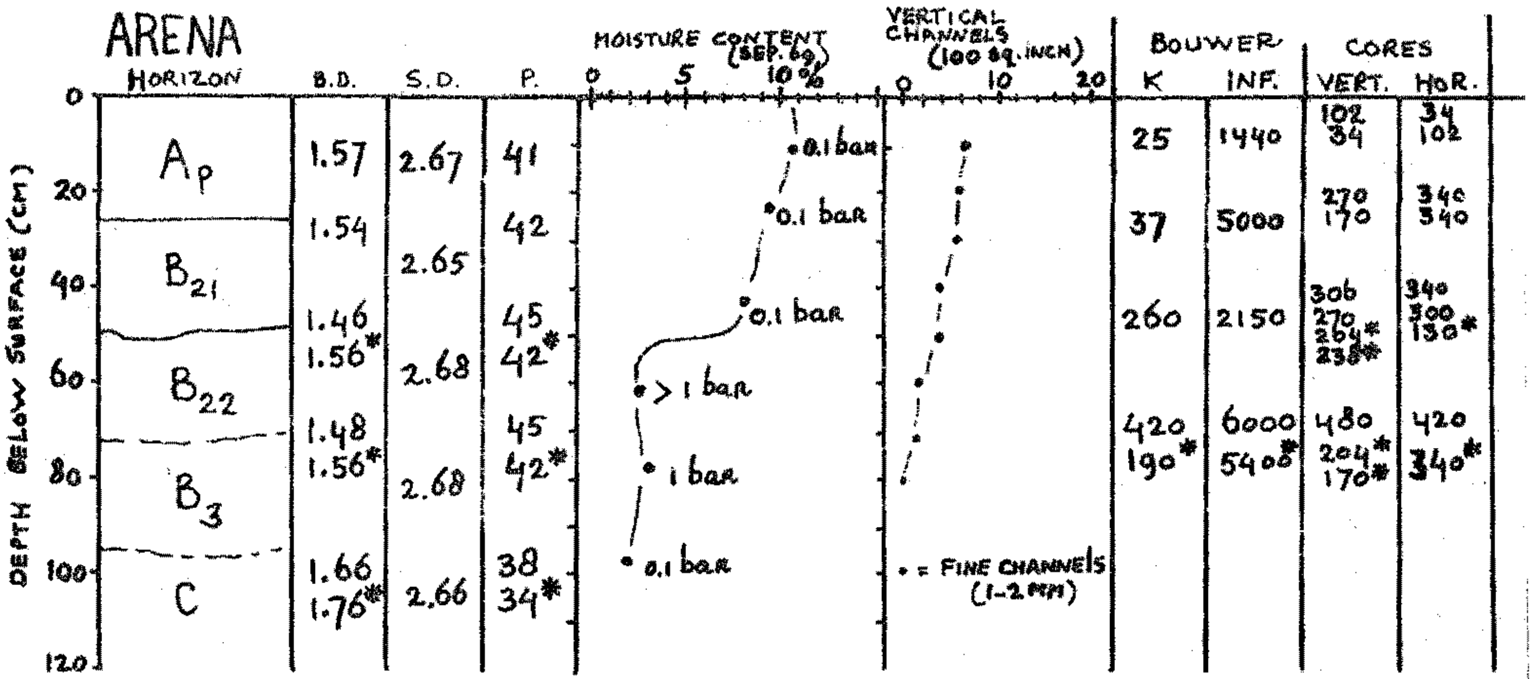

OMRO-2 NATURAL
HORIZONS
B.D.
S.D
P.
MOISTURE CONTENT (SEP. 6g)
VERTICAL CHANNELS
BOUWER
K
INF
CORES
VERT
HOR.
DEPTH BELOW SURFACE (CM)
A1
A2
B1
B21
B22
B3
C
0.98
1.20
1.37
1.62
1.65
2.45
2.67
2.66
2.67
2.79
2.73
60
54
49
42
40
0.01 bar
0.1 bar
0.2 bar
0.1 bar
0.03 bar
0.03 bar
• = FINE CHANNELS (1-2 MM)
21
173
15
370
100
120
125
115
57
47
8
60
49
13
15
4
0.6
2

FIG 3.1.5



* COMPACTED SITE NEAR RAILROAD

FIG 3.1.6

PLA-1 CULTIVATED

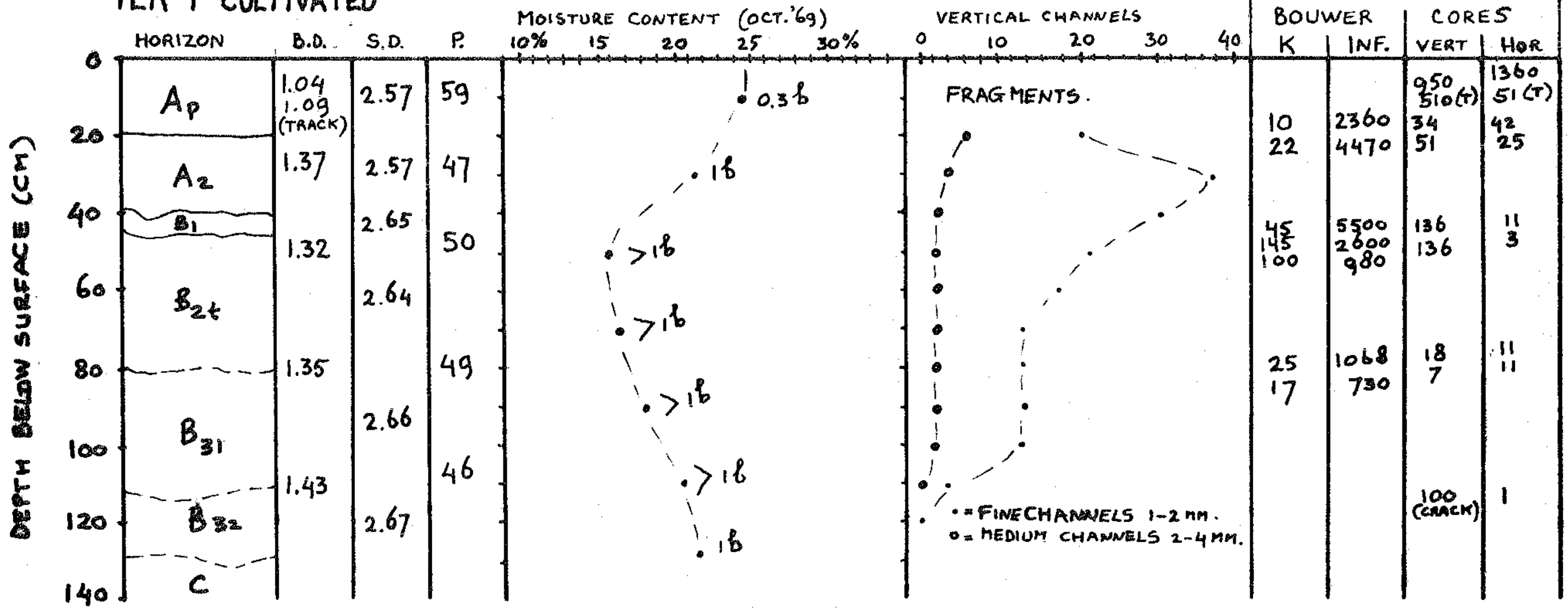
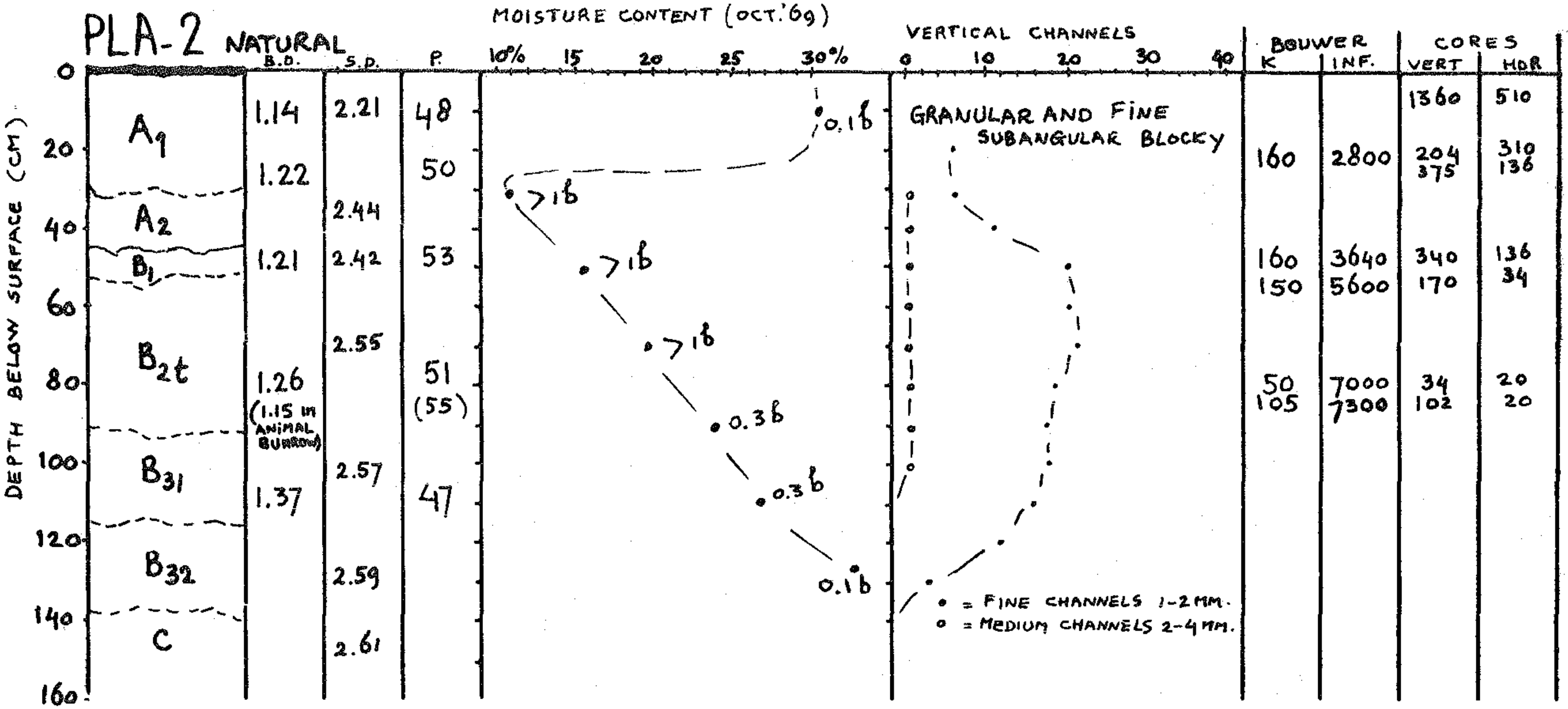


FIG 3.1.7



PLA-2 NATURAL
MOISTURE CONTENT (OCT.'69)
VERTICAL CHANNELS
BOUWER
CORES
B.D.
S.D.
P.
K
INF.
VERT
HOR
DEPTH BELOW SURFACE (CM)
0
20
40
60
80
100
120
140
160
10%
15
20
25
30%
0
10
20
30
40
A1
A2
B1
B2t
B31
B32
C
1.14
1.22
1.21
1.26
(1.15 in ANIMAL BURROW)
1.37
2.21
2.44
2.42
2.55
2.57
2.59
2.61
48
50
53
51
(55)
47
0.1b
>1b
>1b
>1b
0.3b
0.3b
0.1b
GRANULAR AND FINE SUBANGULAR BLOCKY
160
160
150
50
105
2800
3640
5600
7000
7300
1360
204
375
340
170
34
102
510
310
136
136
34
20
20
• = FINE CHANNELS 1-2 MM.
o = MEDIUM CHANNELS 2-4 MM.

General data:

Location: Dane County Wisconsin
Code: CH
Date of description: July 28, 1969 by J. Bouma and F. D. Hole
Parent material: loess (silt loam) over glacial till of Woodfordian (Cary) age
Physiography: site is a part of a glacial moraine
Drainage class: well to moderately well drained
Slope: 3% SW
Erosion: some accumulation in the Ap horizon
Vegetative cover: alfalfa
Groundwater: not observed within depth of observation (240 cm)
Classification: Mollic Hapludalf; fine-silty, mixed, mesic
St. Charles-Batavia silt loam, deep phase; intergrade

Pedon

Ap1	0-20 cm	Black to very dark gray (10YR 2.5/1)*, very dark gray when rubbed (10YR 3/1); silt loam; essentially apedal, with local granular pockets and dense clods; friable; neutral (pH 6.6); abrupt and smooth boundary.
Ap2	20-24 cm	Black (10YR 2/1), black to very dark gray when rubbed (10YR 2.5/1); moderate fine platy; friable; neutral (pH 6.6); abrupt and smooth boundary.
A2	24-33 cm	Very dark grayish brown (10YR 3/2), dark grayish brown when rubbed (10YR 4/2); silt loam; moderate medium platy; friable; slightly acid (pH 6.2); gradual and smooth boundary.
B21t	33-66 cm	Dark brown (7.5YR 3/3), brown to dark brown when broken and rubbed (7.5YR 4/3); silty clay loam; weak coarse prismatic breaking to strong medium subangular blocky; ped surfaces are smooth; root channels are abundant inside peds but do not reach the ped surface; cutans present but it is not determined whether or not they are argillans; slightly firm; strongly acid (pH 5.3); gradual and smooth boundary.
B22t	66-95 cm	Dark grayish brown (10YR 4/2), brown to dark brown when rubbed (10YR 4/3); silty clay loam; moderate coarse prismatic breaking into moderate medium subangular blocky; channels are bordered by grayish brown (10YR 5/2) distinct 5 mm-thick bleached zones that occupy about 20% of the volume of the horizon; mangans on ped faces of prisms with clear root imprints; firm; strongly acid (pH 5.2); diffuse and smooth boundary.
B31	95-136 cm	Dark yellowish brown (10YR 4/4) inside prisms; silty cl. loam; strong coarse prismatic; around root channels reduced zones as in B22t, light brownish gray (10YR 6/2), area 50%; mangans as in B22t; vertical faces of prisms locally with very dark gray (7.5YR 3.5/1) cutans of organic composition with root remnants; plastic and slightly sticky; strongly acid (pH 5.4); clear and smooth boundary.
C	136-240 cm	Dark yellowish brown (10YR 4/4), yellowish brown when rubbed (10YR 5/4); silt loam; apedal, except for some vertical faces of very coarse prisms as in B3; plastic and slightly sticky; slightly acid (pH 6.3); abrupt and broken boundary.
IIC	240 plus	Light yellowish brown (10YR 6/4) sandy loam glacial till; massive to weak medium platy; vertical, joints probably widely spaced; calcareous.

* Moist colors

PEDON MANDT

Profile description

General data:
Location: Dane County, Mandt Farm, College of Agriculture and Life Sciences, University of Wisconsin
Code: Mnd
Date of description: August 5, 1969 by J. Bouma and F. D. Hole
Parent material: loess (silt loam) over glacial outwash at 140 cm depth.
Physiography: site is a part of a glacial moraine
Drainage class: well drained
Slope: 3% to the east
Erosion: slightly eroded, pit is situated on upper part of a field, that slopes downwards.
Vegetative cover: none
Groundwater: not within depth of the pit
Classification: Typic Argiudoll, fine-silty, mixed, mesic. Plano silt loam, sand substratum phase (Waterloo silt loam)

Pedon:

Ap	0-25 cm	Very dark gray (10YR 3/1)[x], very dark grayish brown (10YR 3/2) when rubbed; silt loam; essentially apedal, more porous in lower parts, locally very dense with angular blocky fragments, with local pockets of granular structure; there is a concentration of wormholes in the lower part of the horizon; friable, locally firm; pH 8.0 abrupt and smooth boundary.
A2	25-37 cm	Very dark grayish brown (10YR 3/2), dark grayish brown (10YR 4/2) when rubbed; silt loam; in upper part massive, with very few very fine channels; below 30 cm[x], weak very fine subangular blocky and few very fine channels; friable; pH 7.0; gradual and wavy boundary.
B21t	37-57 cm	Dark brown (7.5 YR 3/2), brown to dark brown (7.5YR 4/3) when rubbed silty clay loam; weak medium prismatic breaking into moderate fine subangular blocky; with skeletans on ped faces; slightly firm; pH 5.5; gradual and wavy boundary.
B22t	57-78 cm	Brown to dark brown (7.5YR 4/3), brown (7.5YR 5/4) when rubbed; silty clay loam; weak medium prismatic breaking into moderate fine subangular blocky; with skeletans on ped faces; slightly firm; pH 5.5 gradual and wavy boundary.
B31	78-108 cm	Brown to dark brown (7.5YR 4/3) on ped faces, brown (7.5YR 5/4) when rubbed and brown (7.5YR 5/3) when broken; silty clay loam; moderate coarse prismatic; distinct argillans on ped faces with root prints, also skeletans; firm; (pH 5.5; clear and broken boundary.
IIB32	108-139 cm	Brown to dark brown (7.5YR 5/2) on ped faces, brown (7.5YR 5/4) when broken and rubbed; silty clay loam and locally sandy; weak coarse prismatic with few

sandstone fragments; slightly firm in heavier textured parts, loose in sandy parts; pH 6.0; clear and broken boundary.

IIB33	139-	Alternating dark reddish brown (5YR 3/2) bands and strong brown (7.5YR 5/6) layers of sand; the bands are massive and brittle; the sand is single grain and loose.

x Moist colors.

PEDON OMRO I

Profile description

General data:
Location: Winnebago Co. Wisconsin: SW¼, SE¼, Sec 6, T18N, R14E.
Code: OMRO1.
Date of description: Sept. 13 by J. Bouma
Parent material: deep calcareous lacustrine heavy clay sediments stratified and alternating with thin layers of silty clay.
Physiography: the area is level, the actual surface is a former lake bed
Drainage class: well drained.
Slope: 0%
Erosion: no evidence.
Vegetative cover: Alfalfa, 20 cm high, to be plowed under as second crop after oats.
Groundwater: not observed within 8 feet.
Classification: Typic Eutrochrept, very fine, mixed, mesic. Oshkosh-like clay; intergrading toward Winneconne with respect to the dark Ap

Pedon OMRO I

Ap	0-20 cm	Black (10YR 2/1), dark gray (10YR 4/1) when dry; clay; apedal, angular fragments separated by vertical cracks extending into the subsoil, locally some pockets with granular structure, fragments of the B horizon occur here, moved upwards by plowing; slightly firm, locally friable; pH 6.9; broken and abrupt boundary.
B1	20-35 cm	Reddish brown (5YR 4/3), idem (5YR 5/3) when dry; clay; strong very coarse prismatic (moderate fine platy in upper part); on vertical prism faces: thick (2mm) cutans composed of topsoil material, with a granular, or very fine blocky structure; very plastic, sticky; pH 7.0; gradual and smooth boundary.
B21	35-58 cm	Reddish brown (5YR 4/3), light reddish brown (5YR 6/3) when dry; silty clay; strong very coarse prismatic, vertical faces with cutans as in B1, moderate medium prismatic breaking to strong fine angular blocky; shiny ped faces with root prints and thin continuous dark reddish gray (5YR 4/2) cutans; very plastic and sticky; pH 7.2; gradual and smooth boundary.
B22	58-80 cm	Reddish brown (5YR 4/3), light reddish brown (5YR 6/4) when dry; silty clay→silty clay loam; moderate coarse prismatic breaking into strong medium angular blocky in upper part; continuous reddish gray (5YR 5/2) cutans on vertical prism faces; thin inclined layers of silty material occur in this and deeper horizons; firm; visible reaction with 2N HCl; pH 7.7; gradual and smooth boundary.

B3	80-110 cm	Reddish brown (5YR 4/4), light reddish brown (5YR 6/3) when dry; silty clay loam; strong coarse prismatic; cutans as B22t; few fine clear concentrations of lime in light red (2.5YR 6/6) nodules with diffuse boundary, and neocalcitans in the lower part of the horizon; firm; violent reaction with 2N HCl; pH7.6; gradual and irregular boundary.
C1	110-135 cm	Reddish brown in 60% (2.5YR 4/4), idem (5YR 4/4) in 60%; silty clay; massive, few vertical prism faces extend in this horizon; many lime concentrations as in B3; friable; pH 7.9; gradual and smooth boundary.
C2	135+	Stratified sandy (2.5YR 4/4) and clayey (5YR 4/4) layers, the latter with many light red highly calcareous nodules (2.5YR 6/6).

PEDON OMRO II

Profile description

General data: This site is about 300 feet from OMRO I on the other side of a fence separating cultivated land and a virgin woodlot-prairie where this pedon is found. General data as OMRO I except for:

Vegetative cover: abundantly growing grasses and herbs cover the soil surface completely; locally rotting tree stemps (*Quercus* sp.) are found, left after cutting the trees about ten years ago. The soil was never plowed.

Classification: Typic Eutrochrept, very fine, mixed, mesic. Oshkosh-like clay, intergrading toward Winneconne with respect to the dark Ap.

Pedon OMRO II:

01	1-0 cm	Very fine brown roots and some rotten branches
A1	0-21 cm	Black (7.5YR 2/1); clay; strong fine granular and moderate fine subangular blocky; locally rotten branches from trees; very friable; pH 7.2; gradual and smooth boundary.
A2	21-24 cm	Brown to dark brown (7.5YR 4/2); clay; moderate very fine subangular blocky; plastic, slightly sticky; pH 7.1; gradual and smooth boundary.
B1	24-40 cm	Dark reddish brown (5YR 3/6); clay; strong very fine angular blocky; plastic and slightly sticky; pH 7.4; gradual and smooth boundary.
B21	40-55 cm	Dark reddish brown (5YR 3/4); clay; inclined gray (2.5Y 6/1) bands of silty material do occur in this horizon and below; weak medium prismatic breaking into strong fine angular blocky; plastic, very sticky; pH 7.4; gradual and smooth boundary.
B22	55-70 cm	Reddish brown (5YR 4/4); silty clay loam; moderate medium prismatic, breaking into strong medium angular blocky; thin reddish gray (5YR 5/2) cutans on ped faces, with very fine root prints; visible reaction with 2N HCl at appr. 65 cm depth; pH 7.4; plastic, sticky; gradual and smooth boundary.
B3	70-90 cm	Yellowish red (5YR 4/6); silty clay loam; moderate medium prismatic in upper part; with common fine clear concentrations of lime in light red (2.5YR 6/6) nodules with diffuse boundary, and neocalcitans; plastic, sticky; violent reaction with 2N HCl; pH 7.7; gradual and smooth boundary.
C	90+	Reddish brown (5YR 4/4) in 60% of volume, *idem* (2.5YR 4/4) in 40%; silty clay loam; massive; many lime concentrations as in B_3; plastic, slightly sticky; pH 7.8.

PEDON ARENA

Profile description

General data:
Location: Iowa County, Wisconsin NE¼, SE¼, Sec 16, T8N, R5E.
Code: Arena
Date of description: October 3, 1969 by J. Bouma
Parent material: windblown sandy sediments near the Wisconsin River
Physiography: the area is a very gently undulating or nearly level sandy plain.
Drainage class: excessively drained
Slope: 0%
Erosion: no evidence, it was observed that wind erosion may be pronounced on bare soil.
Vegetative cover: the site is located in a 24 feet wide area along the railroad track, occupied by abandoned land with wild grasses. A part of this area, a strip 9 feet wide along the fence of the adjacent field, was plowed so as to reduce the risk of fire damage to agricultural crops on the land next to the strip.
Classification: Entic (psammentic) Hapludoll; sandy, mixed mesic. Sparta loamy sand intergrading toward Dakota fine sandy loam.

Pedon ARENA

Ap	0-25 cm	Very dark brown (7.5YR 2/2), brown to dark brown (7.5YR 4/2) when dry; loamy sand; apedal with many very fine (smaller than 1 mm) root channels per cm^2 (estimated at appr: 5); friable; pH ; clear and smooth, locally broken boundary.
B21	25-48 cm	Dark brown (7.5YR 3/3), brown to dark brown (10YR 4/3) when dry , loamy sand, apedal, with appr. 3 very fine root channels per cm^2; friable, locally slightly brittle; pH ; diffuse and smooth boundary.
B22	48-73 cm	Dark brown (7.5YR 3/3), brown when moist (10YR 5/3); loamy fine sand, apedal with few (appr. 2) very fine root channels; friable, locally slightly brittle; pH ; clear and irregular boundary.
B3	73-96 cm	Brown to dark brown (7.5YR 4/4), light yellowish brown when dry (10YR 6/4); fine sand; single grain; loose; pH ; gradual and diffuse boundary.
C	96+	Dark yellowish brown (10YR 4/4); sand; single grain; loose; pH ;

N.B. Soil structure can only adequately be described in micromorphological terms, noting the size shape and arrangement of the primary particles in thin sections. Following this, the top horizons would probably have an intertextic, and the lower horizons a granular basic fabric.

PEDON PLATTEVILLE I

Profile description

General data:
Location: Grant County, Wisconsin; NE¼, NE¼, Sec 1, T2N, R1E.
Code: PLA-I
Date of description: October 29, 1969 by J. Bouma.
Parent material: loess (silt loam) to a depth of 8 feet.
Physiography: the area is gently undulating; as determined by a loess cover over weathered residual limestone.
Drainage class: well drained
Slope: 2% E
Erosion: slight erosion in the topsoil estimated to amount to a loss of about 10 cm., as compared with the adjacent virgin site without erosion.
Vegetative cover: soil was bare at moment of description after harvest of corn about six weeks previsously.
Groundwater: not observed within depth of observation (240 cm)
Classification: Typic Argiudoll, fine-silty, mixed, mesic. Tama silt loam.

Pedon PLA I

Ap	0-20 cm	Very dark gray (10YR 3/1*), grayish brown (10YR 5/2) when dry, silty clay loam; apedal; locally angular fragments and granular pockets around crop residues; locally hard, dominantly friable; pH 6.4; abrupt and smooth boundary.
A2	20-40 cm	Dark brown (10YR 3/3), brown (10YR 5/3) when dry; silty clay loam; locally weak moderate platy in upper part, moderate very fine subangular blocky; slightly firm; pH 5.5; gradual and smooth boundary.
B1	40-50 cm	Brown to dark brown (7.5YR 4/4), brown when dry (7.5YR 5/4); silty clay loam; weak fine prismatic breaking into moderate fine subangular blocky; discontinuous skeletans on ped faces; slightly firm; pH 5.0; gradual and smooth boundary.
B2t	50-80 cm	Brown to dark brown (7.5YR 4/4) cutans on ped faces brown (7.5YR 5/4) when rubbed and light yellowish brown (10YR 6/4) when dry; silty clay loam; moderate medium prismatic breaking into strong fine subangular blocky; prominent, locally continuous skeletans on ped faces; friable; pH 5.2; gradual and smooth boundary.
B31	80-110 cm	Yellowish brown (10YR 5/4) inside peds, very pale brown (10YR 7/3) cutans on ped faces, light yellowish brown (10YR 6/4) when rubbed; silty clay loam; strong coarse prismatic, in upper part breaking into moderate medium subangular blocky structure;continuous skeletans on prisms with local concentrations of clean skeleton grains, slightly firm; pH 5.5; few faint medium yellowish red (5YR 5/6) iron mottles; around some root channels light brownish gray (10YR 6/2)bleached areas; gradual and smooth boundary.

B32	110-130 cm	Yellowish brown (10YR 5/4) inside prisms, dark yellowish brown cutans on ped faces (10YR 4/4); silty clay loam; strong very coarse prismatic; local discontinuous skeletans on ped faces; slightly firm; pH 5.8, diffuse and smooth boundary.
C	130+	Yellowish brown (10YR 5/4); silty clay loam; apedal with many very fine root channels (smaller than 1 mm); some vertical faces of very coarse prisms extend into the C horizon; slightly firm.

* Colors are moist, unless otherwise stated.

PEDON PLATTEVILLE II

Profile description

General data: This site is about 25 feet from PLA-I on the other side of a fence, separating cultivated land and the virgin prairie where this pedon is found. General data as for PLA I, except for:
Slope: 0%, No observable erosion, due to the dense vegetative cover.
Vegetative cover: Agropyron repens; Poa pratensis, Asclepias sp, Solidago sp. and Salsola sp.
Classification: Typic(vermic)Argiudoll, fine-silty, mixed, mesic

Pedon PLA II

02	0-0 cm	Very fine brown roots, and some very fine granules composed of an intimate mixture of organic and mineral particles.
A1	0-30 cm	Very dark brown (10YR 2/2), dark gray (10YR 4/1) when dry; silty clay loam; moderate very fine subangular blocky and strong fine granular, in lower 10 cm; weak fine platy; friable; pH 5.3; abrupt and smooth boundary.
A2	30-45 cm	Very dark grayish brown (10YR 3/2), brown when dry (10YR 5/3); silty clay loam; strong fine subangular blocky and strong fine granular; few, discontinuous skeletans on ped faces; friable; pH 5.0; gradual and smooth boundary.
B1	45-55 cm	Brown to dark brown (7.5YR 4/3) rubbed and broken, brown (7.5YR 5/3) when dry; silty clay loam; weak very fine prismatic breaking to strong fine subangular blocky, granular pockets in pedotubules as in A2; skeletans as in A2; friable; pH 4.8; gradual and smooth boundary.
B2t	55-90 cm	Dark brown cutans on ped faces (7.5YR 3/3), brown to dark brown (7.5YR 4/3) when rubbed, brown (7.5YR 5/4) when dry; silty clay loam; moderate fine prismatic breaking into moderate fine subangular blocky, locally pockets (pedotubules)with granular structure; discontinuous thin skeletans locally on ped faces; friable; pH 5.0; gradual and smooth boundary.
B31	90-115 cm	Brown to dark brown cutans on ped faces (7.5YR 4/3), brown (7.5YR 5/4) when rubbed; silty clay loam; moderate medium prismatic breaking into moderate medium subangular blocky; pedotubules and skeletans as B2t; friable; pH 5.6; gradual and smooth boundary.

B32	115-140 cm	Brown cutans on vertical prism faces (7.5YR 5/4), yellowish brown inside peds (10YR 5/4); silty clay loam; strong coarse prismatic; discontinuous skeletans on ped faces, locally in small concentrations; slightly firm; pH 5.6; gradual and smooth boundary.
C	140+	Yellowish brown (10YR 5/4) silt loam; apedal, with many very fine root channels (smaller than 1 mm); some vertical faces of very coarse prisms extend into the C horizon; slightly firm; pH 5.4.
IIC	190 cm+	Yellowish red (5YR 4/6) silt loam, non calcareous residual weathered material from residual limestone.

Pedon PLA I

Horizon	granulometric composition <2μ	2-20μ	20-50μ	50-100μ	100-250μ	250-500μ	500-1000μ	1-2mm	Fertility characteristics pH	P lbs/A	K lbs/A	Ca lbs/A	Mg lbs/A	org. matter %
Ap	31.1	60.0	6.4	1.9	0.3	0.2	0.1	---	6.4	66	160	3200	1000	3.8
A2	27.5	42.5	28.2	1.3	0.2	0.2	---	---	5.5	15	160	3000	970	1.7
B1	32.5	37.5	27.6	2.1	0.2	0.1	---	---	5.0	12	195	3800	1150	1.1
B2	32.5	35.0	29.5	2.9	0.1	---	---	---	5.2	20	225	4200	1220	0.6
B31	31.2	36.0	30.4	2.1	0.1	---	---	---	5.5	67	240	4100	1220	0.5
B32	27.5	40.0	31.3	1.2	---	---	---	---	5.8	74	225	3600	1100	0.5

Pedon PLA II

Horizon	<2μ	2-20μ	20-50μ	50-100μ	100-250μ	250-500μ	500-1000μ	1-2mm	pH	P lbs/A	K lbs/A	Ca lbs/A	Mg lbs/A	org. matter %
A1	28.9	40.0	28.3	1.7	0.4	0.4	0.2	---	5.3	20	165	2800	590	4.2
A2	31.1	40.0	25.9	2.6	0.2	0.2	---	---	5.0	24	165	2400	650	1.8
B1	33.3	40.0	24.5	1.8	0.2	0.2	---	---	4.8	13	185	2800	870	1.4
B2	33.7	36.3	27.7	2.1	0.1	0.1	---	---	5.0	15	210	3600	1100	1.0
B31	30.0	40.0	27.5	2.5	000	000	000	000	5.6	62	210	3900	1250	0.6
B32	32.5	37.5	27.7	2.2	0.1	---	---	---	5.6	75	245	4600	1520	0.6
C	25.0	42.5	31.4	1.0	0.1	---	---	---	5.4	65	210	3600	1240	0.3

Pedon OMRO I

Horizon	granulometric composition								Fertility characteristics					
	<2μ	2-20μ	20-50μ	50-100μ	100-250μ	250-500μ	500-1000μ	1-2mm	pH	P lbs/A	K lbs/A	Ca lbs/A	Mg lbs/A	org. matter %
Ap	71.1	25.9	0.4	1.0	0.9	0.7	0.1	---	6.9	15	225	9600	5600	7.6
B1	71.1	26.4	0.4	1.0	0.8	0.7	0.1	---	7.0	10	190	6600	2500	1.3
B21	40	50.0	3.4	2.8	2.4	1.3	0.1	---	7.2	8	270	5300	2000	0.8
B22	38.7	53.8	4.6	1.4	1.0	0.4	---	---	7.7	8	235	4100	1650	0.8
B3	36.2	57.5	4.4	1.1	0.5	0.2	---	---	7.6	9	245	4400	1740	0.8
C1	42.5	53.7	2.8	0.5	0.3	0.1	---	---	7.9	7	200	7200	1250	0.6
C2	37.5	58.5	3.0	0.5	0.5	0.7	0.3	---						

Pedon OMRO II

Horizon	<2μ	2-20μ	20-50μ	50-100μ	100-250μ	250-500μ	500-1000μ	1-2mm	pH	P lbs/A	K lbs/A	Ca lbs/A	Mg lbs/A	org. matter %
A1	57.8	28.9	12.1	0.6	0.6	0.6	---	---	7.2	13	220	14800	4400	9.3
A2	68.9	24.4	5.9	0.2	0.2	0.2	0.1	---	7.1	10	175	12800	3440	2.0
B21	75.0	22.5	0.8	0.5	0.4	0.3	---	---	7.4	8	175	7800	2880	1.2
B22	30.0	52.5	11.0	3.2	2.2	1.0	0.1	---	7.5	7	200	4300	1680	0.8
B3	27.5	65.0	4.8	1.2	0.9	0.5	---	---	7.7	6	220	3800	1600	0.8
C	27.5	67.5	2.1	1.0	1.0	0.6	0.3	---	7.8	6	185	7200	1320	0.6

Pedon Charmany

	granulometric composition								Fertility characteristics					
Horizon	<2µ	2-20µ	20-50µ	50-100µ	fine 100-250µ	med. 250-500µ	coarse 500-1000µ	very coarse 1-2mm	pH	P lbs/A	K lbs/A	Ca lbs/A	Mg lbs/A	org. matter %
Ap	15.0	52.5	28.5	2.0	1.1	0.7	0.2	---	6.3	90	135	3600	1020	3.2
A2	20.0	52.5	25.2	1.3	0.5	0.4	0.1	---	5.9	65	140	2500	660	1.3
B21t	27.5	45.0	25.9	1.3	0.2	0.1	---	---	5.1	45	215	3400	900	1.0
B22t	32.5	40.0	25.9	1.3	0.2	0.1	---	---	5.0	77	270	4100	1300	1.1
B31	30.1	42.5	25.4	1.6	0.3	0.1	---	---	5.7	115	280	4600	1400	1.0
C	27.5	45.0	24.5	1.4	.10	0.5	0.1	---	5.1	72	250	3400	1280	0.7
Pedon Mandt														
Ap	20.0	45.0	23.1	2.8	4.7	4.0	0.5	---	6.5	140	200	3600	1090	3.0
A2	25.0	47.5	25.3	1.6	0.3	0.2	---	---	5.7	43	180	2900	900	1.5
B21t	30.0	42.5	26.1	1.1	0.2	0.1	---	---	5.2	120	250	4100	1160	0.4
B22t	30.0	42.5	25.7	1.3	0.3	0.2	---	---	5.1	110	260	4200	1300	1.0
B31	30.0	42.5	24.3	1.3	1.0	0.8	0.1	---	5.1	115	275	4400	1270	0.9
IIB32	20.0	30.0	20.8	3.7	14.4	10.4	0.7	---	5.4	98	250	3500	1040	0.7
Pedon Arena														
Ap	13.3	2.2	2.4	12.1	43.9	24.9	1.0	0.1	6.1	41	100	1800	450	1.8
B21	5.0	7.5	1.8	11.7	46.4	26.6	0.9	---	6.1	60	60	600	140	1.6
B22	5.0	5.0	3.4	17.7	50.2	13.2	0.5	---	5.8	75	60	200	10	1.1
B3	2.5	---	2.9	15.8	62.6	16.0	0.2	---	5.9	105	45	200	20	0.4
C	2.5	---	---	2.5	44.7	50.7	0.8	---	5.9	75	35	150	20	0.2

3.2. The State Percolation Test

3.2.1. Some notes about our tests.

1. Our holes were cylindrical with a diameter of 10 inches, prepared with a post hole digger.
2. We used a hole cleaner of the type that is used with the Bouwer test, to prepare the required "natural soil surface" at the bottom of the hole. It is doubtful to what extent "scratching with a sharp pointed instrument" will help to expose such an interface, particularly in moist or wet soils.
3. In all tests much soil material from the walls of the pit sloughed onto the gravel as a fluid mud. This mud was removed as well as possible, but apparently a considerable amount of this puddled soil material remained on and in the gravel. Use of a stovepipe to be pushed slightly into the surface of the gravel (Mokma, 1967) was not very helpful in avoiding sloughing of soil from the sides of the hole. Water poured into the stovepipe moved through the gravel turbulently up into the hole outside the pipe, causing severe sloughing of the walls. The surface of the gravel within the stovepipe remained clean, however. We used stovepipes in making all our measurements, except in shallow holes in some A_p horizons. The level of the water in the hole or in the stovepipe was measured with a stick bearing a scale in inches, each inch being divided in eight parts. A fixed reference level was established at each test hole.

3.2.2. Discussion of results

Only the tests performed at 80 cm or deeper are reported in graphs because these depths are of particular importance in planning septic tank installations. Results from other tests at 20 cm and 50 cm in some pedons are reported in terms of the final infiltration rates after four hours of measurement. These values, including the final infiltration rates of the

FIG 3.2.5

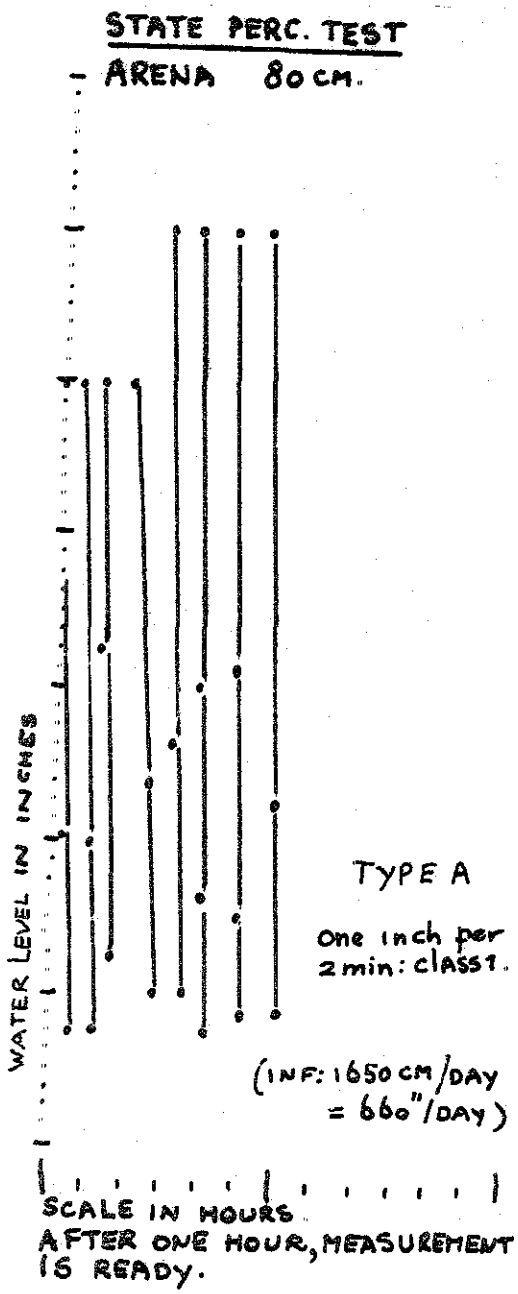
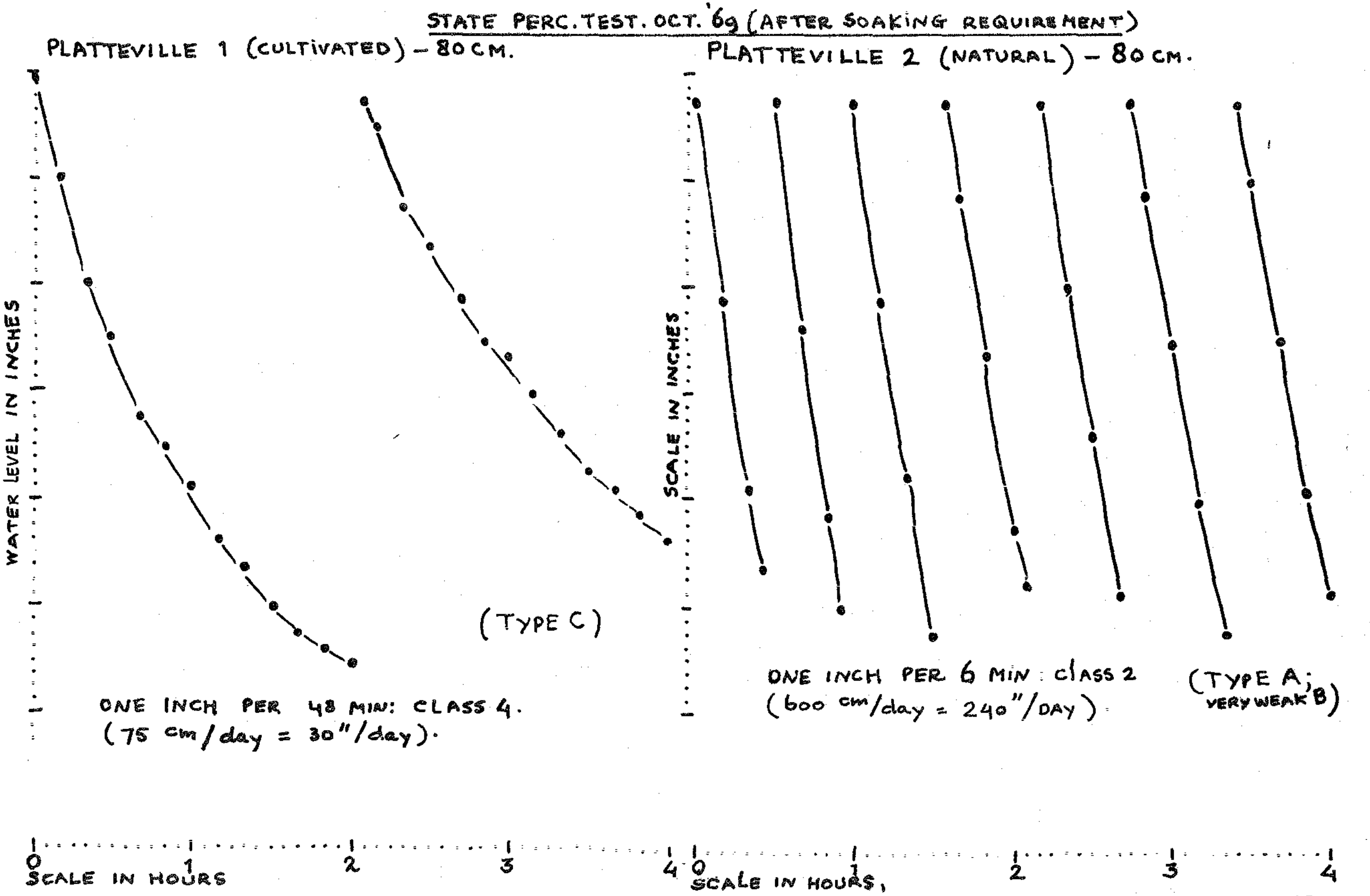

STATE PERC. TEST
ARENA 80 CM.
WATER LEVEL IN INCHES
TYPE A
one inch per 2 min: class 1.
(INF: 1650 CM/DAY = 660"/DAY)
SCALE IN HOURS
AFTER ONE HOUR, MEASUREMENT IS READY.

FIG 3.2.4



STATE PERC. TEST. OCT. '69 (AFTER SOAKING REQUIREMENT)
PLATTEVILLE 1 (CULTIVATED) – 80 CM.
PLATTEVILLE 2 (NATURAL) – 80 CM.
WATER LEVEL IN INCHES
SCALE IN INCHES
(TYPE C)
ONE INCH PER 48 MIN: CLASS 4.
(75 cm/day = 30"/day).
ONE INCH PER 6 MIN: CLASS 2
(600 cm/day = 240"/DAY)
(TYPE A; VERY WEAK B)
0
1
2
3
4
SCALE IN HOURS
0
1
2
3
4
SCALE IN HOURS,

FIG 3.2.3.

OMRO 1 STATE PERC. TEST 80CM DEPTH SEPT. '69 (AFTER SOAKING REQUIREMENTS)

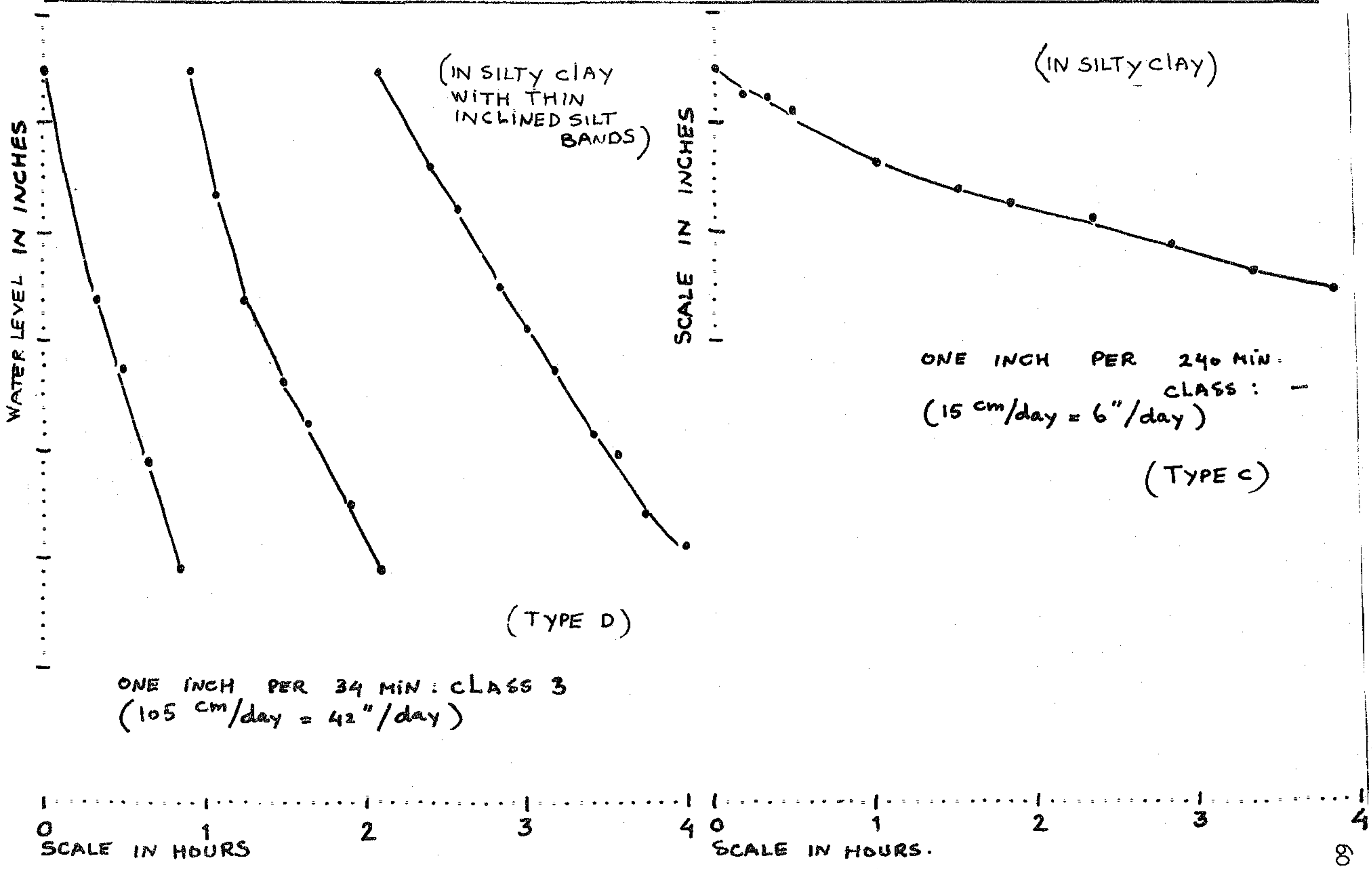


FIG 5.2.2.

MANDT SITE – 80CM STATE PERCOLATION TEST (AFTER REQUIRED SOAKING)

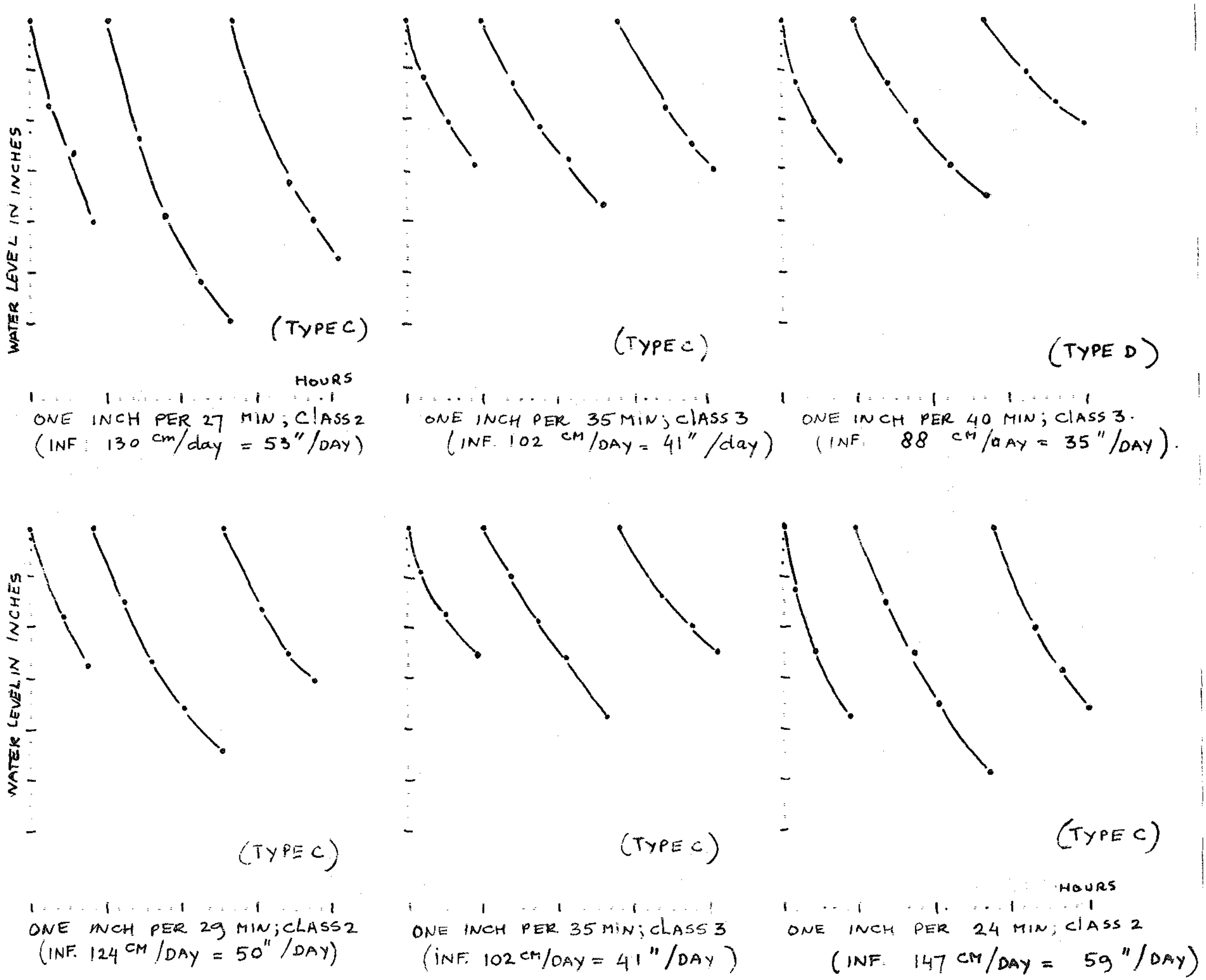
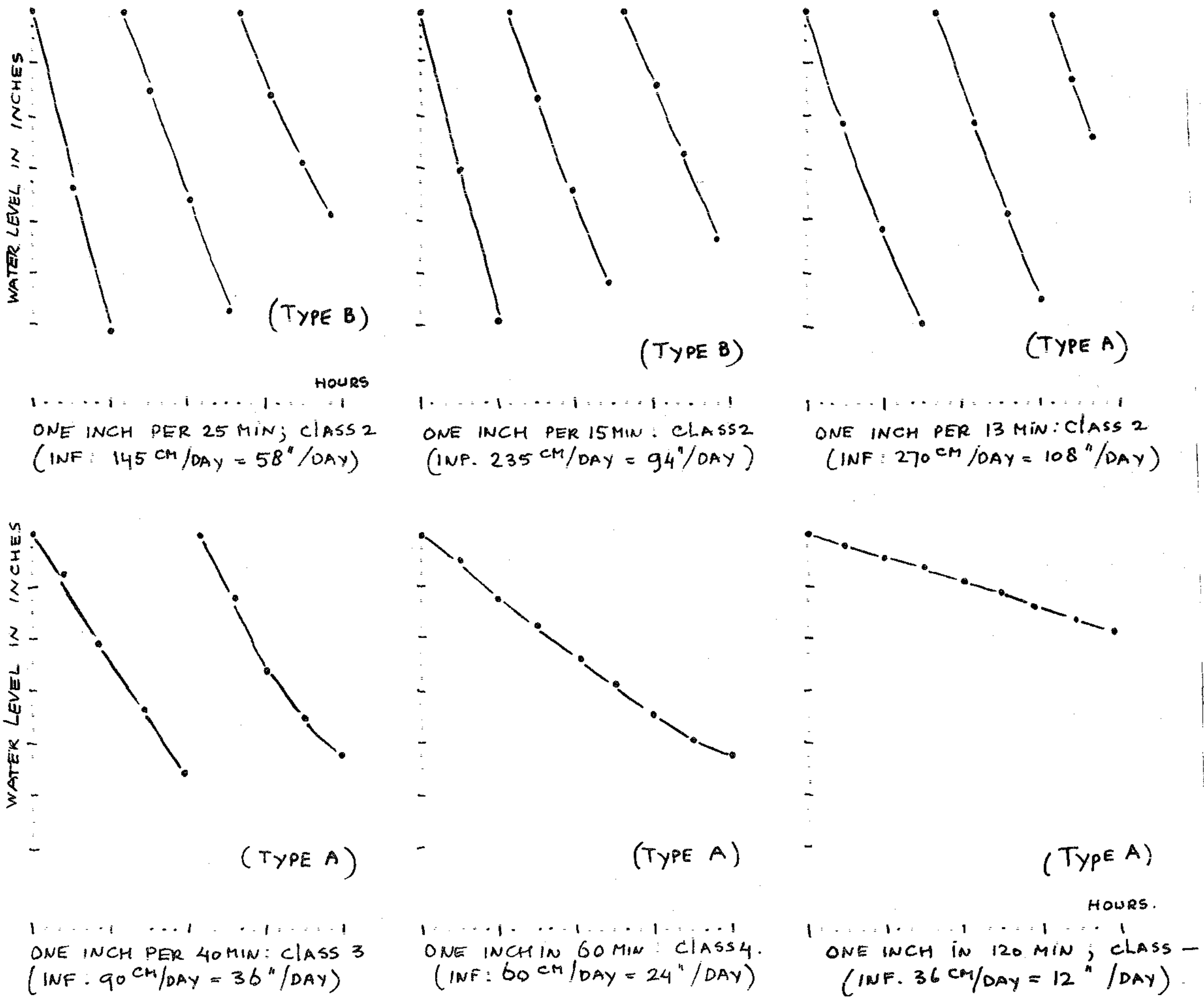


FIG 32.1.

CHARMANY SITE - 120 CM STATE PERCOLATION TEST (AFTER REQUIRED SOAKING)



80 cm level, will be discussed in comparison to the Bouwer test values in Chapter 3.3.1.

The attached graphs (Figures 3.2.1 - 3.2.4) show the pattern of infiltration during the test. The starting point of each line represents a level of approximately 6 inches above the gravel. The slope of this line is determined by the fall of the water surface versus time.

Four different types of curves are given (see Figures 3.2.1 - 3.2.4):

TYPE A The individual lines (or the single line: Charmany 120 cm, no. 6) are straight, and all have the same slope (for example: Arena 80 cm (in table section 3.1), Pla. II 80 cm).

TYPE B The individual lines are straight, but their slope differs: the infiltration rate decreases with time (for example: Charmany 120 cm., nos. 1 and 2; Omro I 80 cm, silty variant).

TYPE C The individual lines (or the single line: Omro I 80 cm, clay variant) are curved. Each individual curve has the same range of slopes as the next or previous one (for example: Mandt 80 cm, Pla. I 80 cm). Infiltration decreased continuously in time with decreasing hydraulic head.

TYPE D Same as C, but the individual lines have each a different range of slope: the decrease in infiltration is proportionally greater during the later stages of a measurement. (for example: Mandt 80 cm; no. 3, Omro I 80 cm, silty clay).

The final infiltration rate is calculated (see State Board of Health, 1969) from:

1. The rate of fall in the last 10 minutes of a one-hour measurement. The measurement is done without previous soaking after percolation of 12" of water in less than 10 minutes (sandy soils: see Arena test).

2. The rate of fall in the last 10 minutes of a one-hour measurement. Percolation of the first 6" of water, after soaking 16-30 hours, occurs within 30 minutes (Fla. II 80 cm).

3. The rate of fall in the last 30 minutes of a four-hour measurement. Percolation of the first 6" of water, 16 to 30 hours after soaking, takes more than 30 minutes. "Adjustment of the water level shall not be made during the last three measurement periods except to the limits of the last measured water level drop".

Type A does not offer problems; the infiltration rate is constant and does not vary with time. For Fla. II (80 cm) we measured for four hours, although one hour would have been sufficient according to the law. The rate remained constant, however, during the next three hours, proving the validity of the results. Type B shows a decrease in infiltration rate with time, possibly resulting from swelling or slaking of the soil material. Apparently there is no effect of the decrease of hydraulic head since each curve, as such, is a straight line.

Types C and D show a strong effect of the magnitude of the hydraulic head: infiltration decreased markedly when the water level in the hole dropped.

Curves of type C show no difference between individual curves during the four-hour measurement as far as slope is concerned, so here the effect of the decreasing hydraulic head is consistent with time. Curves of type D show, except for the effect of decreasing hydraulic head, a further decrease of infiltration with time, probably again due to swelling and slaking. Because of the strong effect of the hydraulic head, a provision was made in the law to avoid complete filling of the hole in the last 1½ hours of a measurement under these circumstances (see point 3 above). This procedure seems unnecessarily complicated and it would be simpler to follow a procedure in which a constant hydraulic head is maintained over the gravel. Infiltration could be measured at regular intervals until constant for a period of, say, at least 2 hours. We will try to apply such a procedure during our measurements in spring. One other major advantage is introduced when this is done: a consistent infiltration rate is used as a criterium, rather than the infiltration rate after a fixed period. The measurement then becomes less arbitrary. In many cases a constant infiltration rate will not have been reached yet after $3\frac{1}{2}$ hours, in others it may have been reached after an hour. However, infiltration rate tests still depend on boundary and initial soil conditions and do not measure an intrinsic soil physical property.

The test is based on the use of tap water and a natural (unpuddled) soil surface. Critics point out that such a test can never provide a good estimate for the potential of a soil to absorb liquid sewage, since clogging of the soil will very likely seal the surface of infiltration (Mc Gauhey, P. H. and J. H. Winneberger, 1963). The same criticism can of course be given for the Bouwer test and the tests on soil cores. These, however, are much better defined in physical terms and can be used as a reliable reference and estimate of the potential soil permeability. The clogging problem requires special study.

3.3. The Bouwer test

3.3.1. Comparison the Bouwer test values with those of the State Percolation Test.

The infiltration rates measured with the State Percolation Test were always higher than the K values measured with the Bouwer tubes (see table 3.3.1.)

TABLE 3.3.1

COMPARISON OF BOUWER K VALUES AND STATE PERCOLATION TEST VALUES, for all measured horizons (in cm/day)

Date	Profile	Horizon	Bouwer-K (cm/day)	State Perc. Test (SPT) (cm/day)	Ratio SPT/K
July'69	Charmany (silt loam) (July'69)	Ap (20)	16 6 Av: 10	360,195,555,360,240,240 Av: 325.	32
		B2 (60)	33,76,57,43 Av: 52	255,240,180,135,205,90 Av: 184	4
		*B3 (120)	22,30 Av: 26	145,35,270,90,60,36 Av: 106	4
Aug'69	Mandt (silt loam (Aug'69)	Ap (20)	6,12 Av: 10	370,1275,720,240,450,625 Av: 610	61
		B2 (50)	32,13 Av: 25	214,128,315,128,128,128 Av: 174	7
		*B3 (80)	12,2 Av: 7	130,102,88,124,102,147 Av: 115	16
Sept'69	Omro I (clay; cultivated) (Sept'69)	Ap (20)	0,10	15,30,15,30,45,90 Av: 37	7
		B2 (50)	2,9 Av: 6	45,30,75,45,135,102 Av: 72	12
		*B3 (80)	5	15,15,90,90,135,240	3up
Sept'69	Arena (loamy sand)	*B3 (80)	420+ 190x	1650+ 2025x	4
Oct'69	Pla I (silt loam; cultivated)	*B3 (80)	25,17 Av: 20	75,120 Av: 95	5
Oct'69	Pla II (silt loam; virgin)	*B3 (80)	50,105,Av: 75	600,520 Av: 560	7

* THESE VALUES WERE DISCUSSED IN SEC. 3.2

\+ NATURAL SITE.

x COMPACTED SITE NEAR RAILROAD.

Differences were particularly large in the Ap horizons of the Mandt and Charmany sites, where the soil was strongly compacted (sec. 3.1 and Appendix 6.1). Worm-channels apparently caused high infiltration rates for the State Test Measurements. Bouwer-K measurements, however, were not strongly influenced by the occurrence of these channels since they did not connect the soil surfaces of the inner and outer tubes of the Bouwer system (sec. 3.3.5). When such channels are open to the infiltration surface, the Bouwer method clearly underestimates the infiltration capacity of the soil. The State test, however, is normally used at depths below 2 feet, in well structured B2 and B3 horizons. Confining attention to these depths, it is found that the State Test values are still a factor 4 to 16 higher than those of the Bouwer test at the same depth. The initial moisture content of the soils was low before these measurements, that were made in summer and early autumn (sec. 3.1). The initially dry profile can be expected to absorb water from the test holes at a rate higher than the hydraulic conductivity, owing to the suction gradients present even after the required soaking period. Since the Bouwer-K values are derived from a limited saturated volume of soil only, we expect that these values more nearly represent expectable seepage rates, particularly during periods when the surrounding soil has a high moisture content, as in early spring. Therefore, measurements at all sites will be repeated in the coming spring, to investigate the relative seasonal variations of both methods. A good method should yield a value that is representative for all seasons.

In profile Omro I (80 cm) a different phenomenon was evident. Here, inclined silty layers are present that influence infiltration through sideways seepage from the State Test holes. Such layers do not influence the Bouwer test to the same degree. With no silt layers bordering the holes, a low infiltration rate was found. This example illustrates the necessity to study the natural profile before testing.

3.3.2 Comparison with permeability values from undisturbed cores.

This comparison is rather difficult, since measurements on cores depend on methods of sampling and of presaturation. Moreover, the special heterogenity of the soil matrix itself leads to high variability between relatively small individual core samples.

In the Bouwer test, movement from the outer to the inner tube involves vertical and horizontal components, hence its results can be expected to depend on the directions of soil voids, as well as their numbers and sizes. In some cases the Bouwer test yielded results similar to those of the undisturbed core tests, as for example, in Charmany at 120 cm. The Bouwer K was approximately 25 cm/day and the same value was measured in a vertical core, containing a large vertical crack. The internal conductivity of the prism itself, both horizontally and vertically, was only about 3mm/day.

In some cases horizontal conductivity seems to be the factor that governs the measured Bouwer-K. This seems to have been the case in the Mandt site, for example, where vertical ped faces were only moderately developed. Vertical saturated conductivity in cores is sometimes particularly high because of the occurrence of vertical worm and root channels (e.g., 700 cm/day in the B_2 and B_3 horizons at the Mandt and Charmany sites). Plugging the channels greatly reduces these values. As mentioned before, vertical channels influence the Bouwer-K value to a much lesser degree.

Cracks and tubular pores in a soil profile generally become constricted at greater depths, or just end, like a worm hole. When a measurement is made in situ, flow through some of the larger voids may be limited by the narrower passages below, whereas the same voids would pierce small core samples and could result in inordinately high conductivity values (see figure 2.4).

A comparison between the Bouwer-K values and the conductivites measured on cores, as they are given in the tables, shows that both values are of the same order of magnitude. Similar general agreement between the two types of measurements was reported by Bouwer (1962) and by Baumgart (1967), working with different soils in Germany. Baumgart (1967) reports that for low conductivities the agreement was reached only when the air from undisturbed cores was first removed in a vacuum. The variability in our experiments was less than in his study, since we used the larger Bouwer tube (25 cm, versus 20 cm diameter) and also considerably larger undisturbed cores (441 cm^3 versus 100 cm^3).

3.3.3 The effect of long duration tests on the measured K value. A Bouwer test normally takes two to four hours. The question arises whether this period is adequate for unsaturated soil to swell to its full capacity. When the soil to be tested is dry, as it usually is in summer, it is rather improbable that complete swelling can occur within four hours. So cracks may not close as completely as they would after a prolonged period of saturation, and measured conductivity will probably be higher than when measured in the same soil in spring. Wert (1969) reported a decline in both infiltration rate and K value with time. Bouwer reports (in an unpublished report: SWC 4-gGl) long duration tests on an Adelanta loam, with pronounced soil structure, in Phoenix, Arizona. Three Double tube installations were tested simultaneously in three trials at a total of nine locations. The depth of the auger holes varied from 76 to 186 cm. The duration of the total test periods ranged from 2 to 7 days with K measurements taken several times daily. In general, consistent K values were obtained after 4 hours. To evaluate this effect under the local conditions of Wisconsin, a long duration experiment was conducted at the Charmany farm, using the city water supply.

Depth of hole: 52 cm. Duration of experiment: 46 hours.

Time after start of experiment	Ratio $2\Delta t/t^2$ eq. lev. extrapol. to H = 0	K	Inf. rate (through inner tube)
3 hours	0.8×10^{-3}	36 cm/day	4000 cm/day
22 "	0.7×10^{-3}	32 "	3400 "
26 "	0.7×10^{-3}	32 "	3200 "
46 "	0.6×10^{-3}	28 "	3100 "

In view of the variability occuring in the natural soil, and of the limitations of accuracy of the measurement itself, this is considered to indicate the consistency of the measured K value in a period of time (2 days) that is often considered to be necessary for complete swelling (compare the State Test precedure in which time allowed for soil swelling is 16 to 30 hours).

The question remains: What would the conductivity have been after, say, three or more days. But this is unimportant, because it is hard to visualize a situation in the context of our experiments in which infiltration would continuously occur at a constant hydraulic pressure of 150 cm, or more. The Bouwer method uses high pressures to create conditions in a short period of time that will resemble those of a saturated soil. We will investigate our pedons again in early spring when natural swelling will have had its maximal effect on void patterns in the soil.

3.3.4 <u>Effect of temperature of the water</u>.

The viscosity of water changes with temperature, therefore hydraulic conductivity is higher at higher temperatures. Klute (in methods of soil analysis p. 219) gives the following correction formula:

$$K_{st} = K_t \; (N_t/N_{st})$$

in which K and N are the conductivity and viscosity respectively. The subscripts T and ST denote the temp. of measurement and the standard temperature respectively. The relation between temperature (in °C) and viscosity (in centipoise) or water is:

0°C	1.787	
5°C	1.519	
10°C	1.307	
15°C	1.139	
20°C	1.002	
25°C	0.890	
30°C	0.797	(from Handbook of Chemistry and Physics).

Our lowest temperature was about 10°C (October, at the Platteville site), highest temperature about 20°C, and average about 15°C. (Note: Water temperature should be measured when the outer tube is being filled, rather than later in the smaller volume of the standpipes where temperatures rise notably and are not representative of the water flowing from tank to outer tube and then into the soil). With water at 10°C the K values should be multiplied by a factor of 1.14 when 15°C is taken as a reference level. When water of 20°C is used, the factor is 0.88. The values listed in this report were not corrected for temperature, since these corrections would be much smaller than the usual variation between replicate measurements. Moreover, the approximations involved in the calculation of K also introduce a range of uncertainty. When the variation of temperature exceeds the 10-20°C range, however, corrections become necessary. The temperature of the water should therefore be measured.

3.3.5 Relation between soil fabric and K values (see pictures, Appendix 5.1)

The rate of water movement through a soil material saturated with water will depend mainly on the occurrence of larger voids. (see section 2.7)

SOIL SURFACE AT BOTTOM OF THE TUBES WITH CHARACTERISTIC STRUCTURES. (SEE TEXT)

APPENDIX (5.1) SHOWS PHOTOGRAPHS OF FABRICS.

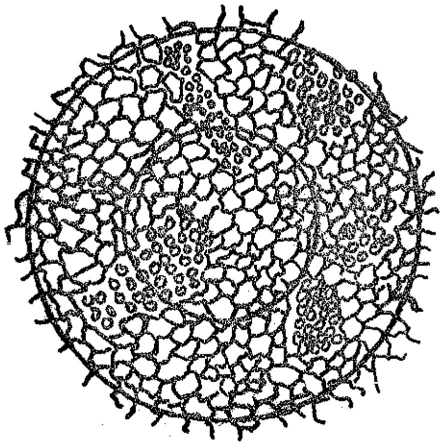


FIG A.

GRANULAR AND FINE SUBANGULAR BLOCKY

(A₁ PLA-II)

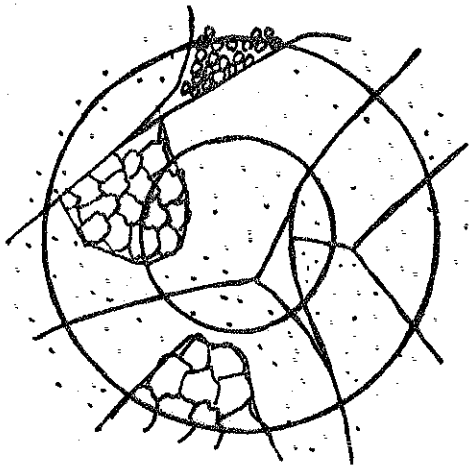


FIG B.

APEDAL; WITH DENSE FRAGMENTS [⁙]

(A_p-MANDT)

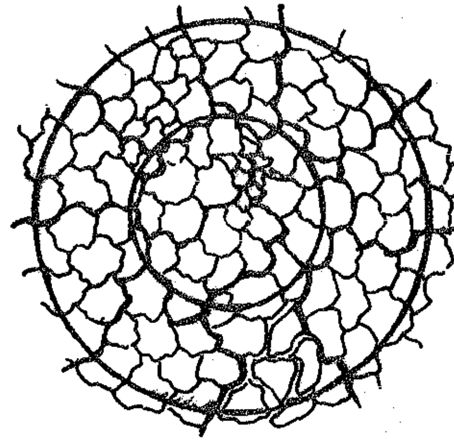


FIG C.

PRISMATIC BREAKING IN SUBANGULAR BLOCKY.

(B_2-MANDT)

FIG 3.3.5

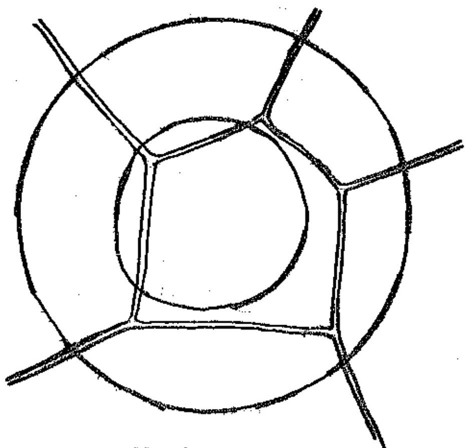


FIG D.

PRISMATIC

(B_3 CHARMANY)

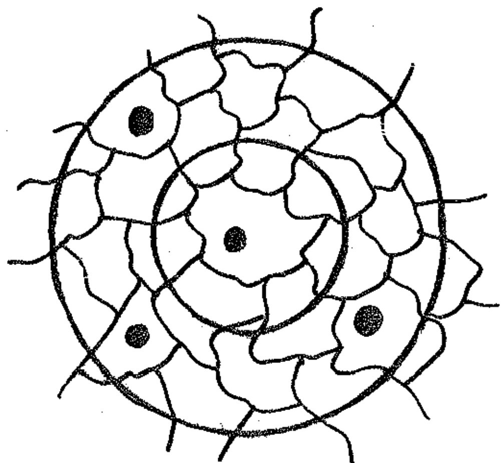


FIG E.

VERTICAL WORM- OR LARGE ROOT CHANNELS (IN SUB. BLOCKY SOIL STRUCTURE)

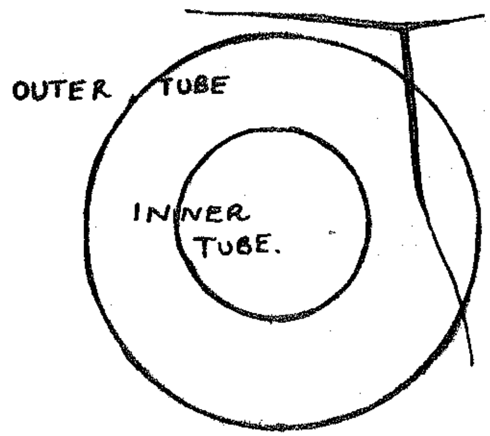


FIG F.

MASSIVE STRUCTURE

(K NOT MEASURABLE; SLIGHT INFILTRATION IN OUTER TUBE MAY OCCUR THROUGH LOCAL CRACK)

(OMRO II - 80CM; SEE TEXT)

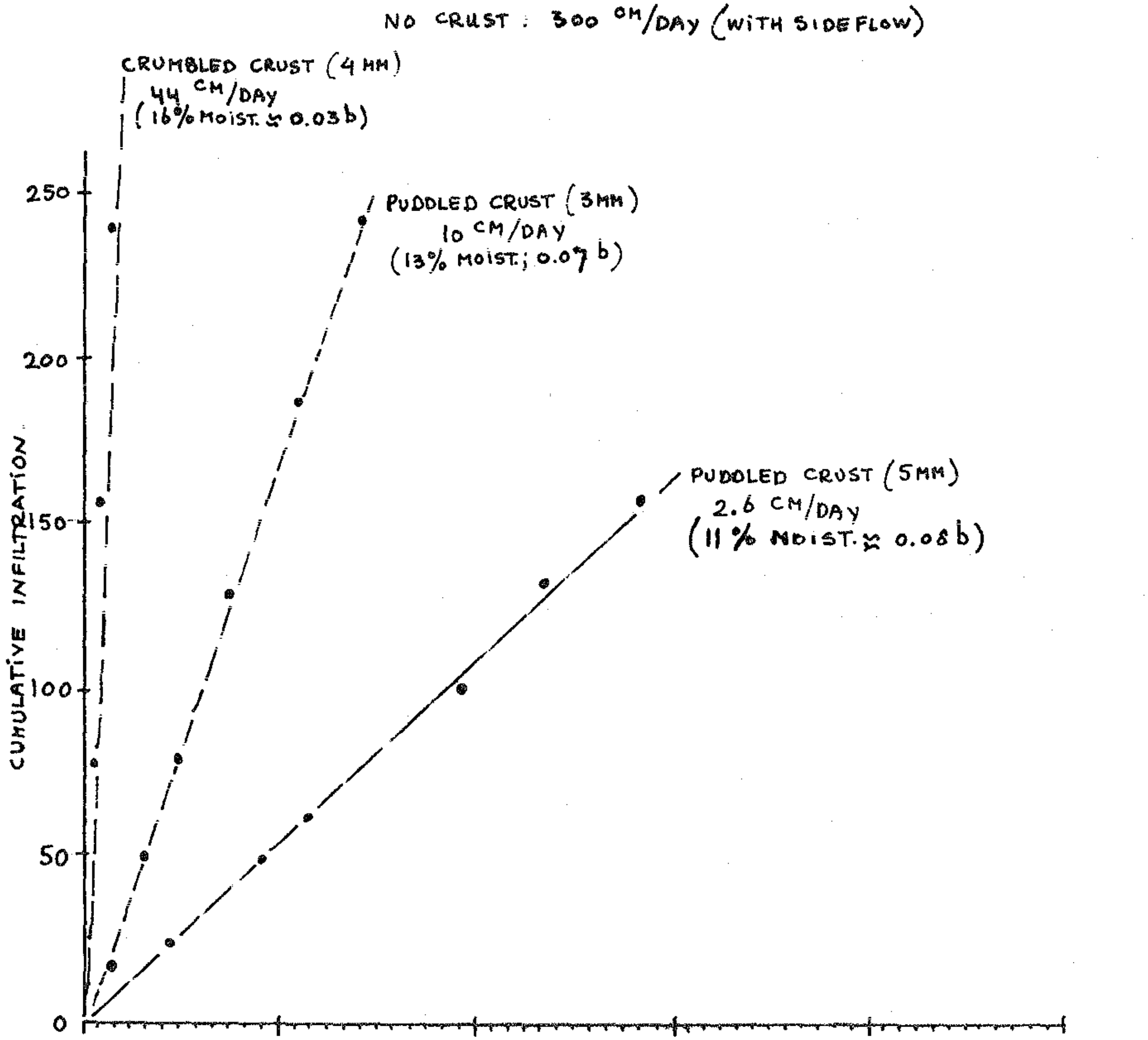
Relatively high values for K are measured when flow from the outer to the inner tube is relatively easy. Figure 3.3.5 shows a granular and fine subangular blocky structure as found for example in A_1 of Pla II (K = 160 cm/day). Continuous pores remain between the small rounded peds even after complete swelling of the soil material. Contrasting with this are topsoil structures in cultivated sites (A_p Charmany, K = 10 cm/day; Mandt, K = 9 cm/day; Pla I, K = 16 cm/day). This type of structure consists of, dense clods with irregular cracks of a pattern different from that of the natural soil (Pla II). In A_p horizons there are usually fewer large voids connecting between the inner and outer tubes and thus the K is lower. The structure in the B_2 horizon is prismatic, breaking into blocky peds. Thus planar voids, capable of conducting water, are present along many ped faces between the inner and outer tubes. Therefore, conductivity in these horizons is always higher than in the B_3 horizons where a prismatic structure is found (figure D). This structure provides fewer planar voids connecting both tubes. The total volume of flow along ped faces involves the relative areas of the walls and also the distances between them. Cracking of soil is most pronounced after drying. Remoistening, as occurs during the Bouwer test, leads to swelling processes which narrow the interpedal voids. In certain clayey soils, swelling upon saturation is more rapid and complete when the soil is initially quite moist (as was the B_2 in the bare field of the Mandt farm, for example, (K = 25 cm/day) in comparison with the otherwise similar B_2 in the alfalfa field of the Charmany farm K = 50 cm/day).

As mentioned earlier, worm channels and large root channels (i.e., cylindrical tubes usually exceeding a diameter of 2 mm) do not influence the Bouwer measurement very markedly if their direction is vertical, since the inner and outer tubes are then not interconnected by channels. Under actual conditions of effluent seepage, large channels will seldom remain open to the soil surface, hence the relatively low K value of the Bouwer test is more realistic than the very high value that would result from infiltration into an undisturbed surface. An example is included to show what happens if the measurement is made in a very compact soil horizon (Omro I, 20 cm; Omro II, 80 cm). When there are no larger pores connecting the inner and outer tubes, no measurable K value can be obtained. It was observed however, that when valves b and c were closed and valve a left open, a slow downward movement in both tubes occurred. Apparently some cracks outside the inner tube connected some water. Infiltration was calculated here for the entire surface, including the inner and outer tubes. This is indicated by an asterix for Omro I, 20 cm and for Omro II, 80 cm (see table 3.1) Such a system, of course, now represents an unbuffered infiltrometer and the resulting infiltration will generally include some lateral flow. In Omro I (20 cm) one relative high K value was measured (10 cm/day). Here, as was evident from examination of the freshly-detached soil surface, a vertical crack occurred through the inner tube, connecting it with the outer tube.

3.3.6 Preliminary conclusion

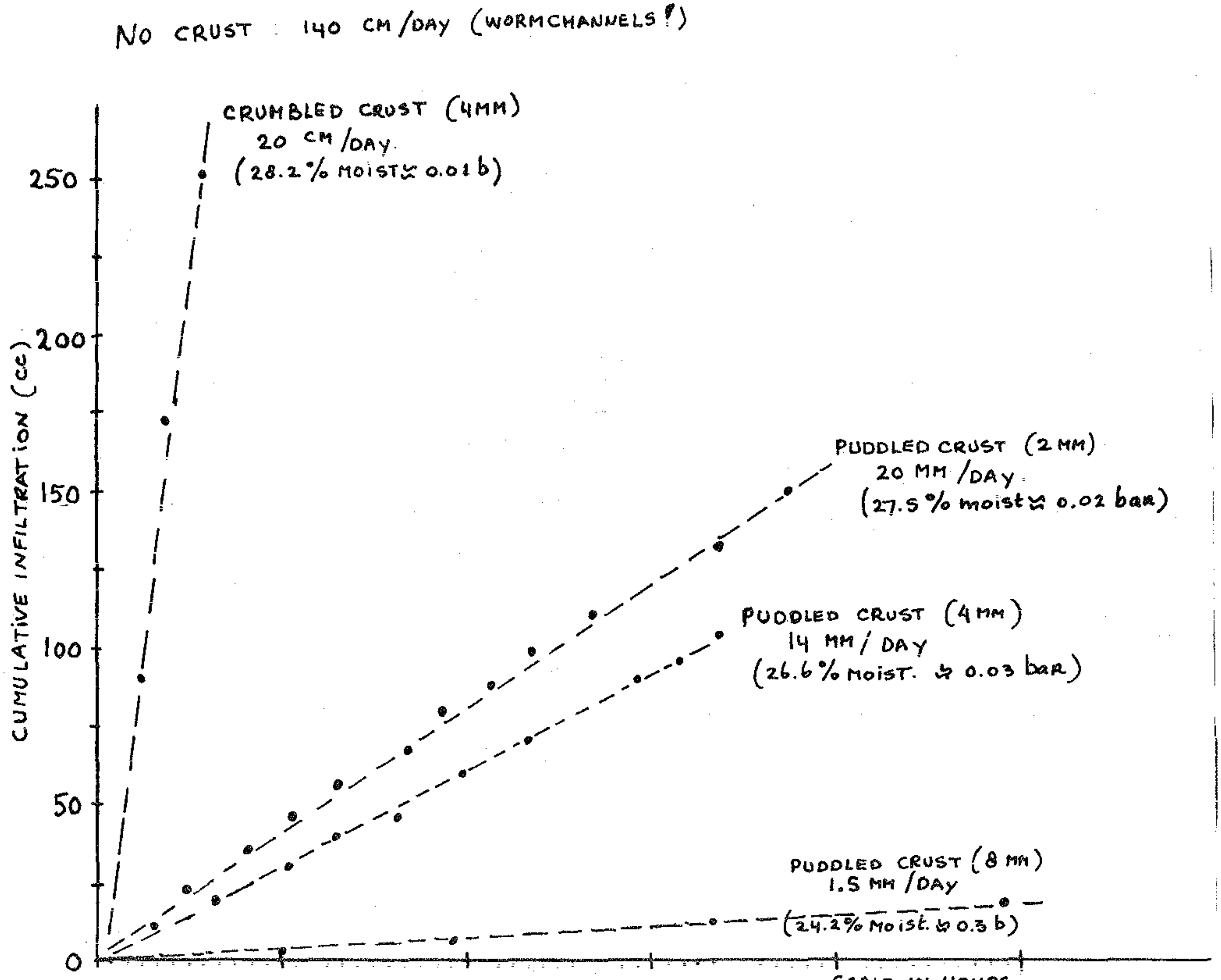
The Bouwer Double-tube method was found to be very useful in measuring the hydraulic conductivity of soil horizons well above the water table. The K-value obtained provides a reference that is physically better defined than infiltration rates determined by arbitrary procedures. The Bouwer-K value results from both vertical and horizontal conductivites of the soil material. Such a value has practical significance when applied to the flow system from a realtively small trench. The factor of seasonal variation has still to be evaluated. Crusting and clogging effects have not so far been considered in this study.

FIG. 3.4.3.



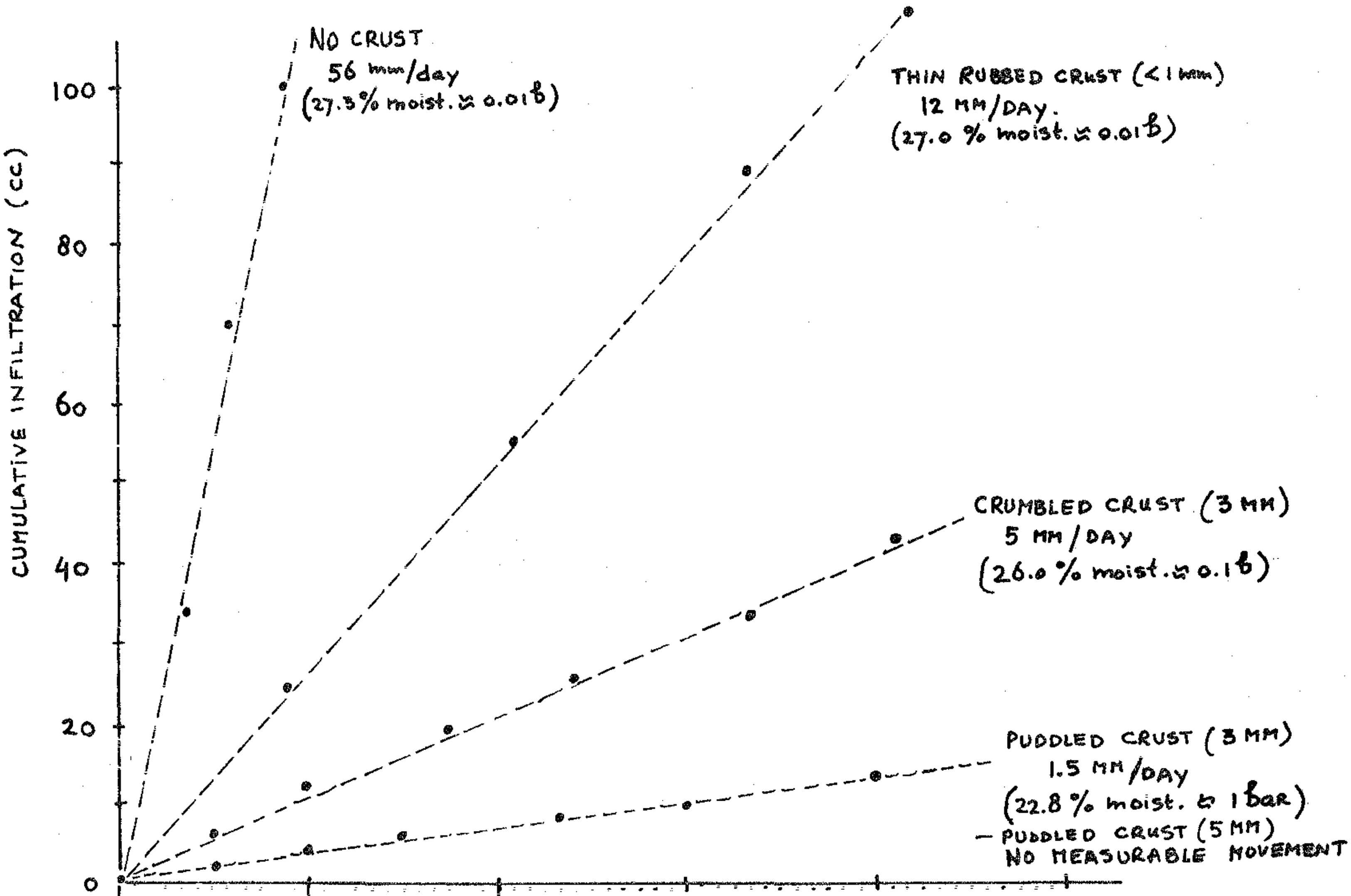
CRUST TEST ARENA (B_2 AT 40CM; ORIGINAL MOISTURE CONTENT : 9.8%)

FIG. 3.4.1



CRUST TEST MANDT FARM (B_2 AT 50 CM, ORIGINAL MOISTURE CONTENT : 22.3 %)

FIG. 3.4.2



CRUST TEST OMRO (B_3 AT 70 CM; ORIGINAL MOISTURE CONTENT: 21.3%).

3.4. <u>Unsaturated-conductivity tests</u>.

The results shown in figures 3.4.1-3.4.4 indicate that thin crusts can strongly reduce the infiltration rate. In the B_2 of the Mandt pedon, for example, infiltration was reduced by 99% (from 144 cm/day to 1.4 cm/day) after application of a thin puddled crust of 4 mm thickness. The suction below the crust was estimated at 0.03 bar = pF 1.5. The thin crumbled crust reduced the infiltration rate to 20 cm/day, approximately the K value measured with the Bouwer tubes. The suction here was estimated at 0.01 bar = pF 1.0 (figure 3.4.1). The already low infiltration rate measured in the B_{22t} of Omro I through a clean soil surface (5.6 cm/day) was reduced to 0.5 cm/day after application of a thin crumbled crust of 3 mm thickness. Suction below the crust was estimated at 0.1 bar = pF 2.0 (figure 3.4.2). In the Arena pedon, the K values were generally very high. In this sandy soil, too, a considerable reduction of infiltration occurred when a crust was formed (figure 3.4.3)

These experiments demonstrate that crusts can greatly reduce infiltration into the soil, and that a characteristic suction will develop in the soil below the crust.

Investigations are being contemplated for the forthcoming season, in which measurements will be made in functioning septic tank systems. The determination of suctions in the soil below the trench will show how effective certain crusts are in reducing infiltration (reference may be made to the Bouwer-K measured at the same depth in the soil next to the trench).

A study of the morphology and genesis of crusts might be useful. It may lead to methods for avoiding or reducing crusting. The problem is complicated by the microbiological origin of surface clogging which seems to be related to soil aeration and to the frequency of use of the trench. Greater attention will be devoted to these factors in subsequent phases of the project.

3.5. Morphologic description of soil structure.

3.5.1. Evaluation of the standard (SSM) system of describing soil structure.

The three grades of structure are described as follows (SSM): (see fig. 3.5.1)

Weak: "peds barely observable in situ". After disturbance: few entire peds, many broken peds and much unaggregated soil material.

Moderate: "peds moderately evident but not distinct in situ". After disturbance: many entire, some broken peds and little unaggregated material.

Strong: "peds quite evident." After disturbance: largely entire peds, few broken peds, no unaggregated soil material. (another criterion, not mentioned for the other classes, is used here: "adhere weakly to one another")

These definitions are rather unclear. Our comments can be summarized in the following points:

1. The procedure of disturbance is poorly defined. Different procedures will lead to different separations into peds, broken peds and unaggregated soil material (see appendix).

2. After applying some standardized disturbance procedure, there supposedly is a mixture of peds, broken peds and unaggregated soil material (N.B. very often one finds clusters of peds held together by roots and/or cutans). These quantities are partly resulting from the "disturbance" procedure itself, partly from the occurrence of surfaces of weakness and from differences between cohesion and adhesion in the soil material. Structures, classified as weak, supposedly break into few entire peds and many broken peds. Moreover, there is assumed to be much unaggregated soil material, that, apparently, never formed a part of a ped. By definition therefore soil structure, in this concept, is heterogeneous: in the natural soil material peds are said to be surrounded by unaggregated soil material. This is also stated to be true for the moderate grade and, although less so, for the strong grade. Our experience, however, does not confirm this concept. On the contrary, we conclude

"GRADE" OF STRUCTURE IS CONFUSING CONCEPT. SOIL STRUCTURE = SIZE, SHAPE + ARRANGEMENT OF PEDS IN A PEDAL SOIL MATERIAL; SOIL CONSISTENCE TO BE NOTED SEPERATELY.

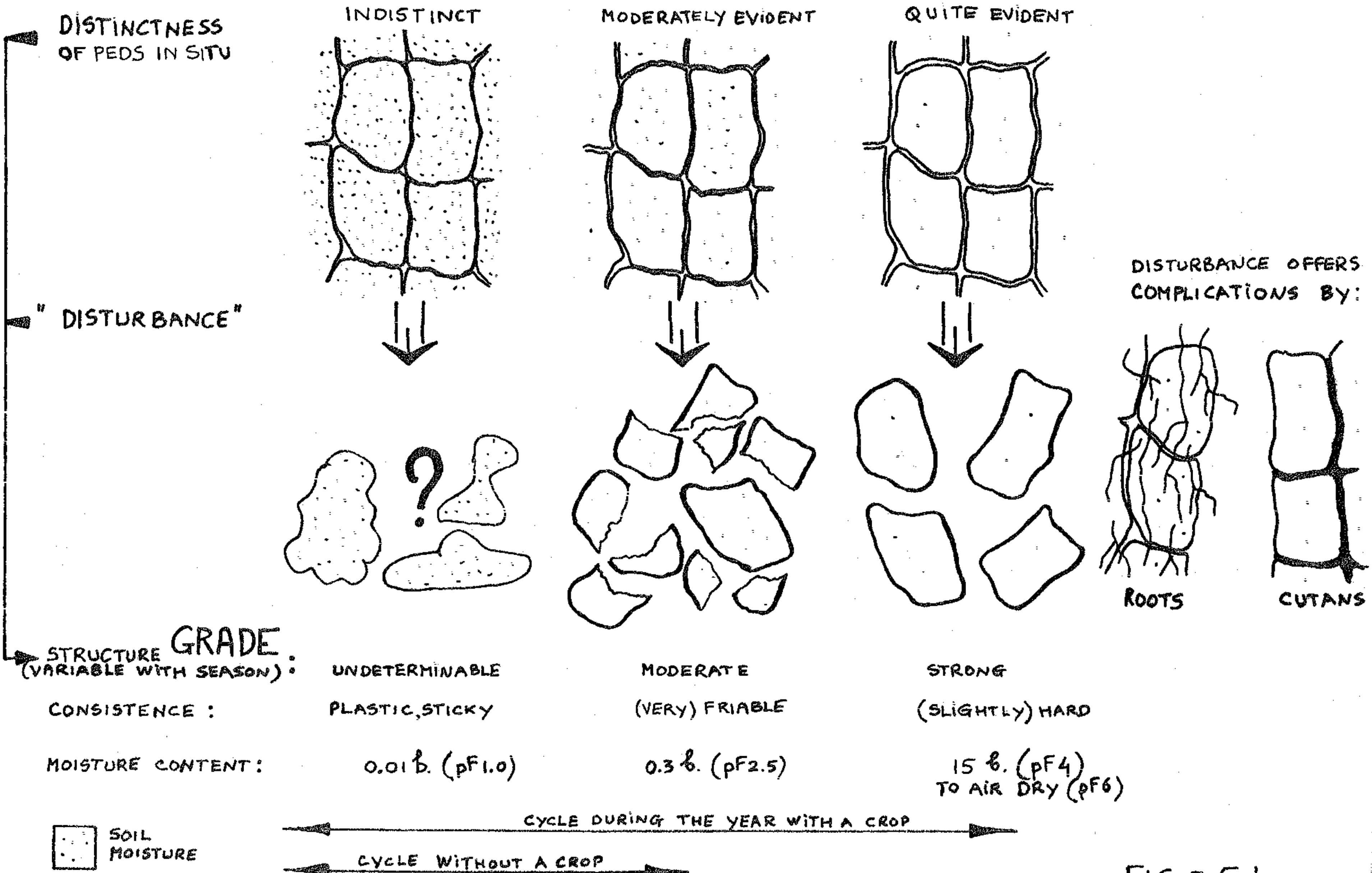


FIG 3.5.1

MODEL OF SEASONAL SOIL STRUCTURE VARIATION IN A PEDAL SOIL MATERIAL, AND THE EFFECT OF "DISTURBANCE", DETERMINING STRUCTURE "GRADE" (SOIL SURVEY MANUAL, SEE TEXT) that soil forming factors usually lead to the formation of a certain degree of aggregation in the soil material as a whole at a certain depth in the soil profile at a certain time although sizes of peds may vary considerably in one layer.

3. Processes of cohesion and adhesion are a direct function of the moisture content of the soil material. The degree of aggregation, being a function of the moisture content, is therefore a variable property for a specific soil horizon during the year. This is mentioned in the SSM, and it is advised to describe the grade of structure at "the most significant moisture content". In a soil profile, a wet condition is " most significant" in early spring; a dry condition is so in summer. The soil has to be considered as a natural body, subject to varying moisture contents during the year, that determine the "aggregation of the primary particles" and "the occurrence of natural surfaces of weakness".

It is useful to distinguish between permanent and seasonal structural features of soils. The SSM lists soil ped shape, size, grade without any such distinction. In actual fact ped shape and size are permanent features while the other two vary seasonally. This seems to be recognized by Brewer (1964) whose definition of soil structure omits grade, and includes voids:

"The physical constitution of a soil material is expressed by the size, shape and arrangement of the solid particles and voids, including both primary particles to form compound particles and the compound particles themselves; *fabric is part of structure that deals with arrangement.*" (p. 132)

A compound particle may be a ped, that is defined as a "natural individual soil aggregate consisting of a cluster of primary particles, and separated from adjoining peds by surfaces of weakness which are recognizable as natural voids, or by the occurrence of cutans".

Brewer's system recognizes the presence or absence of peds. If peds are there, they may be described as to size, shape and arrangement. If peds are lacking, then arrangement of primary particles in the apedal soil material is studied, normally in thin sections. The factors that largely determine the "grade" of structure (SSM) are described by noting soil consistance (SSM) that also involves a "disturbance" procedure.

Some of the discussed phenomena were evident in our study of eight pedons during the field season of 1969. Some horizons were designated in the field as having a "moderate" grade of structure (B_2 Pla II and B_2 Mandt). This "moderate" grade was based on their relative low cohesion, resulting from the relative high moisture content of the soil material (consistance was described as friable). Later, soil peels were made in the laboratory from large air dry undisturbed samples of these horizons (Bouma and Hole, 1965). The soil material was in either case fully structured and all ped surfaces were covered with cutans, identifying the surfaces as parting planes. Therefore this structure was in fact as "strong" as that of the B_2 Charmany of Pla-I. The consistence in these dryer horizons,--that were described in the field as having a strong grade of structure,--was slightly firm.

In studies of soil permeability the occurrence and sizes of larger voids, like surfaces between peds, is an important characteristic. Sizes and shapes of peds determine the morphology of the pores between them. Swelling and shrinkage of the soil material, occurring in the field after wetting and drying, will determine their width in different seasons. This cycle has to be characterized; one picture can <u>never</u> be representative.

Appendix for point 1

Jongerius (1957) suggested two procedures of soil disturbance:

1. Cutting a volume of soil from the soil profile, and observing the quantities of entire and broken peds as well as unaggregated soil material after the disturbance, the quantity of entire peds to be estimated in percentages.

2. If peds are not separated after precedure 1, they are separated by breaking the volume of soil into its composing peds. After breaking by hand the quantity of entire peds is estimated again. Six classes in all are established, according to these procedures, coded as:

		Entire peds in % of soil material				
		0	<10	10-30	0-70	>70
Peds are isolated by cutting a volume of soil from profile	grade:	0		1	2	3
Peds can only be isolated by breaking by hand	grade:	0	$\frac{1}{4}$	$\frac{1}{2}$	$1\frac{1}{2}$	$2\frac{1}{2}$

This method is a more detailed version of the SSM system but does not introduce a new concept.

3.5.2 Soil structure and related properties of the cultivated and virgin pedons of Omro and Platteville.

First the occurrence of channels will be discussed. The largest number of channels is usually found in the B_2 horizon at a depth of about 50 cm. This is particularly true for the channels smaller than 4 mm. The class larger than 4 mm (almost exclusively worm burrows) shows a more uniform distribution with depth. This is to be expected, since large worms apparently travel up and down from the soil surface to considerable depth, through their individual channels. These large pores were observed only in the Charmany and Mandt profiles. The absence of large channels in the other pedons agrees with the fact that earthworms were not observed there.

The smaller number of channels in a topsoil can result from two conditions:

1. Compaction of the Ap horizon by plastic deformation by farm operations, tending to close any existing channels (Mandt 20 cm; Omro I 10-40 cm; and Pla I 20 cm).

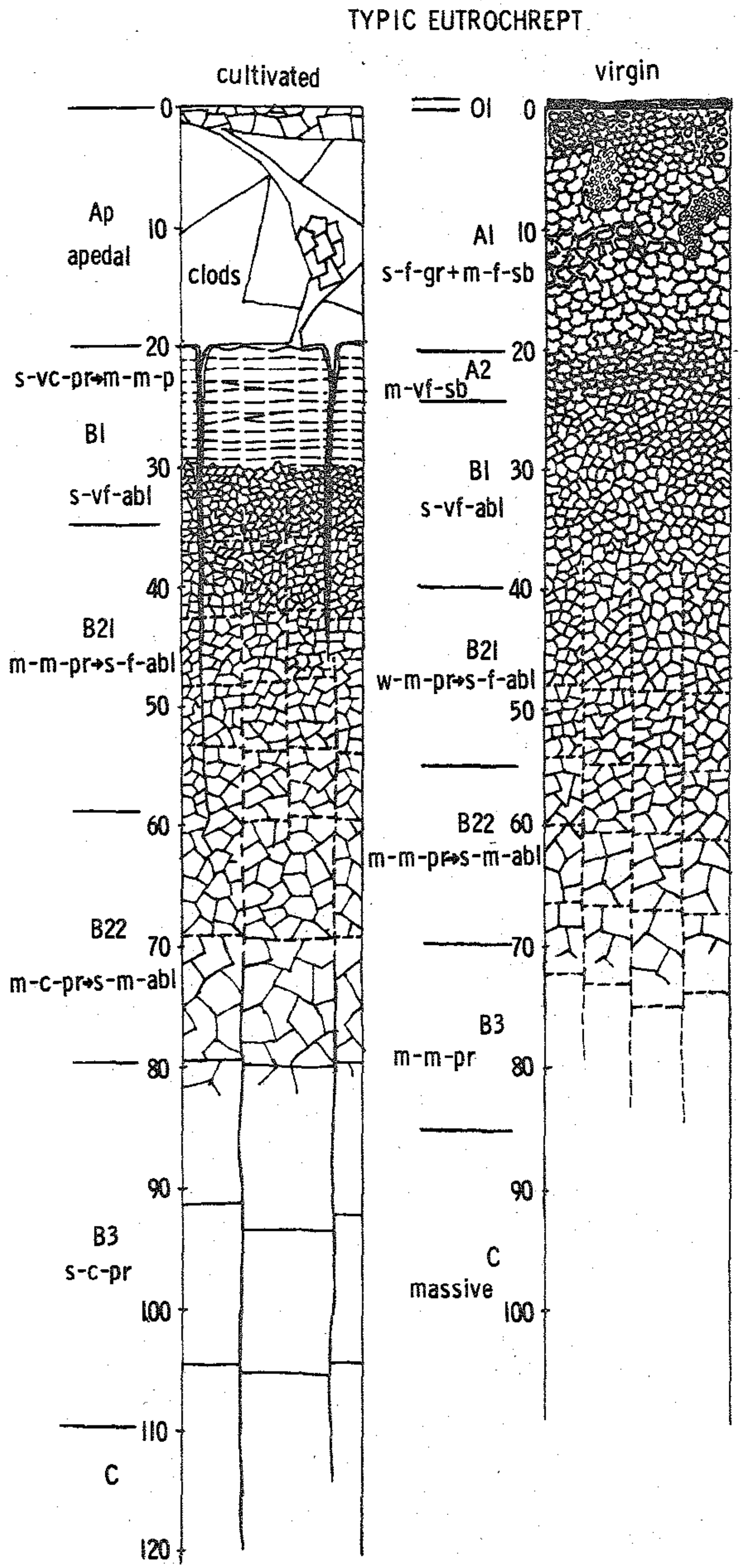


FIG. 3.5.2.1 Soil structure of the OMRO pedons (Oshkosh clay) structure code according to Soil Survey Manual (grade: w,m,s; size: vf,f,m, c; types: p = platy, pr = prismatic, sb = subangular blocky, ab = angular blocky, gr = granular.

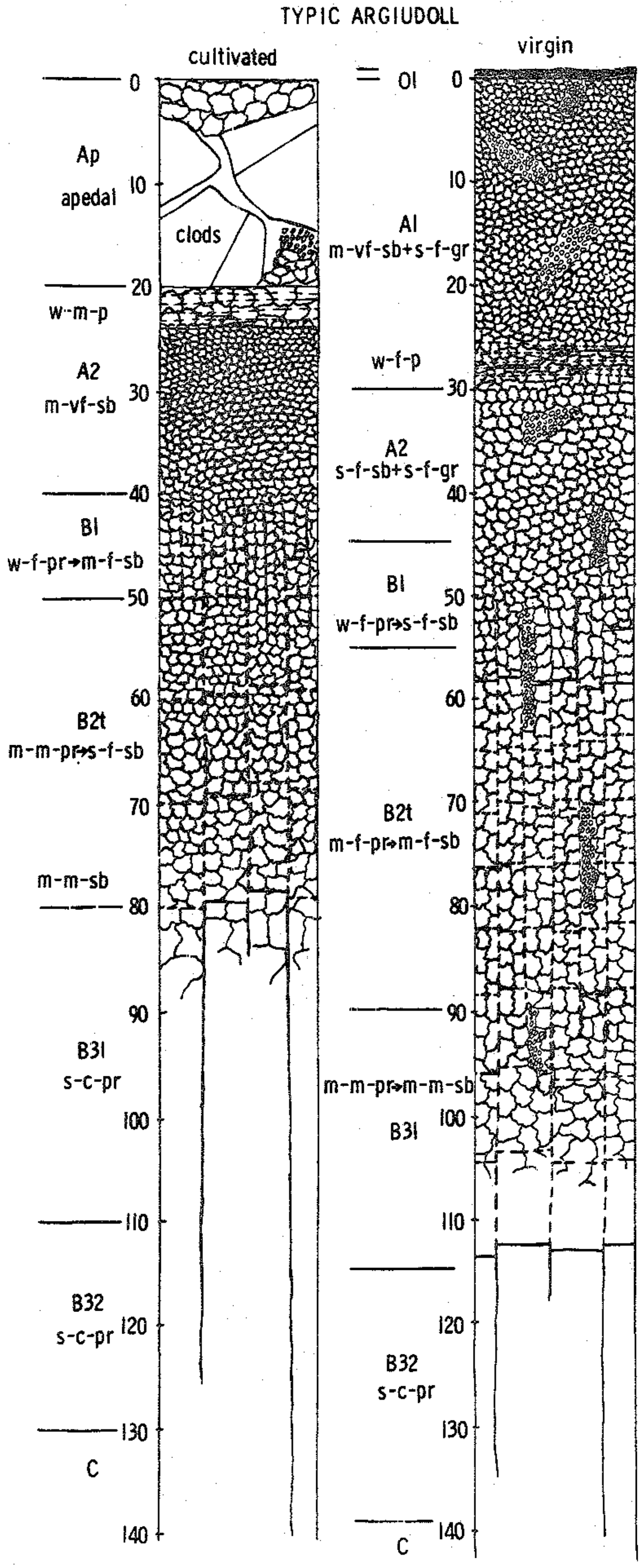


FIG. 3.5.2.2 Soil structure of the Platteville pedons (Tama silt loam)

2. The predominance in a very porous virgin topsoil of granular and fine subangular blocky structures. In such a loose structure, with a low bulk density, individual channels do not really occur. Roots grow through the relatively large interpedal compound packing voids (Pla II 0-40 cm; Omro II 0-30 cm). In such cases the channels are simply not observed nor reported for the upper horizons.

Channels are particularly evident and important, in relatively dense horizons with accomodating peds. In contrast, the compound packing voids between peds are the most relevant structural feature in virgin topsoils. Comparison between the virgin and cultivated sites at Platteville and Omro shows some interesting features. The number of channels in Omro II is considerably lower than in the cultivated Omro I below a depth of approximately 40 cm where both pedons have about the same density. We think this is caused by rooting of agricultural crops, particularly alfalfa. The relative deep rooting, and subsequent moisture extraction by the roots, led to the observed difference in moisture content between the cultivated and the virgin pedon at the moment of sampling. Pronounced dehydration at the cultivated site induced cracking patterns in the subsoil, not found at the virgin site (see soil structure diagrams 3.5.2). The occurrence of these cracks resulted in a clear increase of permeability. The loosening effect of deep rooting is demonstrated by the trends in bulk density as well. Although the topsoil of the virgin Omro II had a much lower bulk density than the topsoil of Omro I, it had a density of 1.62 at 70 cm, whereas at the same depth in pedon Omro I this amounted to only 1.53. Compaction below the plowed layer in Omro I led to a sharp decrease in the amount of channels there. Permeability was reduced to zero except where large vertical cracks had developed in this horizon upon drying. They became partly filled with topsoil, but a considerable permeability could be measured nevertheless along these cracks.

The trends in the Platteville pair of pedons are similar in part. Many channels occur to depths of more than 120 cm depth at the virgin prairie site (Pla II). Most of these channels have apparently been made by ants. The measurement was made in soil near to ant mounds, for these occur spaced about 3 meters apart throughout the prairie remnant. Below the mounds themselves channels larger than 2 mm in diameter are 10 to 40 times more numerous (Baxter and Hole, 1967). The soil material occurring above 50 cm in this pedon is very porous (B.D. = 1.20) and here the channel concept does not apply. In the cultivated pedon (Pla I) compaction occurred in the horizon below the Ap (B.D. 1.27). Hydraulic conductivity was lower. In such a relatively dense horizon, where the peds accomodate each other, channels are very evident. Here, as in Omro I, roots of agricultural crops have created many channels, that remain after decomposition of the roots. We could not establish criteria to separate channels created by roots from those created by ants, unless it is the presence of the obscure "nibbled" or micro-pitted surface of ant burrows. Since ants were not observed at the cultivated site, however, we presume that roots made the channels.

The subsoil below 80 cm is denser in Pla I than in Pla II (B.D. 1.35 versus 1.26, locally 1.15). The volume of channels is reduced in Pla I, the structure was prismatic (see soil structure diagram 3.5.2) and the permeability was less than at the virgin site at the same depth. This is attributed to some erosion of topsoil, bringing the prismatic subsoil closer to the surface. In Pla I no channels were observed below 110 cm; in Pla II channels occurred as deep as 130 cm. Comparison of the moisture contents of both profiles, at the moment of sampling, shows that Pla I was much more strongly dehydrated, particularly below 50 cm, than Pla II. This is the effect of the deep rooting corn crop, as was the case with the alfalfa at Omro I. Rooting, and dehydration by the roots, are not so deep at the virgin paririe site. We suppose therefore that most channels in the horizons below, say, 50 cm of Pla II were made by ants.

Cultivation of both pedons has led to a decrease of the organic matter content of the topsoil. As a result, the particle density of the soil material increased (see tables in 3.1).

3.6. Summary of results

Project: Develop reliable field methods to predict movement of liquid wastes in soils.

Phase 1: Compare the official State Percolation Test with other less empirical physical methods to measure permeability of different soils.

From the results obtained on seven sites, it follows:

1. The Bouwer Double-Tube apparatus measures a considerably lower saturated conductivity than the infiltration rate of the State Test (section 3.3.1.). The Bouwer values, however, correspond reasonably well with the conductivities obtained from both vertical and horizontal undisturbed cores. The high values obtained with the State Test Procedure are probably caused by lateral flow, as well as by soil moisture suction gradients, which are likely to be particularly high in summer. (see data in 3.1) A valid test should give a value that is representative for the soil in all seasons, including, spring, when the soil is wet and initial suctions are low. The K values of the Bouwer test are based on a limited volume of saturated soil and seem therefore to provide a more realistic estimate of the hydrodynamic properties. Before we can be certain about this, however, additional testing on the same sites should be carried out in the spring season.
2. The Bouwer method, as well as the measurements with undisturbed cores, is applied on carefully cleaned soil surfaces. A typical soil surface in a sewage trench will not be like that because of compaction or puddling during the construction of the trench, and because slaking of soil,

accumulation of solid sewage particles and biological clogging may occur during operation of the system. A crust will induce suction in the underlying soil, which may result in unsaturated flow conditions, and hence a much slower infiltration rate. In our crust tests this was well demonstrated. (sec. 3.4) For example: a thin puddled crust 2 mm thick reduced the infiltration rate in the B_2 of the Mandt profile by 99%.

Phase 2: The study during the 1969 field season had other results, less directly related to the central problem.

1. A relation was found between soil structure and saturated hydraulic conductivity. Conductivity decreases with increasing sizes of peds (sec. 2.7, 3.3.5, and 3.5.2). Apparently percolating water follows natural faces of peds, even when the soil is not entirely saturated. This occurs in part because of cutans on ped faces that reduce the movement of water into the unsaturated peds. Saturated conductivity is governed by the occurrence of continuous larger voids, such as cracks. Not only their number but particularly their width is important in this regard. We ascribe the difference in hydraulic conductivity between the Charmany and Mandt sites (with essentially the same type of structure) chiefly to the absence of a crop on the Mandt site in 1969, which permitted relatively high moisture contents and low suctions to persist even in August (sec. 3.1). In July, the Charmany site, on the contrary, already had relatively low soil moisture contents, due to the transpiration of the alfalfa crop. The resulting cracking, or more exactly, the widening of existing cracks, probably caused the higher conductivity. Soil swelling does occur after saturating but by a reduced amount (in the time available for the test) in proportion to the preceding degree of dehydration. The difference in structural grade between the two soils was observed and recorded in the profile description (sec. 3.1) as "strong" at the Charmany site versus "moderate" at the Mandt site. The mechanism of soil

swelling, particularly as it occurs under natural conditions in early spring, needs to be studied more thoroughly in Wisconsin soils.

2. Changes induced in soil by agriculture were studied by comparing virgin and cultivated soils at two sites. The soils were an Oshkosh clay (Omro) and a Tama silt loam (Platteville) (sec. 3.1.). In both cases, growing crops, particularly alfalfa, led to a marked drying of the soil to considerable depth. In the natural profiles effective rooting (see channel diagrams in section 3.1) was not as deep, and dehydration was more restricted to the topsoil. Drying induced cracking patterns in the B_3 horizon of the cultivated clay soil that were not found in the natural site at the same depth. The hydraulic conductivity of the cultivated clay soil was therefore higher in the B_3. Compaction by tillage was confined here to the topsoil, resulting in a strong decrease of hydraulic conductivity. In the silt loam, the cultivated soil was slightly compacted to a greater depth, and the hydraulic conductivity was lower in all the horizons tested. Apparently some erosion had occurred too, bringing the relatively dense subsoil nearer to the soil surface. A loss of organic matter in the topsoils of both cultivated soils resulted in a higher particle density of the soil materials. These examples show clearly that soil profiles, occurring in one and the same soil unit and having a similar classification may differ considerably in physical properties due to management by man in the relatively short period of a century. The State Percolation Test performed at 80 cm depth on both Tama pedons (sec. 3.2) shows considerable differences. The differences in rates of infiltration between the State Tests at the Oshkosh site were caused by the local interlayering of this silty layers in the clay. This shows the necessity of studying the natural profile before testing (sec. 3.2.).

4. Plans for future work

During the coming months we propose to direct the investigation toward problems more directly pertinent to real sewage disposal systems. In particular, attention will be devoted to the following areas: (1) physical and microbiological aspects of soil clogging by sewage effluent; (2) field tests of conditions at sites of actually operating septic systems; (3) quantitative interpretation of the relation between soil fabric and hydraulic conductivity; and, of course, (4) characterization of major soils of Wisconsin with respect to intake and transmission of water and liquid wastes.

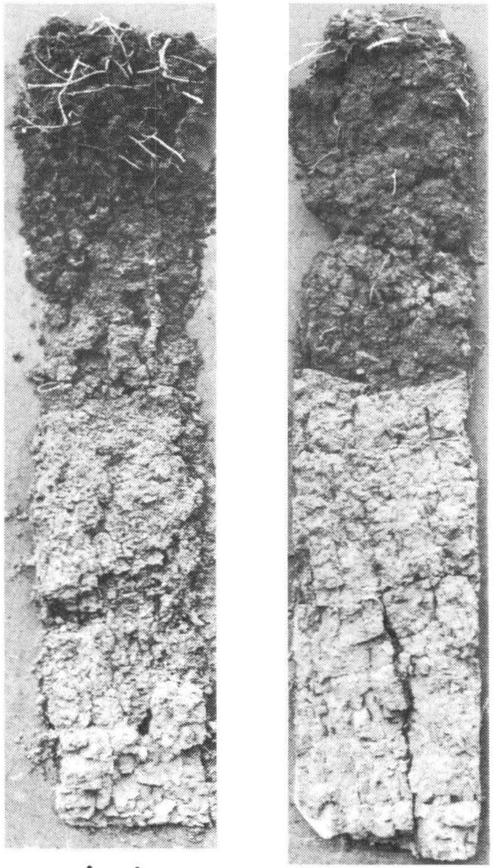
The first of these areas can fortunately be pursued in cooperation with Dr. Elizabeth Mc Coy of the Bacteriology Department on this campus. The studies of Schwartz et al., 1967 clearly demonstrate that microbiological processes, occurring during the infiltration process into the soil, determine whether or not a septic-tank effluent system will function well.

We intend to use columns of undisturbed soil, to be well characterized in physical and morphological terms. Effluent will be applied to these columns in varying quantities and at different intervals. Processes of soil pore clogging, coliform development, nitrification and denitrification, will be monitored in the laboratory. These will be correlated with changes in physical characteristics and processes, such as: infiltration rate, soil suction and moisture content, and oxygen content of the soil air.

Procedures in the second subproject will include tensiometric measurements of suctions and water contents prevailing below and around operating sewage trenches. A representative K-value can be established on the basis of the relation between K and water content for each specific soil matrix. (this value may be considerably lower than the saturated K, depending upon the degree of clogging and crust formation). By these means, an attempt will be made to define the hydraulic flow patterns of typical sewage disposal systems, so that an evaluation can be made of means for improving them. Trenches of different septic tanks will be excavated to permit observation of soil morphology, crusting and patterns of oxidation and reduction. Methods for the prevention of crusting and for the alleviation of crusting effects will also be studied.

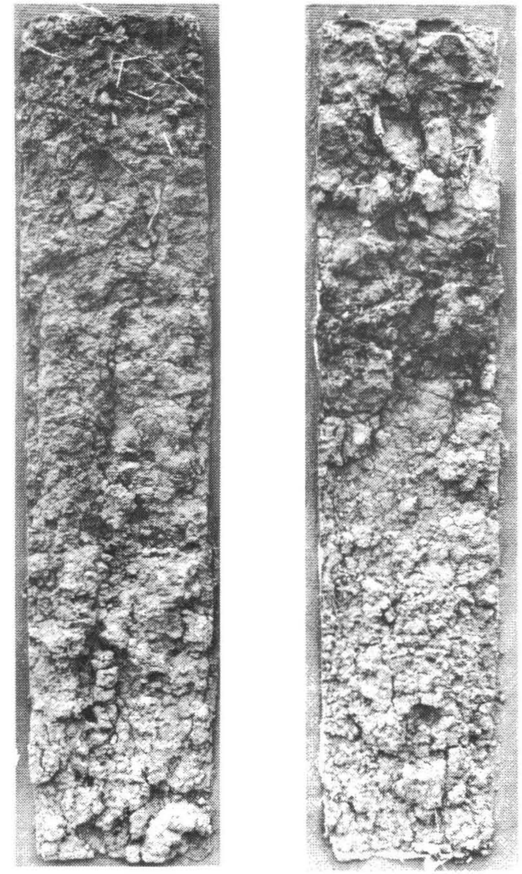
The third subproject will investigate the relation between soil fabric (as observed in the field and in "soil peels") and hydraulic conductivity in quantitative terms. Physical models and equations describing the relation of soil conductivity to pore sizes (e.g., Childs, 1969) will be tested. Processes of swelling of soil will in part determine the size of pores; and hence also the hydraulic conductivity, in the wetted soil layers. We plan, therefore, to repeat in early spring all hydrological measurements, made in the previous summer, in our pedons, so as to assess the factor of seasonal variation.

APPENDIX 5.1



virgin cultivated
TYPIC EUTROCHREPT
Oshkosh clay

OMRO



virgin cultivated
TYPIC ARGIUDOLL
Tama silt loam

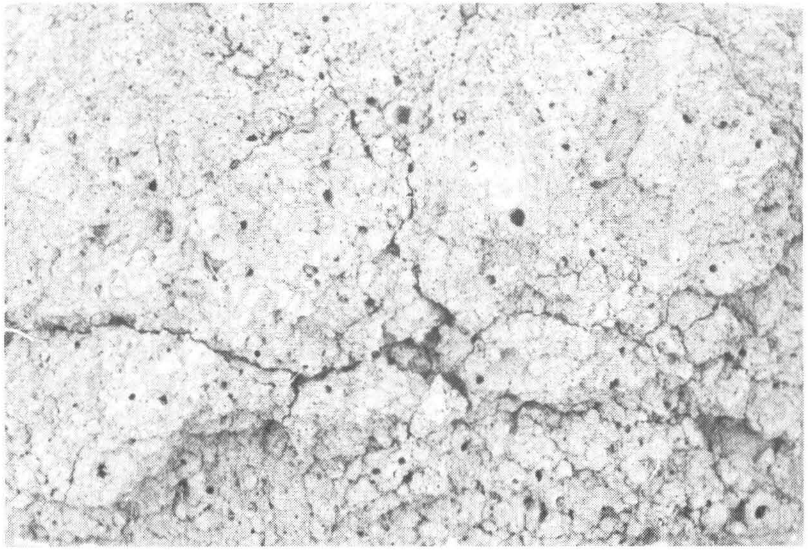
PLATTEVILLE

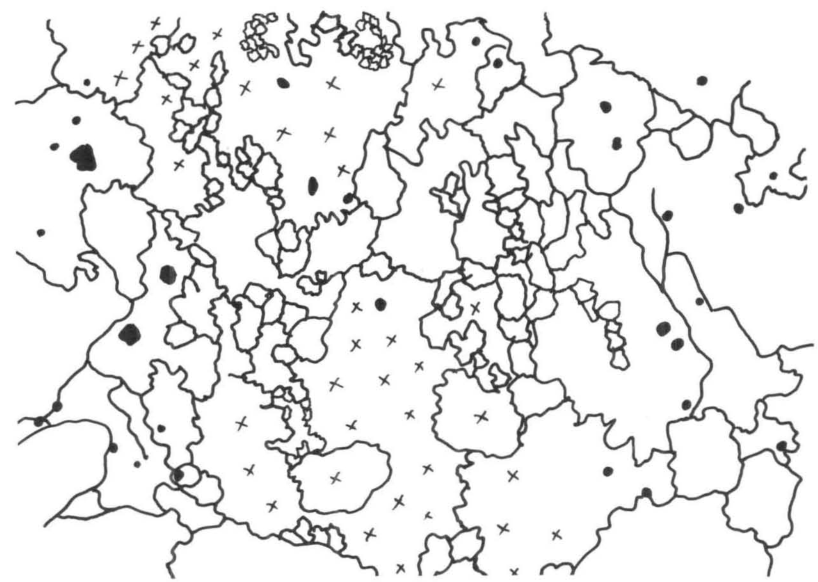
General legend for the following figures, that are horizontal sections as seen in a soil peel, of each pedon at the indicated depth.

natural voids between ped faces

channels

pedotubule



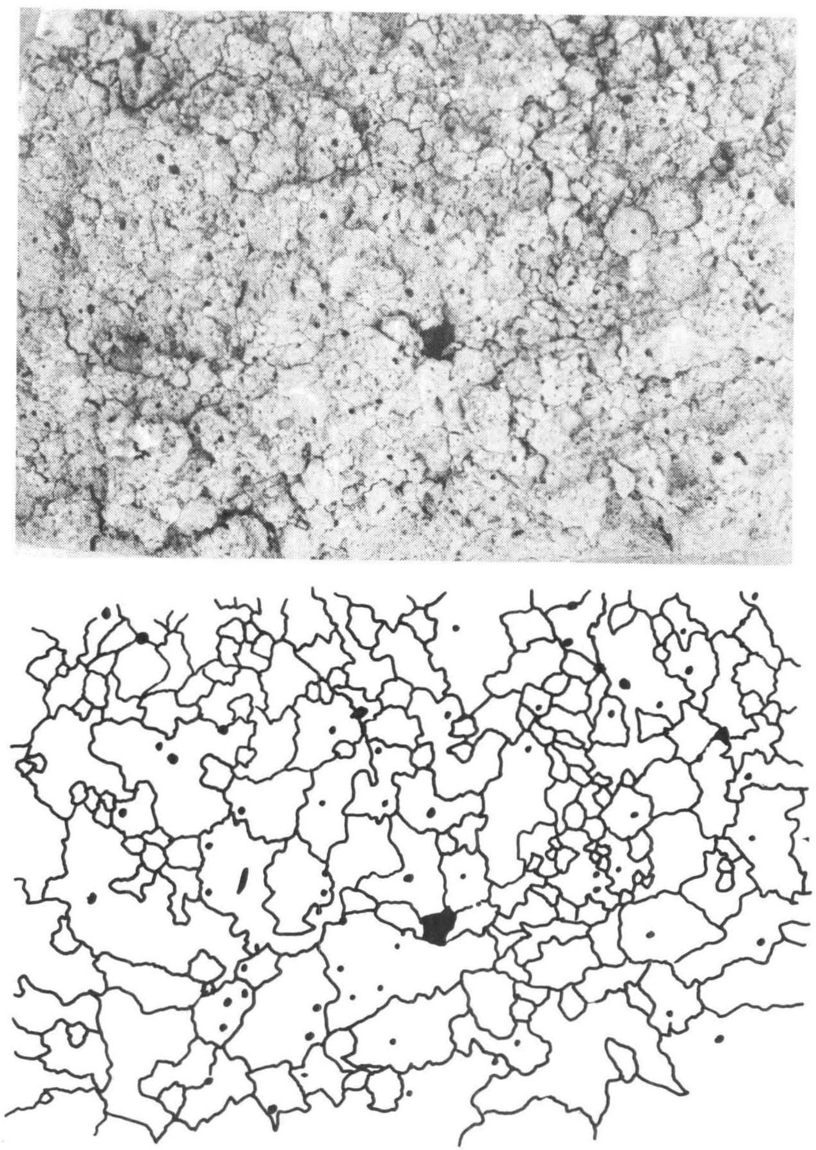


Tama silt loam(cultivated) A2 (20 cm).Structure: Weak medium platy and moderate very fine subangular blocky.
K: 11 cm/day B.D: 1.37 P.V: 47% Part.dens: 2.57.

Tama silt loam (virgin).A1 (20 cm).Structure: moderate very fine subangular blocky and strong fine granular.

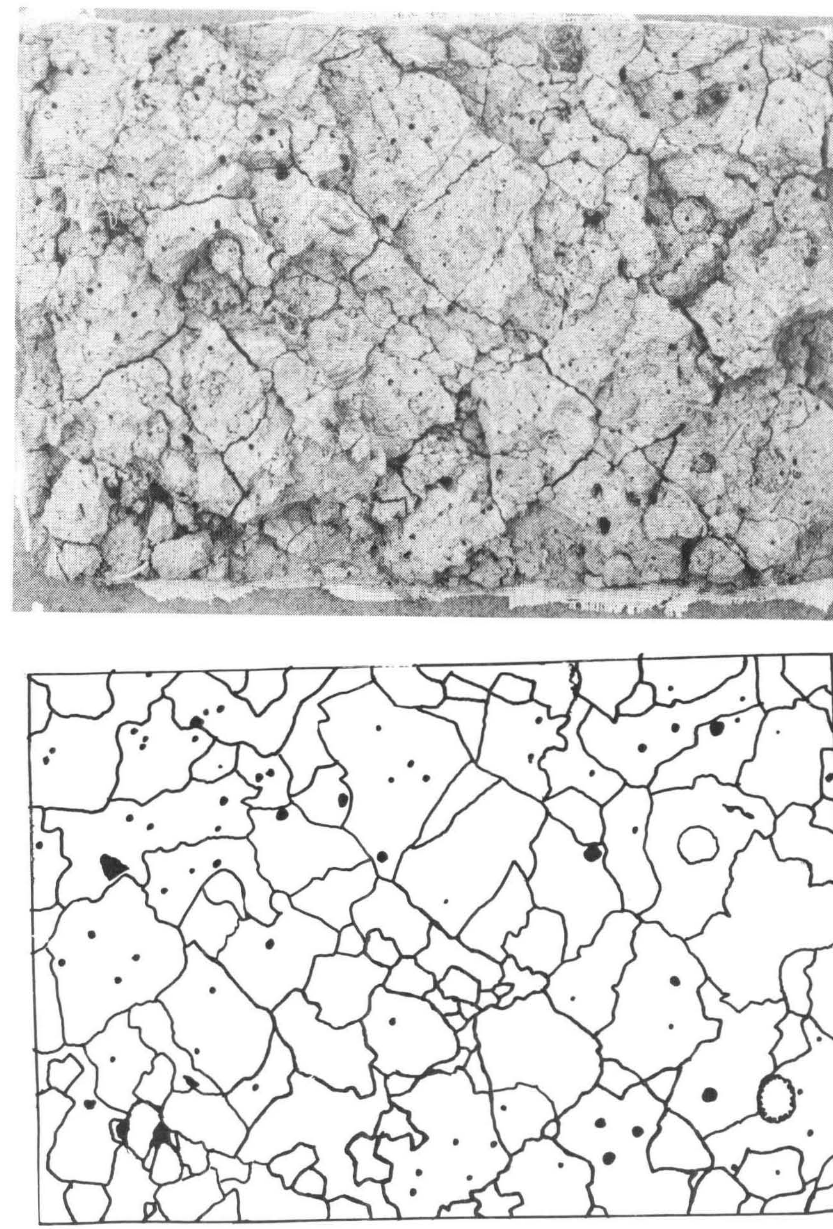
[X X X] : large animal burrow with strong fine granular structure

K: 160 cm/day.B.D: 1.22 P.V.:50% Part.dens.: 2.44



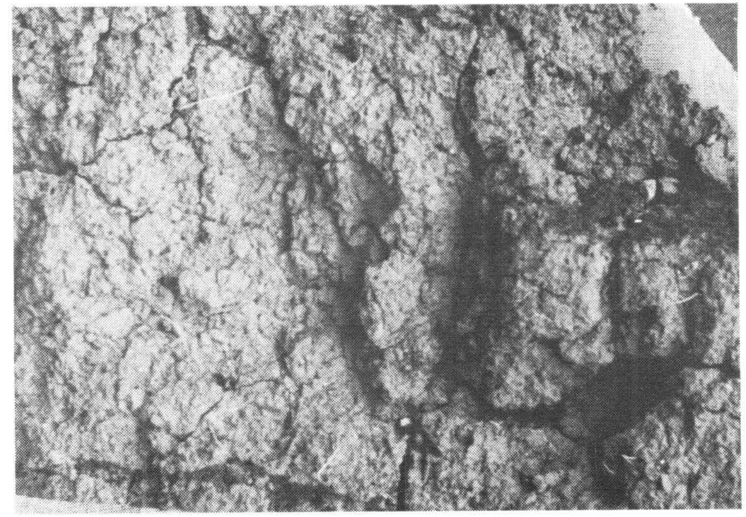
1CM

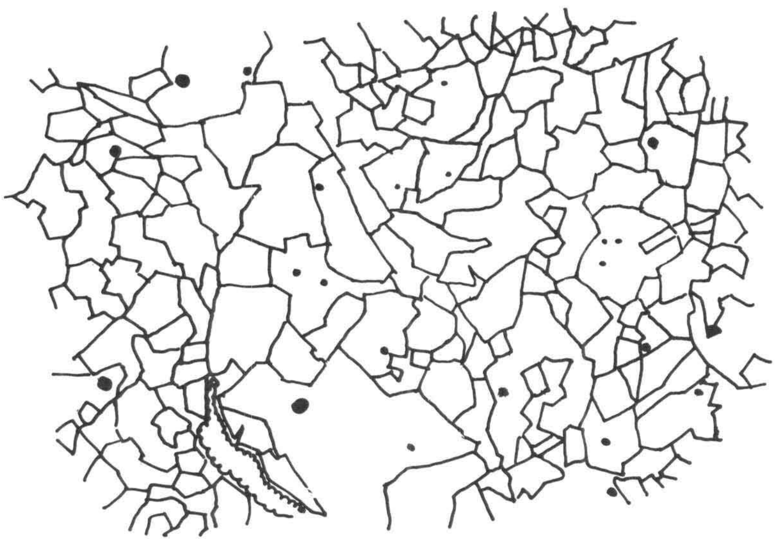
Tama silt loam (virgin).B2t (80cm).Structure: Moderate fine prismatic breaking into moderate fine subangular blocky.
K: 75 cm/day. B.D.: 1.26 P.V.: 51% Part.dens.: 2.55



Tama silt loam (cultivated) B31 (80cm).Structure: Moderate medium prismatic, breaking into moderate medium subangular blocky.
K: 22 cm/day. B.D.: 1.35. P.V.: 49% Part.dens.: 2.66.

1 CM



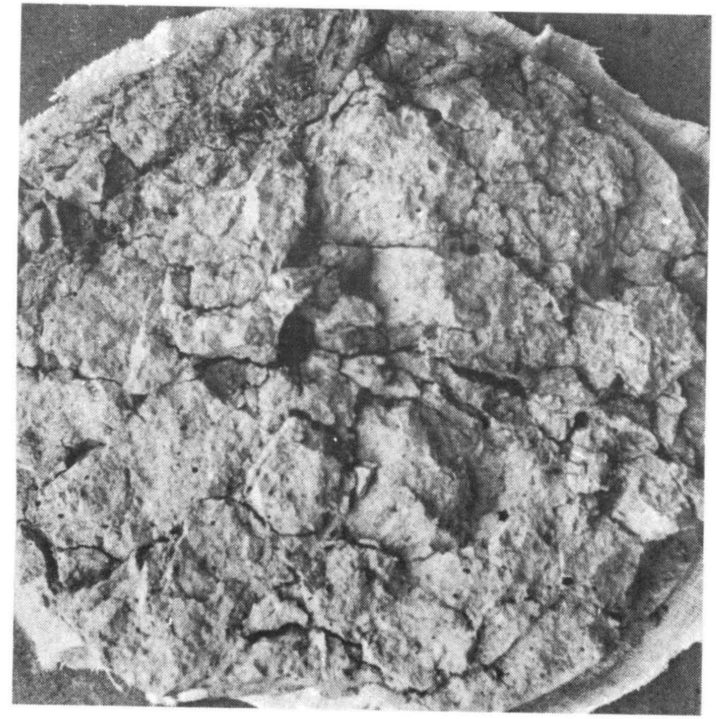


Oshkosh clay (cultivated) B1 (20 cm). Structure: Strong very coarse prismatic and moderate medium platy.

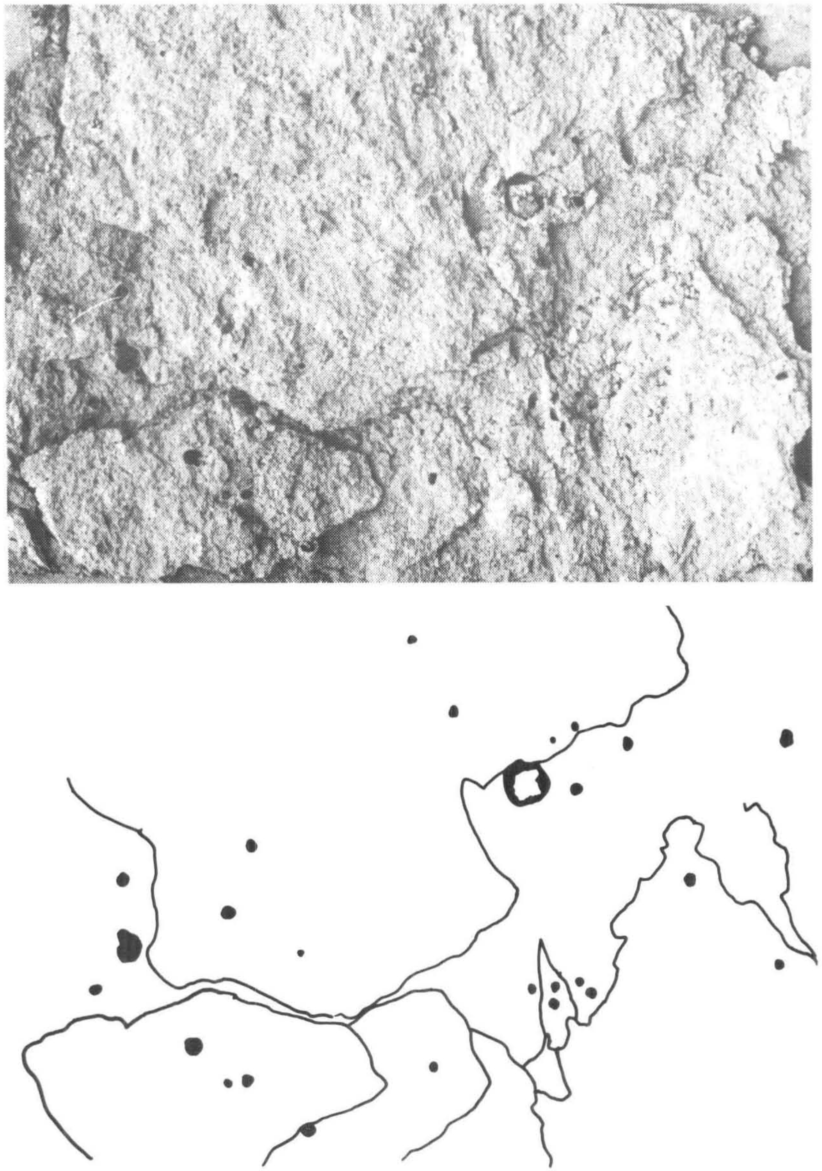
Oshkosh clay (cultivated) B21 (50 cm). Structure: Moderate medium prismatic, breaking into strong fine angular blocky.
K: 6 cm/day. B.D.: 1.43 P.V.: 43% Part.dens.: 2.62

[x x]: Faces of very coarse prisms (partially seen here in three dimensions) covered, and locally completely filled with thick cutans composed of topsoil material.

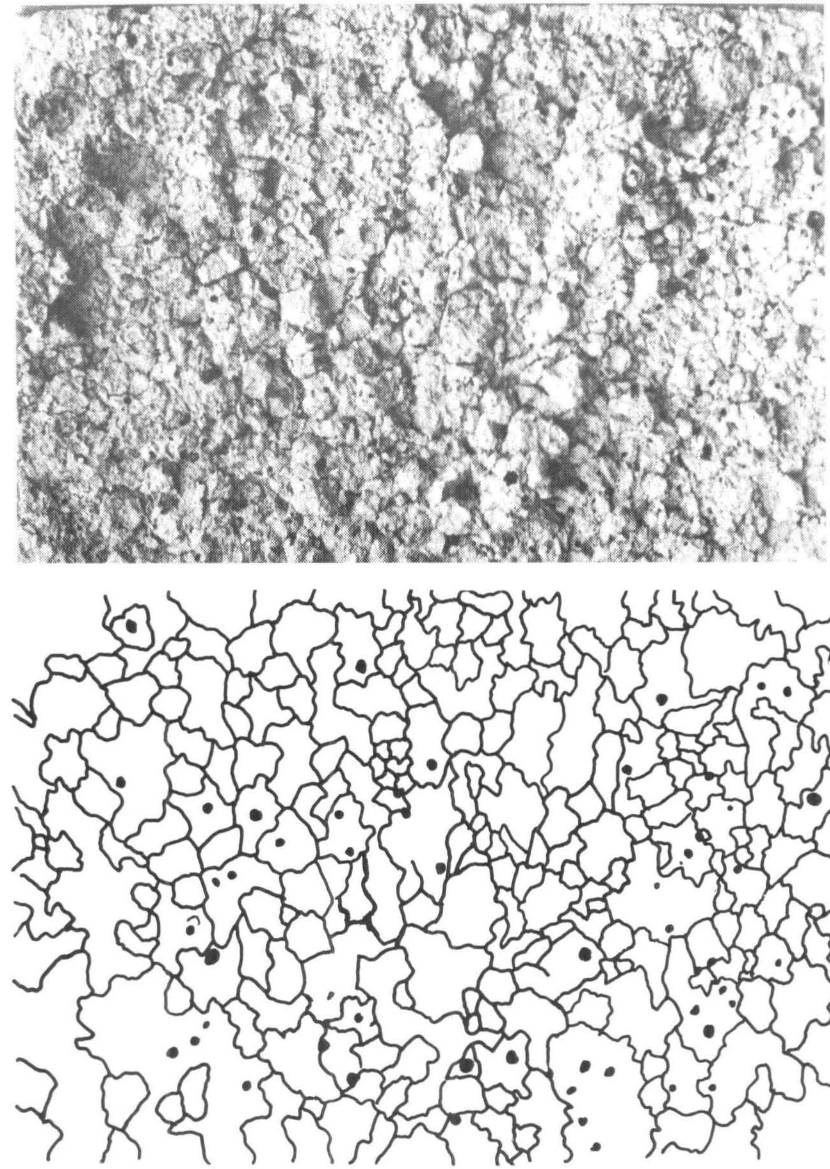
K: 0 cm/day in soil between the prism cracks. K : 10 cm/day through these cracks. B.D.: 1.36 P.V.: 49% Part.dens.: 2.69



Oshkosh clay (cultivated) B3 (80cm). Structure: Moderate MEDIUM prismatic breaking into strong medium angular blocky.
K: 5 cm/day. B.D.: 1.52 P.V.: 44% Part.dens.: 2.73.



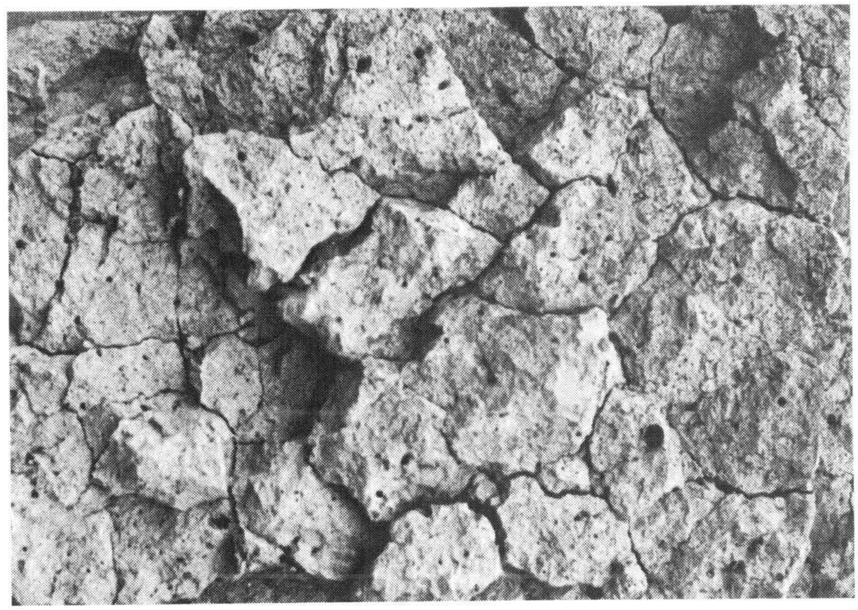
1 CM

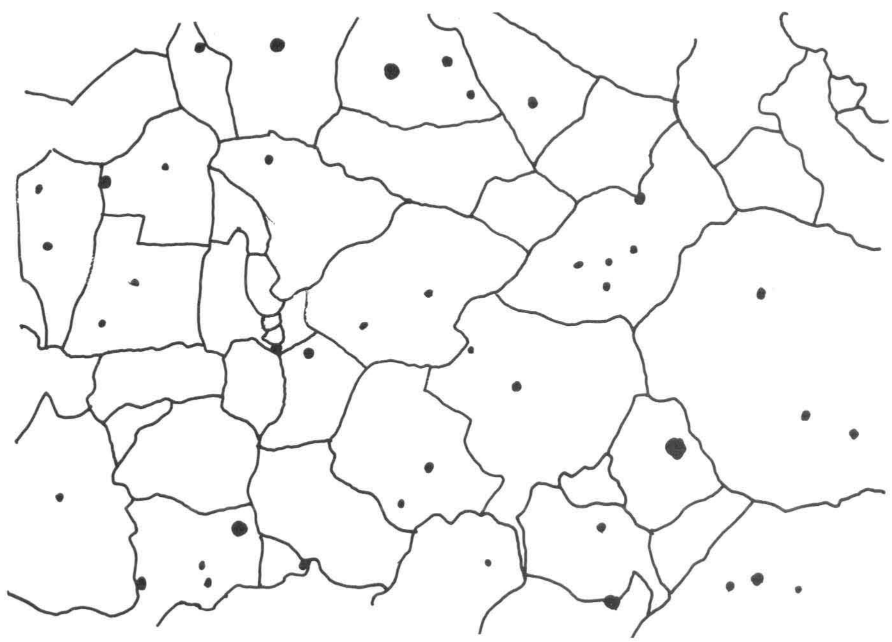


Plano silt loam (Mandt farm). Ap (15 cm). Structure: Apedal with dense clods.
K: 9 cm/day. B.D.: 1.42. P.V.: 44% Part.dens.: 2.51.

Plano silt loam (Mandt farm). B2t (50 cm). Structure: Weak medium prismatic breaking into moderate fine subangular blocky.
K: 22 cm/day. B.D.: 1.41 P.V.: 47% Part.dens: 2.66

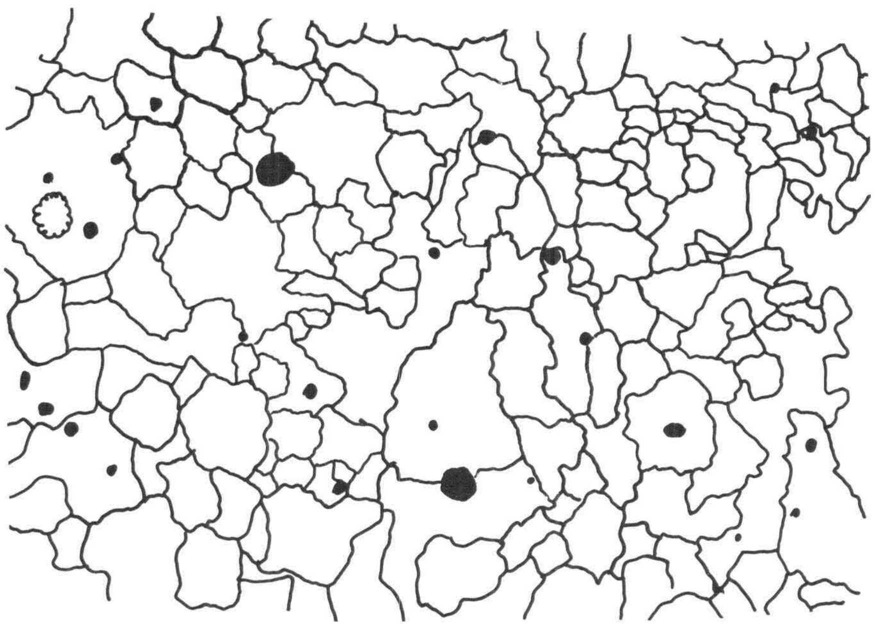
1 CM





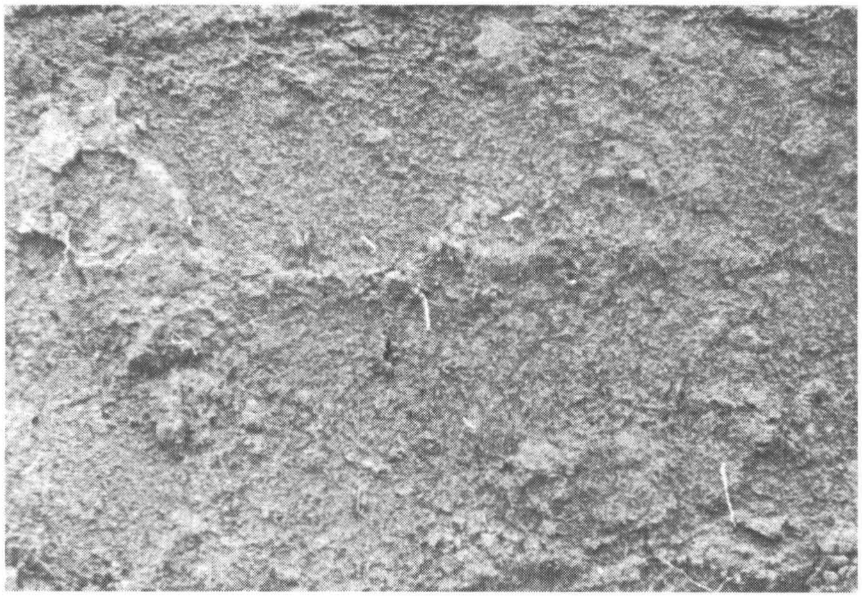
Plano silt loam (Mandt farm). B31 (80 cm). Structure: Moderate MEDIUM prismatic.
K: 7 cm/day. B.D.: 1.45 P.V.: 45%. Part.dens: 2.64

St.Charles-Bavaria silt loam (Charmany farm).Ap (20cm)
Structure: apedal with clods.
K: 11 cm/day. B.D.: 1.37 P.V.: 46% Part.dens.: 2.55.



St.Charles-Bavaria silt loam (Charmany farm).B21t (60cm)
Structure: Weak coarse prismatic breaking into strong medium subangular blocky.
K: 50 cm/day. B.D.: 1.42 P.V.: 45% Part.dens.: 2.58

St.Charles-Bavaria silt loam (Charmany farm).B3 (120cm)
Structure: Strong coarse prismatic.
K: 26 cm/day. B.D.: 1.53 P.V.: 40% Part.dens: 2.62.



Sparta loamy sand (Arena). B3 (80cm).Structure: Apedal, single grain. Basic fabric is probably granular.
K: 420 cm/day. B.D.: 1.48 P.V.: 45% Part.dens.: 2.68

1 CM

Sparta loamy sand (Arena). B21 (40 cm).Structure: Apedal, basic fabric probably intertextic.This causes the moist soil to break into coherent fragments.
K: 37 cm/day. B.D.: 1.54 P.V.: 42% Part.dens.: 2.65.

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STEADY INFILTRATION INTO CRUST-TOPPED PROFILES

D. HILLEL AND W. R. GARDNER
University of Wisconsin, Madison[1]

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Downward infiltration of water into a uniform soil profile ponded at the surface has been studied intensively, especially since the experimental work of Bodman and Colman (1) and the theoretical work of Philip (4). More recently, attention has been devoted to infiltration into a layered soil. Takagi (7) analyzed the steady-state downflow of water through a two-layer profile into a free water table beneath. Where the upper layer is less pervious than the lower, negative pressure (suction) can develop in the lower layer and remain at a constant value throughout a considerable depth-range. Takagi showed that this zone normally begins at the junction of the two layers. Hillel (3) examined steady infiltration into a soil overlain by a thin crust of low conductivity.

Steady-state conditions require that the flux through the crust (q_c) be equal to the flux through the subcrust "transmission zone" (q_u):

$$q_c = q_u$$

or
$$K_c\left(\frac{d\phi}{dz}\right)_c = K_u\left(\frac{d\phi}{dz}\right)_u \qquad (1)$$

where K_c, $(d\phi/dz)_c$, K_u $(\phi d/dz)_u$, refer to the hydraulic conductivity and hydraulic head gradient of the crust and underlying transmission zone, respectively. The gradient through the transmission zone tends to unity when steady infiltration is approached, as the suction gradient decreases with the increase in wetting depth, eventually leaving the gravitational gradient as the only effective driving force. In the absence of a suction head gradient below the crust, we obtain (with the soil surface as our reference level):

$$q = K_u(h_i) = K_c\frac{h_o + h_i + z_i}{z_i} \qquad (2)$$

where K_u (h_i) is the unsaturated hydraulic conductivity of the subcrust zone, a function of the suction head, h_i which develops in this zone, beginning just under the hydraulically impeding crust; h_o is the positive hydraulic head imposed on the surface by the ponded water; and z_i is the vertical thickness of the crust.

Where the ponding depth (h_o) is negligible and the crust itself is very thin and of low conductivity (e.g., where z_i is very small in relation to the suction h_i which forms at the subcrust interface), we can assume the approximation

$$q_u = q_o = K_c\frac{h_i}{z_i} \qquad (3)$$

The condition that the crust remains saturated even while its lower part will be under suction is that its critical air-entry (h_a) not be exceeded (i.e. $|h_i| < |h_a|$).

This together with the condition that the subcrust hydraulic head gradient approximates unity leads to the approximation:

$$\frac{K_u}{h_i} = \frac{K_c}{z_i} = \frac{1}{R_c} \qquad (4)$$

i.e., the ratio of the hydraulic conductivity of the underlying-soil transmission zone to its suction is approximately equal to the ratio of the crust's (saturated) hydraulic conductivity to its thickness. The latter ratio is the reciprocal of the hydraulic resistance per unit area of the crust (R_c).* Also:

$$q = K_u\ (h_i) = h_i/R_c \qquad (5)$$

Where the unsaturated conductivity of the underlying soil bears a known single-valued relation to the suction, it should be possible to

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* A distinction is made between the hydraulic resistance per unit area, defined as above, and the hydraulic resistivity, the latter being equal to the reciprocal of the conductivity.

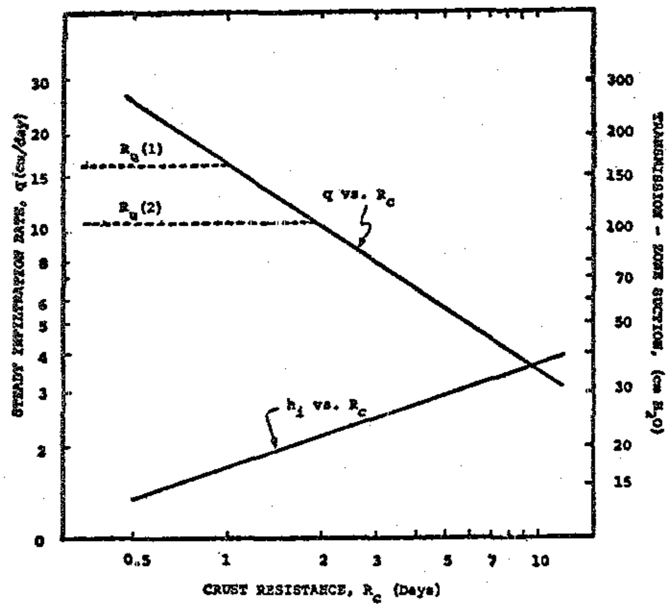

FIG. 1. Theoretical effect of crust resistance upon flux and subcrust suction during steady infiltration into crust-capped columns of a uniform soil with "n" = 2, "a" = 4.9 × 10^3. The broken lines (1) and (2) indicate the hypothetical effect of subcrust hydraulic resistance, R_u: R_u *(1)* < R_u *(2)*. The decreasing q vs. R_c curve applies only where the hydraulic conductance of the subcrust layers is not limiting.

calculate the steady infiltration rate and the suction in the subcrust zone on the basis of the measurable hydraulic resistance of the crust. Where the relation of matric suction to water content is also known, it should be possible to infer the subcrust water content during steady infiltration

Employing a K vs. h relationship of the type $K = a \mid h \mid^{-n}$ (where a and n are characteristic constants of the soil) the following is obtained:

$$q = (a)^{1/(n+1)}/(R_c)^{n/(n+1)} = B/(R_c)^{n/(n+1)} \quad (6)$$

$$h_i = (aR_c)^{1/(n+1)} = B(R_c)^{1/(n+1)} \quad (7)$$

where $B = a^{1/(n+1)}$ is a property of the subcrust soil. The theoretical consequences of equations (6) and (7) are illustrated in fig. 1. These equations indicate how the infiltration rate decreases and the subcrust suction increases with increasing hydraulic resistance of the crust. Gardner (2) has shown that the values of a and of n generally increase with *increasing coarseness, textural* as well as structural, of the soil. Sands may have n values of 4 or more, whereas clayey soils may have n values of about 2. Tillage may pulverise and loosen the soil, thus increasing n, while compaction may have the opposite effect.

Both the crust and the underlying soil are seen to affect the infiltration rate and suction profile, and the crust-capped soil is thus viewed as a self-adjusting system in which the physical properties of the crust and underlying soil interact in time to form a steady infiltration rate and moisture profile. In this steadily infiltrating profile, the subcrust suction which develops is such as to create a gradient through the crust and a conductivity in the subcrust zone which will result in an equal flux through both layers.

This paper describes an experimental test of the above theory.

EXPERIMENTAL

The relationships derived, and the assump*tions upon which they are based,* were tested experimentally in the following two ways:

(1) With models of varying crust hydraulic resistance and identical subcrust soil properties. For such conditions the theory predicts decreasing infiltration rate and increasing subcrust suction with increasing hydraulic resistance of the crust.

(2) With models of uniform crusts and varying subcrust properties. The theory predicts a

dependence of infiltration rate on the hydraulic properties of the subcrust layer, as characterized by its a and n values.

The infiltration tests were carried out with laboratory columns packed into 5 cm. diameter lucite tubes 150 cm. long. The soil was taken from the Gilat Experimental Farm in the Northern Negev of Israel and is a fine sandy loam of loessial origin. A mechanical packing device was employed to assure column uniformity.

In the first series of tests, uniform columns were capped with 10 mm.-thick stabilized surface layers of either aggregates (1–2 mm.) or crusts. These layers were stabilized with a synthetic soil conditioner applied in powder form at the rate of 0.5 per cent of the dry soil weight. The crusts were prepared in molds either by slaking the soil in water, or by puddling the soil mechanically with or without the addition of cement. Measurements were made of the hydraulic conductivities of these layers in specially constructed permeameters. The crusts were mounted in recessed lucite rings and sealed by pouring molten paraffin into the groove around the crust (to fix the crust in place and to prevent boundary flow along the lucite wall). The protruding crusts were then pressed into the soil columns, and their rings sealed to the column tubes by means of transparent adhesive tape. The method of mounting the crusts is illustrated in fig. 2.

To hasten the attainment of steady infiltration, the columns were pre-wetted to a depth of 60 cm. just prior to being capped with the crusts. The subcrust zone was thus nearly saturated at first. During the subsequent infiltration through the crusts the profiles were actually in a process of draining, so that the parameters "a" and "n", obtained by desorption, were properly applicable.

The infiltration trials were conducted by impounding a 5 mm. head of water over the crusts by means of an inverted buret. The infiltration runs were continued at least 24 hours until a constant rate was established and the subcrust hydraulic head gradient was about unity. This gradient was measured with pencil-size tensiometers located 2 and 12 cm. below the crust. Soil water content was determined repeatedly both gravimetrically (by sampling through side holes in the lucite tubes) and volumetrically (by means of a pre-calibrated gamma-ray scanner). In each case the subcrust-zone water content and steady infiltration rate were compared with the corresponding values predicted by use of Equations 6 and 7.

In the second series of tests, similar crusts (1 cm thick, uniformly puddled and stabilized with the soil conditioner) were placed over columns of different aggregate size ranges and different porosities

The aggregate classes were prepared in the following manner: The soil was dried, crushed

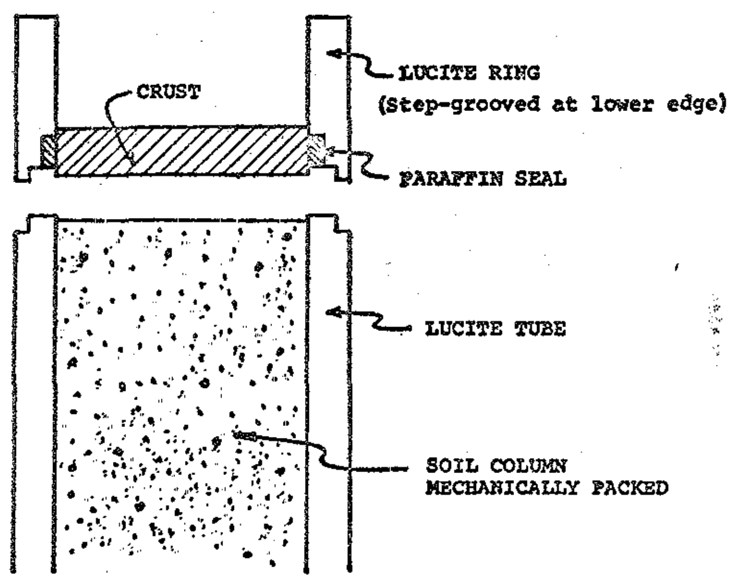

FIG. 2. Arrangement for mounting crusts over soil columns.

TABLE 1

Infiltration tests with similar columns of uniform Gilat loess under different crusts

	Toplayer type	Stable Aggregates	Slaked Crust	Puddled Crust	Puddled and Cemented Crust
Toplayer properties	Thickness, z_i (cm.)	1	1	1	1
	Porosity, P (%)	49	45	38	30
	Conductivity, K (cm./day)	22.1	0.7	0.3	0.1
	Resistance, R (days)	0.5	1.4	3.2	9.1
Sublayer properties	Porosity, P (%)	48	48	48	48
	"a" value	4.9×10^3	4.9×10^3	4.9×10^3	4.9×10^3
	"n" value	2	2	2	2
	Saturated conductivity (approx.) (cm./day)	16	16	16	16
Test results	Flux, q (cm./day)				
	Predicted		13	8	4
	Measured	16.8	13.4	9.5	5.0
	Subcrust suction, h_i (cm.)				
	Predicted		19	25	36
	Measured	5	64	88	102

and passed through a 0.125 mm. sieve. It was then mixed with 0.5 per cent of powdered VAMA soil conditioner ("krillium") and then was wetted in water-filled trays by soaking in cheese cloth. After 24 hours the saturated samples were drained and air-dried. The resulting "cakes" were then pulverized by hand and screened to separate the desired aggregate size classes. The resulting aggregates were found to be highly stable to water. The bulk density of the aggregates themselves was found to be 1.41 ± 0.03 grams/cm^3. These aggregate classes were packed mechanically into the lucite tubes, and the overall bulk densities obtained were 1.03 ± 0.04 grams/cm^3 for the 0.25–0.5 mm. class and 0.94 ± 0.04 grams/cm^3 for the 2–5 mm. class. The hydraulic conductivity vs. suction and water content relations (i.e., the "a" and "n" parameters) were determined by pressure plate outflow measurements according to the method of Rijtema (6).

Effect of Crust Resistance on Infiltration

The experimental results and their comparison with the predicted values of q and h_i are shown in table 1.

It is seen that the measured fluxes (i.e., steady infiltration rate) closely approximated the predicted values of all crust-capped columns. In the case of the aggregated toplayer, which was more porous than the sublayer and did not impede flow, the infiltration rate apparently was regulated by the properties of the sublayer alone.

Comparison of the predicted and measured subcrust suctions shows that the measured values, though higher, paralleled the predicted values and indicated the same trend, namely, an increase in subcrust suction with increasing crust resistance.

Effect of Sublayer Hydraulic Properties on Infiltration

The hydraulic conductivities of the aggregate classes used are shown in fig. 3 (K vs. ϕ). In the range of suctions obtained in the transmission zones during the infiltration through the capping crusts, the following approximate values of the "a" and "n" parameters were found:

0–2 mm. soil: $a = 4.9 \times 10^3$; $n = 2$
0.25–0.5 mm. aggregates: $a = 6.3 \times 10^6$; $n = 4.4$
2–5 mm. aggregates: $a = 2.5 \times 10^9$; $n = 8$

Table 2 shows the comparison between the theoretically predicted and experimentally measured flux and suction values obtained during the infiltration runs (with similar capping crusts).

Comparison of the predicted and measured values of steady infiltration rate (flux) and subcrust suction indicated agreement in trend. The actual discrepancies between these values may result from the errors in the assumed K vs. h relationship, which can be especially serious in the low suction range, where the $K = ah^{-n}$ equation may become inapplicable and where air entry and air entrapment phenomena may occur.

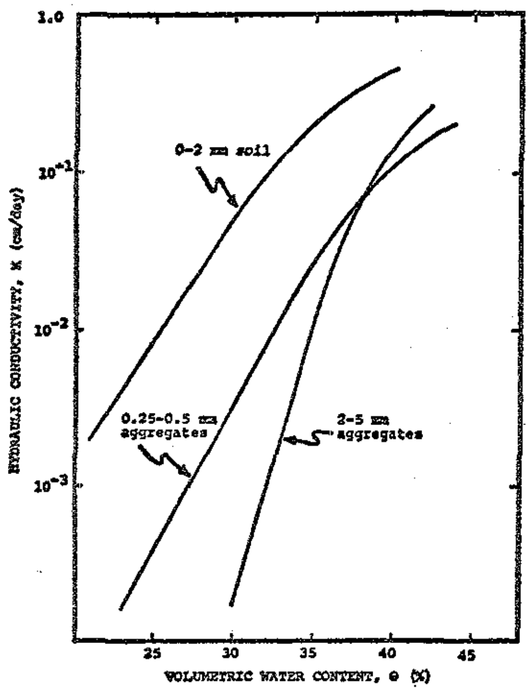

FIG. 3. Dependence of hydraulic conductivity upon water content of the experimental soils.

DISCUSSION

The principal finding derived from the experimental data is that both the fluxes and the moisture profiles during steady infiltration showed reasonable agreement with the theory, i.e., the experimental data paralleled the predicted values of flux and suction. Failure to achieve a more exact agreement is probably due in part to the difficulty in measuring the conductivity of the soil with sufficient precision. However, the agreement is sufficiently good to justify the use of Equation (6) to estimate the infiltration rate for a crusted soil. One cannot otherwise average the conductivity of the crust and the soil properly.

In this paper, the $K = a\,|\,h\,|^{-n}$ equation appeared to fit the data. This may be fortuitous, however. The relation of conductivity to suction, or to water content, may not always be such a simple one. Various equations have been proposed in the literature and could be used to derive comparable expressions for q. The expression used by the authors may also be formulated in the following way, which might have more general validity:

TABLE 2

Infiltration tests with different aggregate classes capped by similar crusts

Toplayer type		Puddled and cemented crust		
Crust properties	Thickness, z_i (cm.)	1	1	1
	Porosity, P (%)	29	29	28.3
	Conductivity, K (cm./day)	8.1×10^{-2}	7.9×10^{-2}	7.8×10^{-2}
	Resistance, R (days)	12.4	12.6	12.7
Sublayer properties	*Aggregate sizes, mm.*	0–2	0.25–0.5	2–5
	Porosity, P (%)	49.8	61.7	65.0
	"a" value	4.9×10^{3}	6.3×10^{5}	2.5×10^{9}
	"n" value	2	4.4	8
	Saturated conductivity (approx.) (cm./day)	16	22	30
Test results	Flux, q (cm./day)			
	Predicted	3.2	1.5	1.2
	Measured	6.1	2.1	2.0
	Subcrust suction, h_i (cm.)			
	Predicted	39	19	15
	Measured	50	50	26

$$K = K_s \left|\frac{h_a}{h}\right|^n; \quad \text{for } |h| > |h_a| \qquad (8)$$

where K is the unsaturated hydraulic conductivity, K_s the saturated conductivity, h the matric suction, h_a the air-entry suction, and n, a characteristic constants.

Stated in terms of Equation (*8*), Equation (*6*) becomes:

$$q = K_s^{1/(n+1)} \left(\frac{h_a}{R_c}\right)^{n/(n+1)} \qquad (9)$$

which can be rewritten as:

$$\frac{q}{K_s} = \left(\frac{h_a}{K_s R_c}\right)^{n/(n+1)} \qquad (10)$$

This indicates that the infiltration rate relative to the saturated hydraulic conductivity of the subcrust soil varies inversely (as a fractional power that is near unity) as the crust resistance and the saturated conductivity. This applies only when the suction which develops under the crust is sufficient to desaturate the soil. The exponential parameter n would tend to become less important as its value increases (as in a coarse soil), since $n/(n + 1)$ would tend more and more to approximate unity.

For the comparison of the infiltration rate into two different profiles, the following expression can be used:

$$\frac{q_1}{q_2} = \left(\frac{K_{s1}}{K_{s2}}\right)^{1/(n+1)} \left(\frac{h_{a1}}{h_{a2}} \frac{R_{c2}}{R_{c1}}\right)^{n/(n+1)} \qquad (11)$$

where subscripts 1 and 2 refer to the two profiles compared. Increasing soil coarseness, either textural or structural, would tend to increase with both K_s and n. Equation (*11*) shows that this might either increase or decrease q, depending on the magnitude of these parameters, as well as on the h_a and R_c values.

The findings of this paper may have practical applications particularly where it is desirable to decrease the soil infiltration rate artificially (e.g., in water harvesting schemes, or in earth-lined storage reservoirs). Under such conditions, the approach presented can aid in determining the desirable crust and subcrust soil properties which can be induced to best advantage.

SUMMARY

A theory is presented which allows the prediction of the steady infiltration rate and of the suction profile of crust capped profiles from knowledge of the hydraulic resistance of the crust and of the unsaturated conductivity characteristics of the subcrust soil. The hydraulic properties of both layers are shown to affect infiltration, and the crust-capped soil is thus viewed as a self-adjusting system in which the properties of the two layers interact in time to form a steady infiltration rate and moisture profile. In this steadily infiltrating profile, the subcrust suction which develops is such as to create a gradient through the crust and a conductivity in the subcrust zone which will result in an equal flux through both layers. The results obtained from laboratory column experiments indicated reasonable agreement with the theory.

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