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English for Specific Purposes and the Use of a Specialist-Informant: Reading Soil Science Journal Articles.

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ABSTRACT

The teaching of highly specialized prose is often troublesome to a language teacher who is not trained in the subject-matter. To approach this pegagogical problem, it has been suggested that teachers should explore the feasibility of using a subject-matter specialist to assist them in reading this type of writing.

Following that suggestion, the present study attempts to respond to a particular situation observed with the graduate students in the area of Soil Science at Universidade Federal do Parana. It examines four journal articles in the field of Soil Science in the light of (i) what the language teacher needs to know in order to understand the pieces, and (ii) what the subject-matter specialist brings to the successful reading of these materials.

The results obtained reveal that relevant and valuable information can be gained and applied by the language teacher through this methodology. In addition to that, it stands as a useful means of providing the teacher with a certain confidence in the target subject-matter, a step which can result in more meaningful instruction.

ABSTRACT

O ensino de textos técnicos altamente especializados é, muitas vezes, problemático para o professor não versado na área técnica. Tendo em vista esta dificuldade, pesquisadores tem sugerido que o professor utilize informantes especialistas na área técnica afim de assisti-lo na compreensão destes textos.

O presente estudo se propõe a seguir esta sugestão, na tentativa de abordar uma situação vivenciada pelos mestrandos da área de Ciência do Solo na Universidade Federal do Paraná. Quatro artigos científicos na área de Ciência do Solo são estudados com base (i) no conhecimento que o professor de Inglês precisa adquirir para entender estes artigos e (ii) no tipo de informação que o informante especialista na área recorre na busca de uma compreensão bem sucedida dos artigos.

Os resultados obtidos revelam que uma quantidade significativa de informação pertinente à área técnica podem ser obtidos e aplicados, se necessário, na sala de aula. Além disso, constata -se que a metodologia empregada pode funcionar para o professor como um fator estimulador de motivação e confiança em relação à área técnica - aspectos altamente desejáveis na criação de um ambiente de ensino positivo.

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I. INTRODUCTION

1.1. The setting

The development of science and the use of English as its principal language of information dissemination have vastly increased the number of university science students attending English as a Second Language (ESL) and English as a Foreign Language (EFL) programs in institutions of higher education around the world. In response to their needs there has been a significant demand for programs and research in English for Specific Purposes (ESP).

ESP programs, to be relevant to the needs of their clientele, must be sustained by effective research. In attempting to incorporate research into instruction, recent studies have advanced two important considerations. First, the specific needs of a specific group of students should be determined. Tarone (1982) rightfully argued that

> In order to design the most useful sort of syllabus for "Engineering English" or "English for Business" we need to determine exactly what sorts of communicative demands will be made on our students in Engineering and Business contexts. We cannot rely on our intuitions ... for this purpose; rather, we need to go into the contexts where our students will be using their English, examine the materials they will need to read ... interview their teachers and employers, and so on (p. i).

Second, granted the knowledge of the specific situation they will be facing, ESP teachers must still overcome the difficulties that highly specialized technical prose often presents to them:

> What are we to do as ESL teachers in the normal situation where we ourselves just do not understand the English language scientific textbooks and professional articles which our students are required to grapple with? (Selinker, 1979, p. 190)

To address this problem, it has been suggested that ESP instructors should carefully examine the possibility of using a subject-matter specialist to help them understand the sorts of technical materials aforedescribed (Selinker,1979, Tarone et al., 1981; Huckin and Olsen, 1984).

1.2. The research project

1.2.1. Rationale

A significant portion of the reading requirements for the courses related to the sub-area of Soil Physics leading to the Master's degree in Soil Science at Universidade Federal do Parana, in Brazil, comes from professional journal articles published in American and British journals.

To date, ESP instruction, available through the Department of Modern Foreign Languages (DELEM) of that university, for these graduate students, has relied on (i) a few written pieces pertaining to different genres (chapters from textbooks and journal articles, for instance) suggested by the faculty of the Department of Soil Science, and (ii) on the ESP teacher's intuitions as to which selections will be used in the classroom, and how the students will accomplish the task of reading them, granted that (a) their knowledge of English does not exceed, with a few exceptions, four semesters of general English study at the secondary school level, and (b) the instructor and the students will meet for two-hour sessions, twice a week during one school semester (a total of sixty hours).

This study was conducted in response to the situation aforedescribed. Its purpose is twofold: one is to identify the nature of the difficulties an ESP instructor faces in her effort to read highly specialized material - in this case, journal articles - in the sub-area of Soil Physics, and the other is to use expert advice from a specialist-informant in that sub-area (i) to assist the ESP teacher in perceiving the complexities commonly found in the writing of Soil Science journal articles, and (ii) to provide some insight as to the type of information that the specialist-informant brings to the reading process of journal articles in that area.

1.2.2. The journal article

A journal article can be broadly defined as a type of scientific writing, based on a single investigation, whose purpose is to contribute to the progress of science and technology (Peterson, 1961).

Morris (1966) identifies two basic types of scientific paper published in journals: the theoretical type, and the experimental research paper which is designed to test a hypothesis or theory.

As Huckin and Olsen (1983) observe, this type of written communication aims at a narrow audience, that is, specialists in a particular field "who share assumptions, knowledge, and backgrounds and who have the need and interest to read carefully" (p. 275). This implied expertise in a particular subject area is often the source of difficulty for the graduate student who is still in the process of becoming an expert, not to mention the plight of the altogether inexperienced ESP teacher.

The organization of articles may vary somewhat in style depending on to which journal they are submitted. Of particular concern to this study are two major publications in the field of Soil Science. They are the Journal of Soil Science, published in England, and the Soil Science Society of America Journal, published in the United States.

In its "Notice to Contributors," the Journal of Soil Science makes some brief recommendations as to the expected format of its papers (see appendix 2a). Aside from this, it simply suggests that authors should follow the style of presentation used in recent numbers of the journal.

The Soil Science Society of America Journal, on the other hand, is far more rigid in its instructions on the organization and format of its articles. Manuscripts submitted for publication must be prepared in accordance with a series of guidelines dictated by the Publications Handbook and Style Manual (1984) published by the American Society of Agronomy, the Crop Science Society of America, and the Soil Science Society of America (see appendix 2b).

Given this perspective, researchers have stressed the need for direct teaching of the organization and rhetorical structure of journal articles (Selinker et al., 1976; Swales, 1981). It might be inferred from this concern that a knowledge of the structure of journal articles aids the comprehension of such texts.

From this point, the investigation proceeds to an examination of some recent developments in ESP research on scientific writing and its pedagogical applications (section II), followed by a description of the research methodology (section III). Section IV accounts for the results obtained from the application of methodology, and, finally, section V presents the conclusions.

II. REVIEW OF LITERATURE

Section II is a *general overview of the different* ESP researchers' have perceived and experienced students' difficulties when dealing with the reading of scientific prose. It departs from an account of how intuitively ESP instructors used to decide what to teach in the classroom, focusing, further, on more recent trends which have been concerned with the need for analysis of the different types of scientific prose students may have to read, prior to the actual teaching of these types.

2.1. Limitations and potentialities of ESP research and instruction

The first attempts at teaching scientific prose were much a result of the teacher's intuitions as to what this type of writing consisted of. Cohen et al. (1979) observed that traditional language instruction dealt with the teaching of scientific prose solely from the perspective that a knowledge of technical terminology, via a glossary, would suffice. The authors maintained that such an approach would not guarantee a successful reading of a scientific piece of writing. In their experience they have noted that even students who have an adequate command of the technical terminology in their academic fields experience so much difficulty and frustration in the reading process that they resort to native language summaries or books on the same subject, or simply do not read the material at all.

Similar difficulties have been reported when language instruction has resorted to the structural analysis of isolated sentences. Students cannot be assured that that practice alone will lead them to read and comprehend passages of continuous prose (Mage, 1981). The problem with this procedure is that language structure represents only part of the competence a student needs to acquire in order to deal with written passages as a whole.

Much of the difficulty students experience in reading scientific prose has been attributed to the rhetoric or organization of information in different genres, for example, introductory textbooks, journal articles, etc. It has been argued that if students should be expected to comprehend a scientific piece of writing in full, they should be taught to recognize rhetorical functions and their relationship to grammatical items (Lackstrom, 1977, Widdowson, 1979, Selinker, 1979). These rhetorical-grammatical relationships appear to be the result of certain assumptions or presuppositions writers of scientific pieces make regarding the readers of such pieces. These assumptions concern the kind and amounts of grammatical-rhetorical information that they assume the readers share with them. The authors aforementioned contended that such presupposed information can be expected to be shared by students who are native speakers of English. The non-native learners, on the other hand, cannot always bring more than a very limited amount of presupposed information to the reading of scientific discourse.They need, therefore, specific training to comprehend those relationships.

Research carried out by the above authors indicated that the rhetorical functions most affected by grammar are those which the writers choose more frequently to transmit the scientific or technical information of a piece of discourse. These are (1) description, (2) instructions, and (3) "the rhetoric of background information", an area which is found in sections of many types of scientific writing (articles, books, reports, dissertations, theses, etc) in which the writers report on the work of others.

The grammatical elements most often associated with the above functions are (1) passive-stative distinctions in the rhetoric of description and of instructions; (2) modal use in the rhetoric of instructions; (3) non-standard use (and non-use) of the definite article in the rhetoric of description and instructions, and (4) tense choice in the rhetoric of description and of background information.

Relying on a different perspective, Walsh (1982) suggested that successful reading for detailed comprehension is directly related to how well students are able to manage three closely related dimensions within a scientific text. These dimensions are the conceptual, the rhetorical and the linguistic.

The conceptual level includes the assumptions made by the writer of scientific texts concerning the conceptual knowledge that the reader brings to the text. These assumptions affect the way in which the knowledge is presented and the language employed in that presentation. Hence, this level can be specially troublesome to students who need to read journal articles. This type of technical communication, as it was demonstrated in item 1.2.2 of the the Introduction, addresses a problem or issue to an audience who possesses a high level of competence in the subject advanced. Not many students, even at the graduate level, can be expected to share such level of competence.

The rhetorical level encompasses the process a writer uses to produce a desired piece of text. This process is basically one of choosing and organizing information for a specific set of purposes and a specific set of readers. The organization and the presentation of such information - facts and hypotheses - are governed by the scientific method in which the following steps are featured (Lackstrom, 1977):

1. Finding a problem;
2. Hypothesizing a solution;
3. Deducing the consequences of the hypothesis;
4. Testing the hypothesis against its logical consequences;
5. Observing the results;
6. Reaching a conclusion concerning the validity of the hypothesis.

In scientific writing, particularly in journal articles, the method manifests itself in the outline of formal scientific reports, as follows:

I. Introduction
II. The Experiment
    A. Apparatus
    B. Procedures
III. Results
IV. Discussion

The Introduction bears the statement of the problem along with the hypothesis and the consequences of that hypothesis. The description of the Experiment renders the test of the hypothesis against its consequences followed by a statement of the observed results. The Discussion section presents the conclusions concerning the validity of the hypothesis along with any practical or theoretical consequences that result from that validity. Lackstrom further suggested that a developed competence in the rhetoric of scientific writing "can ease the burden of comprehension of EST passages" (p.60).

Louis Trimble and his colleagues have also studied the rhetorical organization of scientific texts. They have formulated a model of description, called the "EST rhetorical process chart" in which the total discourse is analyzed in terms of four rhetorical levels (A, B, C and D). Rather than focusing on isolated items of information, the chart aims at examining larger discourse units in which these items are found. From examinations of paragraph development, the model was proposed as follows:

EST RHETORICAL PROCESS CHART*

LEVEL DESCRIPTION OF LEVEL

A The Objectives of the Total Discourse

EXAMPLES:
1. Detailing an experiment
2. Making a recommendation
3. Discussing experimental methodology
4. Presenting new hypotheses or theories
5. Presenting a "survey article"
6. Presenting a "descriptive catalog"
7. Presenting repair, installation, maintenance, and operation information in a manual.

B The General Rhetorical Functions Employed to Develop the Objectives of Level A

EXAMPLES:
1. Stating purpose
2. Reporting past research
3. Discussing theory
4. Stating the problem
5. Reporting results
6. Reporting conclusions
7. Justifying experimental procedures
8. Presenting information on apparatus: description
9. Presenting information on apparatus: operation
10. Presenting information on experimental procedures
11. Referencing an illustration
12. Relating an illustration to the discussion
13. Presenting information on data gathering in an illustration

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C The Specific Rhetorical Functions Employed to Develop the General Functions of Level B

EXAMPLES:
1. Definition
2. Reference to known definitional information
3. Classification
4. Reference to known classificational information
5. Description: physical and function
6. Description: process
7. Instructions
8. Information transfer

D The Rhetorical Techniques that Provide Relationships Within and Between the Units of Level C

EXAMPLES:
1. Time order
2. Space order
3. Causality
4. Result
5. Comparison
6. Contrast
7. Analogy
8. Exemplification
9. Conditionality

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*This chart is discussed in Lackstrom, Selinker and Trimble, 1973; in Selinker, Todd-Trimble and Trimble, 1976; and in Trimble, 1977.

Level A gives the purpose of the total discourse which is usually found in the introductory section of a scientific piece. Level B consists of the major portions of a text which together comprise the total discourse. Sections headings and sub-headings are to be found in this level. According to the authors, the rhetorical process is best seen operating at levels C and D. Level D consists of one or more rhetorical techniques a writer chooses or may be required to use as the most functional for presenting the framework into which the items of Level C fit or the most functional for showing the relationships between these items.

Selinker et al. (1978) have used this model in teaching ESP students, and have found that making the students aware of the development of a text first retards their reading. As they grasp the fundamentals of the process, however, "they come to read more fluently and at the same time with a firmer understanding of the function of each part of the text than before" (p. 319).

Finally, the linguistic level can be described in terms of grammar and vocabulary.

Grammatical choice has been investigated in conjunction with rhetorical functions. Several grammatical elements have been found to cause difficulty to ESP students. Some of the most recurrent in ESP research have been (i) reference or anaphora, (ii) connectives and transitional phrases, (iii) verb tense, (iv) modal verbs, and (v) the passive versus the active voice.

Tyma (1977) hypothesized that if a student could not understand anaphoric references such as it/they and deictics; this, those; demonstrative + adjective + synonym such as these three factors, the student would not be able to understand the text in which they occurred very well. Also with regard to reference, Cohen et al. (1979) found that ESP students had difficulty in perceiving that two or more terms referred to the same item, a phenomenon called "contextual paraphrase". In failing to perceive contextual paraphrase, students were probably storing and retrieving lexical items separately "without realizing that they could be equated in meaning" (p. 561).

Connectives and transitional phrases, such as however, therefore, on the other hand, even though, are, like anaphoric devices, syntactic markers of cohesion. Cohen et al. (1979) observed in their study that ESP students failed to respond to the presence of these phrases in different passages. Some connectives, such as thus, they state, were unknown to the students and/or ignored by them. On a three-paragraph reading, the ESP students apparently missed the cross-paragraph transitions whereas the native speakers' "responses suggest that these words played a significant role in their understandings of the passage" (p. 558). They warn, however, that encouraging the student to look for overt markers may make them dependent on the syntactic devices resulting in their failure to recognize implicit relationships that may exist between sentences.

Verb tense in scientific writing has also been a focal point in ESP research. Of the twelve traditional verb tenses in English, only three are used with significant frequency in scientific writing: the simple present, the simple past and the present perfect. The simple present is basically used to express "timeless" generalizations, for example, "Water boils at 100° C." In contrast to the simple present, the simple past tense specifies a particular event or condition which occurred or existed at some time in the past but which no longer occurs or exists. The present perfect, on the other hand, is used to report on actions that were carried out in the past but are still producing effects in the present time. Aside from these more elementary considerations, major tense distinctions have recently been examined in relation to the rhetorical function of "reporting past research." Lackstrom et al. (1973) have reported that

> Detailed analysis has shown that the past tense is used when the past research does not bear directly - in terms of importance - on the work described in the report. In contrast, the present perfect tense is used when the past research is directly related - in terms

> of importance - to the work described in the report (p. 133).

In an attempt to investigate the extent of application of these claims to different types of scientific literature, Oster (1981) examined two journal articles in Chemical Engineering. Her conclusions are

> (1) The present tense is used (i) when it refers to the quantitative results of past literature that are supportive of or nonrelevant to some aspect of the work described in the article, and (ii) to refer to past literature, rather than to discuss it. (2) The present perfect is used (i) to indicate the continued discussion of some of the information in the sentence in which the present perfect tense occurs as a main tense, and (ii) to claim generality about past literature. (3) The past tense is used (i) to claim nongenerality about past literature, and (ii) when it refers to quantitative results of past literature that are nonsupportive of some aspects of the work described in the technical article (p. 77).

This perspective allows Oster to further suggest that verb tenses also function as cohesive devices in a text:

> When the present perfect tense is used ... the reader would expect some sort of continued discussion ... When the past tense is used ... the reader would not expect some sort of continued discussion ... It appears, then, that the choice of verb tense reflects technical writing strategies for including information about past literature in a report, and for signaling to the reader that the information will or will not be pursued in the subsequent discourse (p. 87).

Swales (1981) also investigated verb tense in reporting past literature. Unlike Oster who attempted to correlate tense with a set of semantic notions, Swales studied the choice of tense in relation to different structural possibilities from which an author may choose when crediting past researchers. After investigating sixteen introductory sections to journal articles from the field of Biology and Medicine, he noted three structural possibilities which can be exemplified as follows:

Type A: Swales (1980) suggested that the passive voice is used to focus attention on the grammatical subject.

Type B: It has been suggested (Swales, 1980) that the passive voice is used to focus attention on the grammatical subject.

Type C: The passive voice is used to focus attention on the grammatical subject (Swales, 1980).

Type A shows "strong author- orientation" and can be correlated with the past tense. Type B which contains a reporting verb, like suggest, showing "weak author-orientation" (author is referred parenthetically) can be correlated with the present perfect. Finally, type C which shows "subject- orientation", no reporting verb and the author is referred parenthetically, are normally in the present tense.

Research of this sort can have important pedagogical applications. Oster's findings, for instance, do not contradict the descriptions of the functions of verb forms generally found in "general English" grammars. They do, however, add new dimensions that could be supplied in addition to the grammatical interpretation so as to make the explanations more relevant to the students. For example, to say that the present perfect signals a "continued discussion" is another, less abstract, way of saying that the present perfect expresses an action begun in the past that has relevance to the present.

In other studies focusing on the verb phrase, modal verbs have been the target of ESP research. Commonly found in scientific writing, especially in journal articles, modal verbs belong to a class of words in English which present semantic and structural difficulties to students (Lackstrom, 1978; Huckin and Olsen, 1983; Trimble, 1985).

Huckin and Olsen (1983) discussed these verbs in three groups arranged according to a scale of degrees of "obligation," "probability," and "ability."

In their scale of "obligation" (Figure 1), the most frequently used modals in scientific writing are *must*, *should*, *can*, and *may*, particularly with statements describing procedural correctness. The authors add that the reason for positioning *can*, *may*, and *could* near the middle of the scale is "that the action of the main verb is neither required nor prohibited, but optional" (p. 430).

Figure 1 Modals indicating degrees of obligation

MUST, have to [informal] shall* SHOULD	REQUIRED ↑
CAN, MAY, could	
do not have to [informal]	
SHOULD NOT CANNOT, MAY NOT, could not MUST NOT	↓ PROHIBITED

*As used in legal documents (contracts,building codes, etc.)

In the scale of "probability" (Figure 2), *may*, *will*, and *would* are the most frequently used verbs in scientific writing, especially in the drawing of hypothetical statements, and throughout the sections of a scientific report.

Figure 2 Modals indicating degrees of probability

LOGICALLY NECESSARY ↑	MUST, have to [informal] WILL, WOULD SHOULD
	is, (are, will) probably, it is probable (likely) that, is(are) likely to
	MAY, MIGHT, COULD,can, possibly (adverb), it is possible that (for)
	MAY NOT, MIGHT NOT
	is(are, will) probably not, is (are) unlikely to
↓ LOGICALLY IMPOSSIBLE	SHOULD NOT WILL NOT, WOULD NOT, CANNOT, COULD NOT, MUST NOT, It is impossible for

As to "ability" (Figure 3), the dominant modal is can, followed by "the more hypothetical could" (p. 437).

Figure 3 Modals indicating degrees of ability

CAPABLE	CAN, COULD, (is,was,were) able to
↑	would be able to
	should be able to
	may (might) be able to
	may (might) not be able to
↓	would not be able to
INCAPABLE	CANNOT, could not, is (are,was,were) not able to

Trimble (1985) noted that the difficulty which students may experience with modals lies in what he called "meaning shift," i.e., the commonly taught meanings for some modals are not appropriate to the discourse context. He observed that the modals should, may and can, in the rhetoric of instructions, often have the force of must.

Studies of the frequency of the passive voice versus the active voice in scientific prose have resulted in contradictory claims. Herbert (1965) argued that "the majority of sentences in technical writing are in the passive form because the technical writer wants to be objective and impersonal" (p. 28). In agreement with this view, Swales (1980) advanced specific reasons for this preference:

> The first reason for this is that the passive sentences do not mention people. For a scientist many references to people are unnecessary and confusing...
> A second reason ... is that the subject is a very important part of the sentence. (Remember 'fronting' and how scientists often put a great deal of information into the subject.)...
> A third reason ... is that passive sentences may be a little shorter (pp. 40-41).

More recent studies, however, have suggested that the generalization concerning the prevalence of the passive form should be approached with caution. Focusing on a single discipline, Tarone et al. (1981) and Wingard (1981) disputed that generalization by observing that the active voice occurred with greater frequency in astrophysical journal articles and in medical texts. Given these findings, the editorial comment made in reference to Wingard's article seems appropriate:

> The possibility that grammatical structures may occur with varying frequency from text to text, even within a single field, should make researchers cautious about making sweeping generalizations about "the grammar of EST" (p. 64).

Studies on the lexis of scientific writing have focused on three areas: (i) specialized scientific vocabulary, (ii) "sub-technical" vocabulary, and (iii) noun compounds (Walsh, 1982; Trimble, 1985).

In any examination of the vocabulary of a scientific piece of writing for instructional purposes, the specialist vocabulary seems to deserve special attention. Gaining access to this specialized vocabulary may be particularly troublesome for the ESP teacher unless he/she decides to approach it through a specialist informant (Selinker, 1979) or team-teaching (Johns and Dudley-Evans, 1985). On the other hand, Trimble (1985) argued that ESP teachers need not devote special attention to this body of words as it is difficult for

> a teacher not trained in science to 'teach' technical vocabulary to students who have already learned or are learning this highly specialized lexis in their subject-matter courses (p. 128).

According to this author, instruction should concentrate on the other two lexical areas already mentioned: sub-technical vocabulary and noun compounds.

"Sub-technical" vocabulary, a term proposed by Cowan (1974), can be defined as "context independent words which occur with high frequency across disciplines" (p. 391). These words are not exclusive in use or application as the specialist words and can be found in more general contexts. To this group of words, Trimble added "common words that occur with special meanings in specific scientific or technical fields" (p. 129). The term base is one of the several examples given by this author to illustrate this point. Following are the specific meanings the term acquires when it is used in different fields:

> Botany: "The end of a plant member nearest to the point of attachment to another member, usually of a different type."
> Chemistry: "A substance which tends to gain a proton."
> "A substance which reacts with acids to form salts."

> Electronics: "Part of a valve [US 'tube'] where the pins that fit into holes in another electronic part are located. "The middle region of a transistor."
> Navigation: "In a navigation chain, the line which joins two of the stations." (p. 130)

Regarding noun compounds, Swales (1980) observed that scientific writing is characterized by complex subjects and simple verb forms in contrast to conversational and literary English. Noun compounds, or complex noun phrases, can be defined as a group of two or more nouns plus adjectives which together express a single concept. These structures have received a great deal of attention in research because of the difficulty they cause students. Such difficulty is usually associated with the fact that the process of compounding is not present in the students' native language. Along with this constraint, Maldonado (1983) stated that students tend to be word by word readers and miss these meaningful units.

Interpreting noun compounds correctly as meaningful units is a two-step process. The first involves an awareness of the reader that in compounding the rightmost noun is the head noun and the other nouns or adjectives preceding it are qualifiers; the second requires the reader to determine meaningful relationships between the units of a compound and combine them appropriately. These meaning relationships are semantic in nature, and include the following types: purpose, composition, principle of operation, mode of operation, shape, size location, name of creator and restricted reference (Bartolic, 1978).

2.2. Using informants in ESP research

The usefulness of working with informants - specialists or students - in ESP research has been ascertained in the literature, especially in the past seven years.

Selinker (1979) addressed the common ESP problem of how to teach the use of highly specialized technical prose which the ESP teacher cannot easily understand. In order to gain access to the total meaning of the piece, and to avoid reliance on intuitions which may lead to misinterpretations, a specialist-informant should be consulted. An important outcome of this procedure is that the language teacher is able to gain some relevant experience in even the most difficult aspects of the material his/her students will be required to read.

Mackay (1979) was equally concerned with the language teachers' general lack of training in fields of science and technology. As most ESP teachers are products of an arts and humanities training, they may not only lack a solid background in different branches of science and technology, but also interest in these areas. This state of affairs often results in teachers conveying feelings of ignorance and alienation, and students, as a consequence, losing respect for teachers who are unable to respond to their needs and goals. Mackay noted that ESP teachers are not expected to be specialists in the fields of study with which their students are involved. They should, however, become familiar with the branch of science with which they will be involved in teaching so as to assure a more positive and motivating environment in the ESP classroom. Mackay suggests that the ESP teacher should consult one or two basic introductory textbooks in the science concerned along with a "sympathetic and patient scientist" who will supply explanations whenever needed (p. 109).

Cohen et al. (1979) also used informants - students, in this case - in an attempt to discover what is problematic for non-native readers who need to read material in English in a specialized field. In a series of four studies which spanned the field of Genetics, Biology, Political Science and History, the authors concluded that student difficulties were related to three areas: (i) heavy noun phrase subjects and objects, (ii) syntactic markers of cohesion, and (iii) the role of specialist vocabulary in scientific texts. The study also enabled the authors to get some insights as to the processes the students used to derive meaning of the different passages as well as regarding the specific elements in the text which may be responsible for appropriate and inappropriate interpretations.

Tarone et al. (1981) examined the occurrence and rhetorical function of passive and active verb forms in two American journal articles in Astrophysics. They stressed that the knowledge of a subject-area specialist - the astronomer Vincent Icke, in this case - was "absolutely essential" to the investigation (p. 125).

Huckin and Olsen (1984) replicated Selinker's (1979) experiment, but instead of using just a specialist-informant, they recruited the author of the prose in question. Some of the recommendations from their study are: (i) that ESP researchers should have an understanding of the conventions and methodology of the field with which they will deal; (ii) that they should strive to see information structure more through the eyes of specialist-informants and less through those of the linguist. In other words, the LSP teacher should not attempt to lead the informant toward any one particular interpretation when interviewing the informant.

Zuck and Zuck (1984) pursued similar problems to those of Selinker (1979) and Huckin and Olsen (1984), but instead of obtaining interpretations from a specialist-informant or an author, they consulted a range of people on several aspects of a text. Those consulted were specialists (biologists) and non-specialists (ESL teachers) with some of each group being native English speakers and some not. The informants were requested to perform three tasks: (i) assess the difficulty of a journal article for students, (ii) select key words and phrases, and (iii) devise questions. Among the results obtained were certain contrasts found between the groups regarding such features as assessing the certainty of claim and distinguishing explicit from implicit information.

III. METHODOLOGY

3.1. Approach

Following in part Selinker's approach proposed in his article "On the Use of Informants in Discourse Analysis and 'Language for Specialized Purposes,'" this study examined four journal articles in Soil Science - sub-area of Soil Physics - of which two were published in the Journal of Soil Science and two in the Soil Science Society of America Journal. These articles were investigated in the light of two basic research questions (R.Q.):

> R.Q. 1: What does a non-native speaker of English, who is an EFL teacher, but who is not trained in Soil Science (Soil Physics, in particular) need to know in order to understand a journal article in that discipline?
>
> R.Q. 2: What sort of information does a non-native speaker of English, who is not an EFL teacher, but who is trained in the field of Soil Science, bring to the reading process of journal articles in that discipline?

These questions were, in turn, processed in terms of classes of questions the EFL teacher asked the specialist-informant in her attempt to gain a better understanding of the articles, and classes of information the trained reader in the field brought to the articles in his effort to comprehend them. The answers to these questions are, at times, limited to what both the ESP investigator and the specialist-informant regarded as the type of knowledge that should be handled by an EFL teacher.

3.2. The specialist-informant

The specialist-informant selected to be consulted in the course of this study was Glaucio Roloff, an adjunct professor of the Department of Soil Science at Universidade Federal do Parana. Mr. Roloff, a native Portuguese speaker, has taught Soil and Water Management and Conservation to undergraduate and graduate students at U.F.Pr for five years. He has published articles in the Soil Science Society of America Journal, Journal of Soil and Water Conservation, among others, and, although not a native speaker of English, speaks, reads and writes with native fluency. He has also acted as a reviewer of papers in the areas of Soil Physics and Soil and Water Conservation and Management. He holds a Master of Science degree from the University of Missouri-Columbia, and is currently working on the research for his Ph.D. dissertation at the Department of Soil Science at the University of Minnesota in Saint Paul.

3.3. Procedure

As requested by the investigator, article selection by the specialist-informant was based on which articles the students would be required to read in the course of their graduate studies. Among several choices, the informant narrowed his selection to the following four articles (see appendix 1 for the original texts):

(1) J. M. Tisdall and J. M. Oades: "Organic Matter and Water-Stable Aggregates in Soils."

(2) P. Germann and K. Beven: "Water Flow in Soil Macropores: I. An Experimental Approach."

(3) R. R. Allmaras, R. W. Rickman, L. G. Ekin, and B. A. Kimball: "Chiseling Influences on Soil Hydraulic Properties."

(4) M. Al-Durrah and J. M. Bradford: "New Methods of Studying Soil Detachment due to Waterdrop Impact."

The investigator proceeded to the preparatory sessions. These sessions were designed for the EFL teacher to read the articles and elicit, on her own, the problems areas in each one of them. These problem areas are brought to light as classes of questions in the Results section.

As soon as the preparatory sessions were concluded, the investigator arranged a series of six meetings (each lasting about ninety minutes) with the informant. In these meetings, the EFL teacher presented and discussed the problem areas with the informant, and, as a result, the informant provided some valuable information as to how, he, as an experienced reader of journal articles in Soil Science, managed the comprehension of the pieces.

IV. RESULTS

The description of the findings which follow is a result of the meetings between the investigator and the specialist-informant. These findings are set forth through a set of principles called classes of questions and classes of information which are, in turn, arranged according to three levels: the conceptual, the rhetorical and the linguistic. As previously stated, the classes of questions reflect areas of pedagogically relevant information which the investigator felt she could only obtain from a specialist informant in the field of Soil Science. The classes of information, on the other hand, mirror the types of suitable information an expert reader brought to a successful comprehension of the same articles in that field of study.

As an attempt to provide a practical research solution to a pedagogical problem, this taxonomy aims at bridging the gap between the limited amount of specialized knowledge an ESP instructor can apply to the reading of highly specialized scientific writing and the adequate training an expert possesses and fully uses in the reading process of the same type of writing.

CLASSES OF QUESTIONS AND CLASSES OF INFORMATION

1. The conceptual level

Class 1: Perception of the difficulty of the articles.

In class 1 the investigator attempted to find out from the informant how difficult he felt the four articles would be for the graduate students, and where the difficulties lay. Difficulties, in this context, refer to the complexities generated by the nature of the subject matter present in the articles.

The informant was asked to assess the difficulty of the articles on a scale of 1 to 5 (1 = easy, 5 = difficult).

Article 1 was ranked at 3. Its difficulty was attributed to two factors. One was the subject matter itself, soil structure, and the other was the extensive literature survey upon which the authors draw to build a foundation for their proposed model of soil structural arrangement. According to the informant, this article is a good example of the degree of complexity that this subject matter may reach as a result of the large number of variables which must be accounted for when dealing with it. Some of these variables would be: microbiological activity, type and amount of clay present in the soil, water regime, crop and season, etc.

Article 2 was ranked at 4 in the scale. Like article 1, this piece of research centers its argument around a particularly intricate subject, in this case, water flow in soil as influenced by macropores. Because soil scientists have not been able to measure macropores, the results of the experiments that have been conducted are based solely on the effect of macropores which they believe are present in a soil. This is the case of this article. As part of one the most recent trends in Soil Physics, this paper studies the effects of macropores on soil water flow. Until the late 1970's the effect of macropore flow was not well established, and it was assumed to fall within the existing theory described by an equation given by Richards in 1931. In this paper the authors show that macropores have a significant effect in water flow, but only under conditions of abundant water supply to them.

Article 3, like article 1, was ranked at 3. In this paper, the authors study the effect of chiseling under field conditions using, perhaps, the most accurate method, yet difficult to undertake, to determine hydraulic conductivity and soil water characteristics. The difficulty of the paper lies in the discussion of the methodology used and the results. In the methods and materials section the reader is expected to be familiar with the details of the theory of unsaturated soil water flow which will have direct implications on the discussion of the results. When reading the results obtained for the two treatments - before and after chiseling - the reader should realize that there are real differences between them although these differences are not statistically significant.

Article 4, ranked at 2, was felt by the informant to be the one which would present the least amount of difficult to the non- specialist reader, or to a student who has not studied Soil Physics (soil shear strength, in particular) in depth. The accessibility of the content is largely due to the fact that (1) the authors draw upon a limited number of concepts to fulfill their objective, for example, "shear strength"," matric potential," and the relationship "drop splash" versus "shear strength", and (2) that these concepts are fairly straightforward to understand in case the reader should request an explanation.

Class 2: Assumptions on shared background knowledge.

As a type of scientific writing whose aim is to contribute to the progress of science and technology, a journal article addresses a problem or issue which is important to its audience. The presentation of information is adapted to meet the needs and expectations of an expert in a subject.

Given this perspective, the investigator felt that having some discernment of the scope of the field as it applied to the chosen articles could motivate her, as an ESP teacher, to tackle the content of the four articles more appropriately. More importantly, this sort of information could be directly used in the ESP classroom with students whose undergraduate studies did not focus on Soil Science. Prior to the actual reading of the articles, the investigator asked the specialist-informant to provide her with some notion regarding the background knowledge that would be required for an adequate comprehension of the pieces. This approach in no way implied that the investigator, as a result, would "know" the science or technology treated in the articles. It did provide her with a more confident attitude towards the reading of highly specialized content as well as a more manageable picture of the concepts and the basic terminology therein. In terms of pedagogic applications, the students would be the ones to ultimately profit from such an approach. If they are given a fairly clear idea of the scope of the field from which the target articles develop, it seems that they could prepare themselves for the reading task more adequately.

Here are the views of the informant regarding the presupposed knowledge that a reader of the articles should possess if his/her goal is their full comprehension. Anticipating the complexity that the subject matter would pose for the ESP instructor and, eventually, for some students, the informant recommended the reading of specific chapters of key introductory textbooks in Soil Physics.

Article 1 presupposes an adequate understanding of three areas. One is soil mineralogy with a special focus on the mineralogy of clays and oxides. The second involves organic matter dynamics, for example, sources of organic matter decomposition, fractions, etc. The third includes theories of structure development, mainly aggregate formation. Background reading material suggested by the informant for these three areas would be found in chapters five ("Nature and Behavior of Clay") and six ("Soil Structure and Aggregation") in Hillel (1980) and in chapters eight ("Interaction of Clay with Water and Organic Compounds") and twenty-one ("Soil Structure and Soil Tilth") in Russell (1973).

Article 2 assumes knowledge of basic soil physical properties, especially of soil water and pore distribution. The basic concepts and principles regarding these properties are well laid out in chapters seven ("Soil Water: Content and Potential") and eight ("Flow of Water in Saturated Soil") in Hillel (1980).

Article 3 requires an adequate background of the mechanisms of saturated and unsaturated water flow through soil. In addition to this, a knowledge of tillage operations and their effects, particularly those regarding chisel plowing and moldboard plowing. Given these assumptions, the informant referred the investigator to the same chapters seven and eight in Hillel as well as chapter nine ("Flow of Water in Unsaturated Soil") in that textbook.

Article 4 would be best comprehended if the reader understood (1) the mechanism of raindrop detachment, that is, the effects of water erosion processes, (2) soil mechanics, especially the concept of "shear strength" as the maximum resistance of a soil to forces acting at right angles to the direction of movement, and (3) soil water potential or the status of water in a soil. An adequate source of information of this nature would be chapter nine (items 9.2 and 9.3) in Marshall and Holmes (1981).

2. The rhetorical level

Class 1: Article organization

All four articles reflected the hypothetico-deductive scientific method. The investigator also noted that articles 1 and 2 revealed greater flexibility in form and style as allowed by the editorial board of the Journal of Soil Science, whereas articles 3 and 4 from the Soil Science Society of America Journal predictably showed a high degree of standardization in form and style (see item 1.2.2 of the Introduction and appendices 2a and 2b).

Article 1, however, was particularly problematic for the investigator. Unlike the other three articles which were relatively short, and employed a common basic structure to develop their arguments (1. Introduction; 2. Materials and Method; 3. Results; 4. Discussion), the authors of article 1 chose a different arrangement for their argumentation. This choice posed a number of difficulties to the investigator. One of them was related to the absence of major section markers. This particular feature prevented the reader from discerning what was background information from what was the actual discussion of the proposed model of soil aggregation. The investigator inquired the informant whether there were any special reason(s) for such a choice. According to the informant, the organization elected by the authors, controlled by a number of sub-sections, may be confusing on a first encounter. However, it not only serves the purposes of the paper adequately, it can also be seen as a useful guide for the reader to assimilate the dense amount of information more easily. In each sub-section which precedes the actual proposal of a model of soil aggregation, the authors present a great deal of evidence related to (i) soil aggregation mechanisms, (ii) organic carbon content effects on water-stable aggregates, and (iii) aggregate organization. Step by step this dense body of facts lay the ground for the proposition of their model.

The informant observed that this type of article, which draws on extensive literature survey to propose a model, and, therefore, can be very useful to students, is not commonly found in publications in the field.

3. The linguistic level

Class 1: The use of tenses

Regarding the use of tenses in the articles, the investigator was interested in whether the use of certain tenses in particular sections of the articles could lead to any special meanings. As to the function of "reporting past research," for instance, the investigator inquired the informant if he felt that the use of certain tenses could be correlated to any degree of relevance to - or support of - the writers' current work, as advocated by Lackstrom et al. (1973) and Oster (1981).

Puzzled with the question at first, the informant noted that, perhaps, only the authors of the articles themselves would be able to say definitively whether a given reference is more or less relevant than others to their research. Then, he added that such a correlation appeared not to hold for these articles because article writers in this field tend to cite only past research that is directly relevant to the work in question. This is also a recommendation present in the manuscript format for journal articles submitted to the Soil Science Society of America Journal which advises writers to cite only past research that is relevant to the research in discussion (see Appendix 2b, item 4). Eventual past research which is non-supportive of an author's study would often be accompanied by some linguistic clue - the connector however, for instance - in the text. That would direct the reader to a conclusion.

As that correlation did not seem possible to be drawn, the informant observed that the decision an author makes whether to use one tense over another was, perhaps, the result of other constraints. The investigator then suggested the possibility of application of Swales' analysis of tense in reporting past research.

Swales' hypothesis were: (1) Type A references to past research correlated with the simple past tense; (2) type B references are correlated with the present perfect tense; type C references are correlated with the simple present tense. Although Swales' examination was restricted to the introductory sections to journal articles, this study examined both introductory and non-introductory sections of the four articles. The sentences considered were those containing references to past research in which both an author's name and a date of publication appear.

When all references to past research were extracted from the four articles, there was found to be a total of 127 references. Of these, 71 (56%) were Type C, 49 (39%) were Type A, and 7 (5%) were Type B. When the references were categorized according to tense, the following results were obtained:

Table 1: Function "reporting past research" in four Soil Science journal articles

Tense	Type A	Type B	Type C
Present	3 (6%)	0	58 (82%)
Past	45 (92%)	1 (14%)	13 (18%)
Present Perfect	1 (2%)	6 (86%)	0
Total	49 (100%)	7 (100%)	71(100%)

Total of references to past research = 127

Based on these results, the validity of Swales' paradigm could be verified when applied to the writing of these journals articles. Therefore, the following conclusions could be drawn:

(1) Type A references are strongly correlated with the past tense. The instances in which Type A references are used with the present tense (6%) can be correlated with the sub-function "making passing reference to past research." (Oster, 1981).

(2) Type B references are clearly correlated with the present perfect tense.

(3) Type C references are strongly correlated with the present tense. There is evidence that Type C references which favor the past tense (18%) can be correlated with the sub-function "reporting the results of past research" (Oster, 1981). The informant verified the application of the analysis and agreed that it was a legitimate means of investigating the use of tenses in reporting past research in his study area

Class 2: Interpretation of modal verbs

Modal verbs, such as can, could, may, might, should, will, would and must, were found frequently in the writing of the journal articles examined. Of 103 instances of modal use in the four articles, the verb may appeared in 45 (44%), the verb can in 22 (21%), the verb could in 9 (9%), should and would in 7 (7%), and will and must in 6 (6%) of the cases.

The high frequency of the modal may, particularly in article 1, led the investigator to search for a reason with the informant. He noted that soil scientists often work within research areas (as in article 1) in which a great deal of variability is observed, but not enough research that has accounted for this. As a result, researchers must often argue within degrees of probability as well as resort to educated guesses and assumptions. This mood of uncertainty is often conveyed by the modal may.

As to the interpretation of the modals *can* and *should*, the investigator suggested the analysis which follows. Such approach has been discussed in the literature and further thought appropriate by the informant.

With regard to the modal *can*, the second most frequently used in the articles examined, it was observed that besides its two most common functions - as an indicator of a degree of ability and probability (see appendix 3) - it was also used as an indicator of a degree of obligation, with statements describing procedural correctness (Huckin and Olsen, 1983), as examples (1) to (3) show:

(1) "The organic binding agents involved in stabilizing aggregates *can* be considered in three main groups ..." (article 1, p. 149)

(2) "The minimum dimensions of macropores, as these large pores are called, *can* be estimated from the relationship between the radius *R* ..." (article 2, p. 1)

(3) "Where more than two tensiometers are used an average hydraulic gradient *can* be calculated by taking ... (article 2, p. 5)

Another point of concern with modals was their interpretation. Interpreting modals in different contexts correctly may sometimes be difficult The difficulties arise when these verbs shift from their "standard" meaning when used for certain rhetorical purposes. It has been suggested that the modal should has the meaning of must in the rhetoric of instructions (Trimble, 1985).

The occurrence of meaning shift was investigated in the four articles. After all modal instances found in these articles were examined, shift in meaning was observed with the modal should. Of its seven occurrences, five (listed below) indicated that the verb should could clearly be read as must - in the sense of obligation. All of these instances occurred in the rhetoric of description, as it was further verified by the informant.

(1) "Such water-stable aggregates should be porous (pores > 75 m so that they remain aerobic." (article 1, p. 141)

(2) The pores between the aggregates should be large enough to allow rapid infiltration and drainage." (article 1, p. 141)

(3) "Therefore, the soil water properties of both the macropores and the micropores should be determined on the same sample..." (article 2, p. 3)

(4) "The bottom of the sample should be a plain surface... (article 2, p. 5)

(5) "Fine sand is used to give a good contact between the sample and the plate which should be fully saturated with air-free water..." (article 2, pp.5-6)

Class 3: Lexis: specialized terminology

Sub-class 1: Noun compounds

As predicted by the investigator, noun compounds were extensively found in the writing of the four articles.

The difficulties encountered by the investigator to interpret them were related to the technical concepts involved rather than to the actual analysis of the clusters. As soon as the informant was notified of that difficulty, he advised the investigator to consult the Glossary of Soil Science Technical Terms (1984). Many of the terms selected as problematic by the investigator were not defined in the glossary. Although some of them were, the definitions were virtually inaccessible to the investigator. The inaccessibility was largely due to the degree of precision at which the definitions were prepared, demanding from the reader (the investigator) a fairly solid knowledge of Soil Science and related areas (Chemistry, Microbiology, among others) which the investigator simply did not possess. An example of this complexity could be found in the definition of the term matric potential as:

> the amount of work that must be done per unit quantity of pure water in order to transport reversibly and isothermally an infinitesimal quantity of water, identical in composition to the soil water, from a pool at a specified elevation and the external gas pressure of the point under consideration, to the soil water (p. 22).

Bearing in mind that the comprehension of the articles could be improved if she could gain access, even if partial, to the meaning of those units, the investigator arranged another meeting with the informant. As a result of this session, not only more tangible definitions were obtained (see appendix 4), but also a new perspective of the dimensions of the field. The compounds which needed the informant's clarification of meaning are arranged in Appendix 4. Also, the informant thought appropriate to call the investigator's attention to certain terms which he considered essential to the comprehension of the articles. These are arranged in Appendix 5.

Sub-class 2: Sub-technical vocabulary

In this sub-class, head was the only sub-technical term which posed a problem to the investigator. It appeared in article 2 in collocation with the words falling and device (falling-head device) and in articles 3 and 4 in collocation with the adjective hydraulic (hydraulic head). Unable to determine its meaning clearly by using a dictionary and the Glossary, the investigator resorted to the expertise of the informant. His answer was that head meant pressure in these contexts.

V. CONCLUSION

In recognizing the difficulties an ESP teacher may have in the intensive reading and, further, the teaching of highly specialized authentic material, this study attempted to show that problems of this nature can be overcome with the assistance of a specialist-informant from the target scientific field.

The results obtained were prompted by constraints related to (i) the genre of writing investigated, (ii) the degree of subject-matter knowledge the ESP teacher possessed in Soil Physics prior to the beginning of the study, and (iii) the purpose in reading. The nature of the reading task, namely to read four journal articles in the field of Soil Physics for detailed comprehension, demanded consultation with an expert as the only means available to the language teacher to safely prevent misinterpretations.

The areas in which the contribution of the specialist-informant was considered essential were at three levels. At the conceptual level, (i) his comments on how he perceived the difficulties in each article and where they lay, and (ii) his views regarding the presupposed knowledge a reader of the articles should possess if his/her goal is full comprehension of the pieces. At the linguistic level, his observations regarding the use of (i) modals in the articles, and (ii) lexical items, the cases in which interpreting specialized terminology (noun compounds, in special) was problematic to the investigator. Finally, at the rhetorical level, his remarks clarifying certain organizational aspects of article 1 to the investigator, who was facing difficulties in discerning what was background information and where the actual discussion of the model of soil aggregation began.

The knowledge gained from this study, coupled with the application of appropriate reading strategies, puts the ESP teacher in a position to teach those selections more confidently and more adequately. In addition to that, the experience earned through the project has the potential to be directly applicable to the reading of other journal articles in the same field.

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APPENDIX 1

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Organic matter and water-stable aggregates in soils

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Summary

The water-stability of aggregates in many soils is shown to depend on organic materials. The organic binding agents have been classified into (a) *transient*, mainly polysaccharides, (b), *temporary*, roots and fungal hyphae, and (c) *persistent*, resistant aromatic components associated with polyvalent metal cations, and strongly sorbed polymers. The effectiveness of various binding agents at different stages in the structural organization of aggregates is described and forms the basis of a model which illustrates the architecture of an aggregate. Roots and hyphae stabilize macroaggregates, defined as > 250 μm diameter; consequently, macroaggregation is controlled by soil management (i.e. crop rotations), as management influences the growth of plant roots, and the oxidation of organic carbon. The water-stability of microaggregates depends on the persistent organic binding agents and appears to be a characteristic of the soil, independent of management.

Introduction

Good structure for crop growth depends on the presence of aggregates of soil particles 1 to 10 mm diameter which remain stable when wetted. Such water-stable aggregates should be porous (pores > 75 μm diameter) so that they remain aerobic, and yet possess sufficient numbers of pores 30–0.2 μm diameter to retain water for the growth of plants. The pores between the aggregates should be large enough to allow rapid infiltration and drainage.

When an unstable air-dried aggregate is wetted rapidly it slakes into smaller sub-units which may also be aggregates (Emerson, 1977). Slaking is common and occurs in a wide range of soils where the aggregates are not strong enough to withstand the pressures of entrapped air in capillaries or the pressures due to swelling. In the field, slaking of aggregates occurs mainly in surface layers since those below the surface are protected from air-drying and from rapid wetting. Severe slaking with little or no dispersion is serious, particularly where soils are irrigated, because the slaked layers limit infiltration of water and emergence of seedlings.

The sub-units or small aggregates produced by slaking may also be unstable so that individual clay particles may disperse. Spontaneous dispersion occurs if the clay swells to such an extent that the attractive forces between the particles are no longer

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strong enough to hold them together (Emerson, 1977). The particles of clay are released slowly and appear as a spreading cloud around the aggregate (Arnold, 1978). In the field the dispersed clay may block pores which transmit or store water, and slaking and dispersion together produce undesirable structures such as surface crusts. Swelling and dispersion are largely a function of the exchangeable ions associated with the clay, e.g. sodium and magnesium, and electrolyte concentration. However, other materials which influence the surface properties of clay minerals may favour flocculation or dispersion. There is some evidence that organic anions promote dispersion, by blocking positive sites on colloid surfaces, and by complexing polyvalent cations in solution (Bloomfield, 1963; Gillman, 1974). On the other hand, organic polymers may promote flocculation (Greenland, 1965).

While flocculation and dispersion appear to be largely electrostatic phenomena, the stabilizing of larger aggregates involves cementing or binding agents which may be inorganic, organo-mineral associations or organic.

Clay may bind particles into aggregates, but aggregates bound by aluminosilicates only are unlikely to maintain their integrity when wetted. Hydrous oxides of aluminium and iron cement particles together in water-stable aggregates with diameters greater than 100 μm, especially in soils which contain more than 10 per cent sesquioxides. The full extent of cementation by oxides is evident in bauxite and ferricrete (Kroth and Page, 1946; Chesters *et al.*, 1957; Kuznetsova, 1966; Krishna Murti *et al.*, 1977). Highly disordered aluminosilicates and calcium carbonate also act as cementing agents. In spite of the generally stable aggregation of calcareous soils, the mechanisms of binding have not been defined. The influence of calcium carbonate may be due, in part, to the concentration of calcium ions in the soil solution which limits dispersion and swelling of the clay (Rimmer and Greenland, 1976).

Organo-mineral associations function as binding agents in aggregates, particularly those less than 250 μm diameter (Edwards and Bremner, 1967; Hamblin, 1977; Turchenek and Oades, 1978).

The inorganic binding agents may be regarded as permanent cements and if they are dominant, the presence of organic glues may be of little extra benefit. Regular cultivation may reduce the content of organic matter and the chemical fertility with little influence on the physical properties of such soils. However, in the surface layers of many agricultural soils, it appears that organic matter plays a major role in binding aggregates to withstand stresses caused by rapid wetting.

Relation of water-stable aggregates to organic carbon content

There have been numerous correlations between the content of organic carbon in soils and water-stable aggregation and some of these are shown in Table 1. The correlations have not always been good for any one or all of the following reasons: (a) only part of the organic matter is responsible for water-stable aggregation, (b) there is a content of organic carbon above which there is no further increase in water-stable aggregation, (c) organic materials are not the major binding agents, (d) it is the disposition rather than the type or amount of organic matter which is important, and (e) some of the water stability in virgin soils is related to physical factors such that the particle reorganization associated with the first disturbance of virgin soil reduces water stability (Heinonen, 1955; Malik *et al.*, 1965, Greenland, 1971*b*; Low, 1972; Tisdall and Oades, 1980*b*). The stability is sometimes related better to free

Table 1

Organic matter and aggregate stability

46 silt loams (Strickling 1950)
Aggregate stability = 16.9 (org. matter) − 13, $r = 0.87$

519 North American soils (Kemper and Koch, 1966)
Aggregate stability = 40.8 + 17.6 log (org. C) + 0.73 clay − 0.0045 $(\text{clay})^2$ + 3.2 Fe_2O_3

189 British soils (Williams 1970)
% water slaking = 2.47 + 0.47 coarse particles (6–0.02 mm) − 5.95 (org. C)

28 hard-setting red-brown earths (Grierson 1975)
Aggregate stability = 0.82 + 2.13 (org. C) − (0.6 ESP + 0.3 EMgP)

9 red-brown earths (Tisdall and Oades 1980*b*)
Aggregate stability = 21.5 (org. C) − 20.3, $r^2 = 0.93$.

organic materials than to total organic carbon because this fraction acts as a substrate for microbial production of organic glues (Oades, 1967), and/or because this fraction is a measure of roots and hyphae.

The management of a soil can change the content of organic matter by a factor of two or three and there are sufficient data to show that this change can occur under different climates (Table 2).

Decrease in organic matter

Cultivation is exploitive and causes a decline in the content of organic matter. This decline is aggravated if fallow is included in the rotation where the soil is cultivated to ensure no plant growth, or where crop residues are removed (Ramig and Mazurak, 1964; Ridley and Hedlin, 1968; Emmond, 1971; Martel and Paul, 1974; Juo and Lal, 1977). Where soil is cultivated frequently, aggregates are exposed frequently to physical disruption by rapid wetting and raindrop impact as well as to shearing by implements. The net effect is to expose inaccessible organic matter to micro-organisms and to stimulate oxidation and loss of organic matter (Low, 1954; Rovira and Greacen, 1957; Clement and Williams, 1958; McCalla, 1959; Martel and Paul, 1974; Adu and Oades, 1978). This decline in organic matter is usually accompanied by a decrease in the number of water-stable aggregates.

Increase in organic matter

Organic matter may accumulate under good pastures because the annual addition of phytomass is greater than under crops, e.g. cereals. As well as adding organic residues to soils, growing plants appear to retard the decomposition of organic matter in soils (Führ and Sauerbeck, 1968; Jenkinson, 1977). The number of water-stable aggregates increases under good grass pastures. Because the increase in stable aggregation under pastures is related to the length of root and of vesicular-arbuscular (VA) mycorrhizal hyphae (Barley, 1953; Clement, 1961; Tisdall and Oades, 1980*b*) and because organic residues accumulate at the surface, most of the aggregation is in the top layers of soil (Clement and Williams, 1958).

Table 2

Management and contents of organic matter in soils

Soil	*Treatment*	*% organic matter*	*Reference*
Silt loam Iowa	Continuous blue grass	3.36	Johnston *et al.* (1942)
	Corn oats–clover rotation	3.46	
	Continuous corn	2.86	
Silt loam Ohio	Continuous blue grass	3.35	Strickling (1950)
	Corn–ryegrass rotation	2.17	
	Corn–soybean rotation	1.75	
Rothamsted	Ley 7 years	3.4*	Clement and Williams (1964)
	Arable 7 years	2.2*	
Sod-podzolic Timiryazev	Virgin soil	2.21	Kononova (1966)
	Continuous rye 48 years	1.55	
Chernozem Lenin State	Virgin soil	4.33	Kononova (1966)
	Old arable	4.00	
Silt soil Lincolnshire	Grassland 100 years	7.58*	Low (1972)
	Arable 25 years	2.16*	
Alfisol Nigeria	Non-tilled	4.52*	Lal (1974)
	Tilled	3.38*	
Red-brown earth Australia	Pasture 30 years	5.30*	Turchenek & Oades (1979)
	Wheat fallow rotation	2.08*	
Alfisol Nigeria	Cover crop	3.14*	Lal *et al.* (1979)
	Weed fallow	2.74*	

* Obtained from 2 × % organic carbon.

Aggregate organization

Introduction

There is sufficient information available to indicate that water-stable aggregates with diameters of a few millimetres are not simply a random arrangement of the various particles responsible for the texture of the soil. A prerequisite for water-stable aggregation is flocculation of clay particles—the first stage in the construction of a stable macroaggregate.

Emerson (1959, 1977) suggested that parallel clay crystals (about 5 μm diameter) are grouped together closely enough (about 0.1–1.3 μm apart) to behave in water as a unit called a *domain*. His model, which is not drawn to scale, shows that organic matter stabilizes the aggregate mainly by forming and strengthening bonds between domains and between quartz particles and domains, though the quartz particles may also be linked directly by organic matter.

Quirk and Aylmore (1971) used the term *quasi-crystals* to describe the regions of parallel alignment of individual lamellae of aluminosilicates in montmorillonite, which exhibit intra-crystalline swelling; they used the term *domain* to describe the regions of parallel alignment of crystals for illite and other clays with fixed lattices, which exhibit inter-crystalline swelling only.

Several models have been proposed to describe the way in which individual mineral particles are held together to form water-stable aggregates of soil. Misuno and Sudo (1958) and Sudo (1962) suggested that particles < 20 μm diameter are bound into water-stable secondary particles 20–60 μm diameter, and that these secondary particles in turn form larger soil aggregates.

Edwards and Bremner (1967) suggested that macroaggregates (> 250 μm diameter) consist of complexes of clay–polyvalent metal–organic matter (C–P–OM) where clay is bonded to humified organic matter through polyvalent metals. Particles of C–P–OM and (C–P–OM)$_x$, both of which are < 2 μm diameter, form microaggregates ((C–P–OM)$_x$)$_y$ which are < 250 μm diameter. Bonds of C–P–C and OM–P–OM, and even of aluminium or iron oxide, or H-bonds may occur also. Edwards and Bremner (1967) suggested also that fragments of humified organic matter may be bonded to a single clay particle, and that a single fragment of humified organic matter may be bonded to more than one clay particle.

The interactions between organic polymers and mineral surfaces are complex but the mechanisms are known and have been reviewed by Greenland (1965, 1971*a*), Mortland (1970) and Theng (1979). The most important mechanism of interaction probably involves bridges of polyvalent cations between the surface of the clay particles or hydroxy polymers and the ligand groups of organic polymers, e.g. carboxyl groups.

Organization of an aggregate from a red-brown earth

The model which we propose is based mainly on information available for red-brown earths and which is taken from the following papers: Burford *et al.* (1964), Turchenek and Oades (1978), Fordham and Norrish (1979), Tisdall and Oades (1979), Tisdall (1980), and Tisdall and Oades (1980*b*).

In this model there are four stages of aggregation:

< 0.2 μm → 0.02–2 μm → 2–20 μm → 20–250 μm → > 2000 μm

The model may apply generally to soils where organic matter is the main binding agent, but the levels of aggregation may differ. For example, in a black earth, aggregates 1000–2000 μm diameter slaked directly to water-stable particles of about 30 μm diameter (Collis-George and Lal, 1970).

Each stage of aggregation in a red-brown earth is considered in turn.

Aggregates > 2000 μm diameter

In red-brown earths with high contents (> 2 per cent) or organic carbon, water-stable aggregates > 2000 μm diameter consist of aggregates and particles held together mainly by a fine network of roots and hyphae, and in soils which contain low contents (< 1 per cent) of organic carbon, by transient binding agents only. Because the stability of particles $>$ 2000 μm diameter is related to the growth of roots and hyphae, the stability is controlled by agricultural practices.

Inorganic binding agents including highly disordered aluminosilicates and crystalline iron oxides also stabilize aggregates $>$ 2000 μm diameter but to a lesser extent than organic materials. A cross-section of a water-stable particle $>$ 2000 μm diameter impregnated with white Araldite (Ciba-Geigy, Australia) shows that the particle is porous (Fig. 1a), and consists mainly of particles of about 20–250 μm diameter (Fig. 1b).

Aggregates 20–250 μm diameter

Aggregates 20–250 μm are stable to rapid wetting and are not destroyed by agricultural practices; even in an old arable soil, more than 70 per cent of water-stable particles were 20–250 μm diameter. However, aggregates 20–250 μm diameter can be destroyed by ultrasonic vibration. Aggregates 20–250 μg diameter consist largely of particles 2–20 μm diameter bonded together by various cements including persistent organic materials and crystalline oxides and highly disordered aluminosilicates. The aggregates 20–250 μm diameter are very stable partly because they are small, but also because they contain several types of binding agents whose

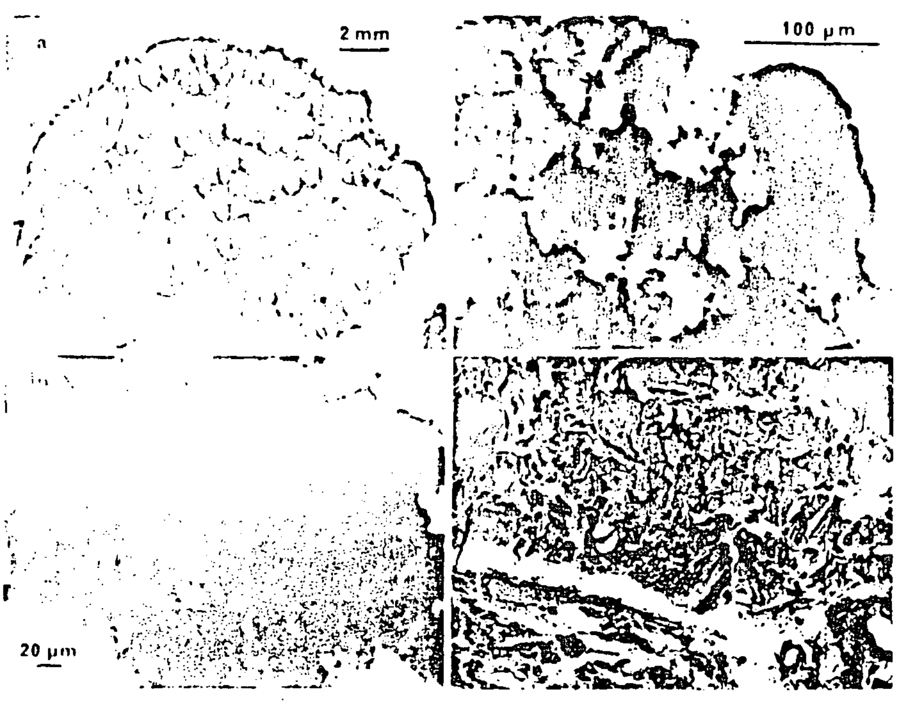

Fig. 1. (a) A cross-section of a water-stable particle > 2000 μm diameter from a red-brown earth, impregnated with white Araldite. (b) & (c) Enlargements of (a). (d) Transmission electron micrograph of an an ultra-thin section of rhizosphere soil. (Micrograph courtesy of Dr R. C. Foster, CSIRO, Division of Soils, Adelaide, South Australia.)

effects are additive. The individual organic bonds must be strong because particles. 20–250 μm diameter contained less than one-half as much organic carbon as the much less stable particles $>$ 250 μm diameter. It is not easy to define the site or size of the organic materials within stable particles 20–250 μm diameter because the clay is associated intimately with the organic material. A cross-section (Fig. 1c) and a scanning electron micrograph (Fig. 2) of a water-stable aggregate 20–250 μm diameter show that the aggregate consists dominantly of particles of about 2–20 μm diameter. Particles 20–250 μm diameter would be included in the stable micro-aggregates $((C\text{–}P\text{–}OM)_x)_y$ described by Edwards and Bremner (1967).

Aggregates 2–20 μm diameter

Water-stable aggregates 2–20 μm diameter consists of particles $<$ 2 μm diameter bonded together so strongly by persistent organic bonds that they are not disrupted by

Fig. 2. Scanning electron micrograph of part of a water-stable aggregate 50–250 μm diameter, from the FW rotation of Urrbrae fine sandy loam.

agricultural practices; some particles 2–20 μm diameter from under old pasture resist ultrasonic vibration for 5 min. Particles 2–20 μm diameter, obtained by ultrasonic dispersion or trituration from soils with high contents of clay and high base status, often have high contents of organic materials (Oades and Ladd, 1977; Turchenek and Oades, 1978). This organic-rich fraction (2–20 μm diameter) is often highly water-stable especially in chernozemic soils and in soils under old pasture (Pokotilo, 1967; Turchenek and Oades, 1978).

A transmission electron micrograph of rhizosphere soil shows a water-stable particle 2–20 μm which consists of particles < 2 μm diameter (Fig. 1d) bound closely together. Fordham and Norrish (1979) also described particles which were bound together by strands of glutinous material, probably organic, to this level of aggregation. However, some particles 2–20 μm diameter are probably simply large floccules (see below).

Development of stable particles 2–20 μm diameter

Electron micrographs of soils or thin sections of soils in the rhizosphere show individual bacteria or colonies of bacteria surrounded by a capsule, composed of carbohydrate, to which particles of fine clay appear firmly attached. The clay particles, which may enclose the bacteria completely, are sometimes oriented tangentially to the bacterial surface to a distance of 0.1 μm from the bacterial surface (Marshall, 1976). The fact that such associations between live bacterial cells and clay particles appear to form aggregates 2–20 μm diameter is supported by the results of Hattori (1973), Ladd *et al.* (1977) and Ahmed (1981), who found that a large part of the microbial biomass was present in silt-sized fractions. However, since only about 2 per cent of the organic matter in soils consists of biomass (Jenkinson and Rayner, 1977), silt-sized aggregates consisting of living bacteria must be newly formed aggregates. When the bacterial colony has died and its contents have decayed, characteristic fibrous components of the bacterial capsule remain (Foster, 1978), thus leading to an older aggregate; the remains of the colony with its capsule cannot be identified as such, but appears as a matrix of organic matter binding particles of clay. This organic matter can be seen in the transmission electron micrograph of a thin section of soil from the rhizosphere (Foster, 1978, Fig. 2). There is also chemical evidence that aggregates 1–5 μm diameter are old and protect organic matter, which consists mainly of humic acids, within the aggregates (Oades and Ladd, 1977). However, aggregates derived from bacterial colonies may represent only a small number of particles stabilized by microbial debris since fungi contribute more to soil organic matter than do bacteria (Paul and van Veen, 1978). Some fungal hyphae were shown to produce a layer of amorphous material, probably polysaccharide, to which particles of clay were attached firmly (Tisdall and Oades, 1979). Fragmentation of the hyphae could lead to small aggregates stabilized by fungal debris. The hyphal fragments could be derived from VA mycorrhizal fungi which were associated with a living plant, or from saprophytic fungi which grew rapidly in the soil after the addition of readily decomposable material. As with the bacterial colonies, further decay of the hyphal fragment could lead to a matrix of physically protected organic matter within a water-stable aggregate.

Aggregates < 2 μm diameter

Water-stable particles < 2 μm diameter are often floccules where individual clay plates (which may consist of individual lamellae or groups of lamellae) come together to form a fluffy mass. Initially, the plates are not parallel but are attracted edge-to-edge to form an open card-house structure (Quirk, 1978). However, on drying, the system tends to lower its entropy, so that the plates become parallel and if aligned perfectly will form a crystal 4 nm wide. The crystals may than be joined into larger units with slit-shaped pores 2.5–4.1 nm between the crystals (Murray and Quirk, 1979). In surface soils, perfect alignment of clay plates probably occurs rarely so that the arrangement within particles $< 2\,\mu$m diameter is probably somewhere between that of a card-house structure and that of a crystal. The plates are held together by van der Waal's forces, H-bonding and coulombic attraction. However, the charges of ions associated with the surface of clay are influenced by organic and inorganic materials (Greenland, 1965, 1971*a*). For example, organic materials may increase or decrease the attraction between the particles.

Some particles $< 2\,\mu$m diameter have been shown to be aggregates of very fine material held together by organic matter and iron oxides. In particles $< 2\,\mu$m diameter, organic material is probably sorbed onto the surface of clays and held firmly by the various bonds described in reviews on organo-mineral interactions.

An idealized model can be drawn to scale showing that an aggregate of soil is built up of structural units of various sizes held together by various binding agents (Fig. 3).

In soil there is considerable overlap between the proposed stages leading to an aggregate several millimetres in diameter, although there appears to be sufficient evidence to warrant the proposed stages, particularly the larger features. The evidence indicates that there is not a smooth continuum of sizes of water-stable particles and that stability of the particles at each stage is associated with a dominant binding agent.

It would be interesting to examine other soils with different textures to determine the size of particle produced by slaking and by physical dispersion.

Nature of organic binding agents

The organic binding agents involved in stabilizing aggregates can be considered in three main groups based on the age and degradation of the organic matter and not on the proportions of chemically defined components. The various binding agents determine the age, size and stability of aggregates. The three groups of organic binding agents considered are transient, temporary and persistent.

Transient binding agents

Transient binding agents are organic materials which are decomposed rapidly by microorganisms. The most important group is the polysaccharides including (i) microbial polysaccharides produced when various organic materials are added to soil, and (ii) some of the polysaccharides associated with roots and the microbial biomass in the rhizosphere (Russell, 1973; Oades, 1978). Polysaccharides are produced rapidly (Harris *et al.*, 1966; Aspiras *et al.*, 1971) but are decomposed rapidly, and are associated with large ($> 250\,\mu$m diameter) transiently stable aggregates (e.g. Guckert *et al.*, 1975).

Based on data from Griffiths and Jones (1965), Harris *et al.* (1966), Baver *et al.* (1972), Guckert *et al.* (1975), Hepper (1975) and others, it is possible to generalize with respect to the dynamics of water-stable aggregates in soil after the addition of

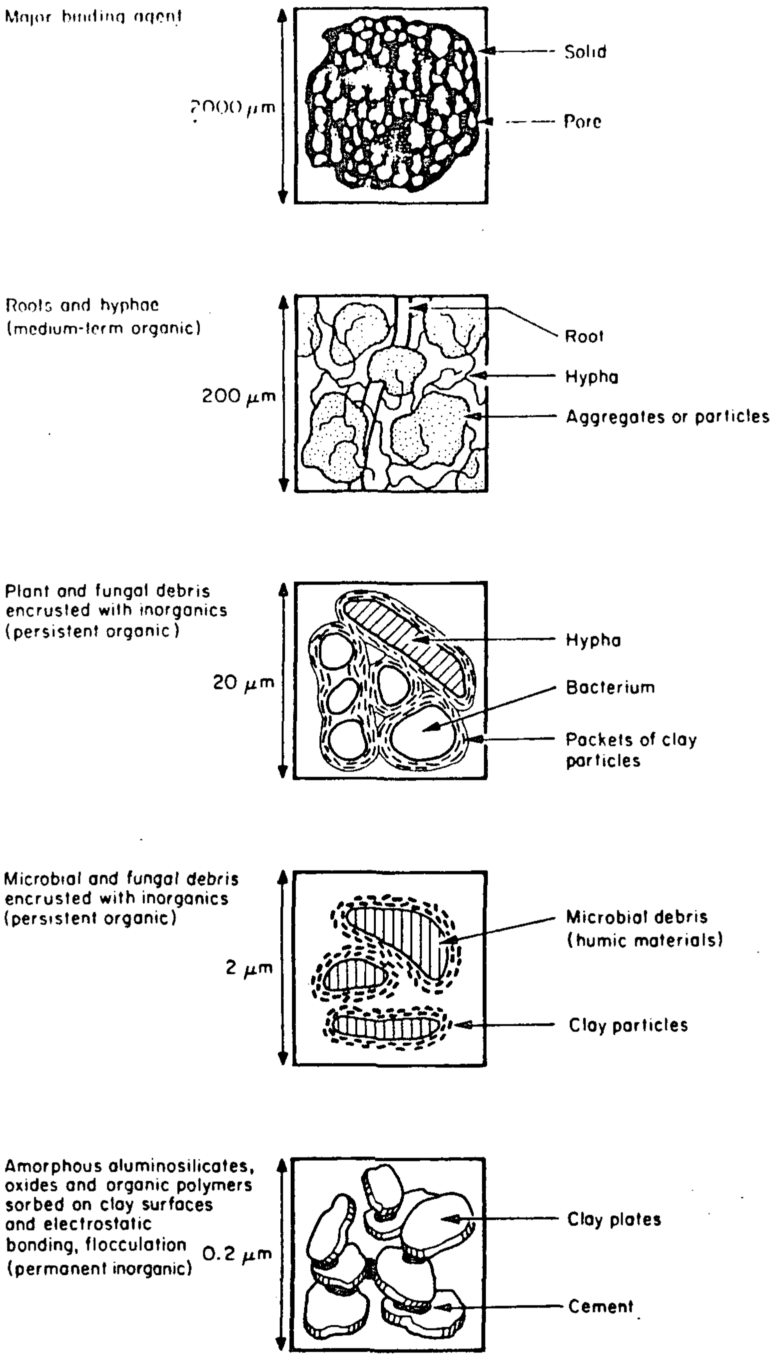

Fig. 3. Model of aggregate organization with major binding agents indicated.

organic materials (Fig. 4). Readily available substrates, e.g. glucose, increase water-stable aggregation which is transient (several weeks) because the glues are decomposed readily; treatments with periodate indicate a dominant role for polysaccharides. Less readily available material, such as ryegrass tissue, leads to a gradual increase in water-stable aggregates which persist for several months; polysaccharides are involved to a lesser extent. More recalcitrant substrates, e.g. cellulose, slowly give rise to limited water-stability which persists for months and is not significantly sensitive to periodate.

During the growth of plants, all three mechanisms are involved so there is an increase in water-stable aggregates which persists for months because roots and associated hyphae are decomposed slowly (Tisdall and Oades, 1980*a*). Some of the polysaccharides may be protected from microbial degradation by association with metal ions or tannins or by sorption on the surfaces of clays (Martin, J. P., 1971; Griffiths and Burns, 1972). Such materials and their binding action would then become persistent, even for several years.

The significance of polysaccharides as glues in soil aggregates has been reviewed several times (e.g. Swincer *et al.*, 1968; Martin, J. P. 1971; Cheshire, 1979). Many microorganisms produce exocellular mucilages or gums which are dominantly polysaccharide. Some of these organisms exist in soils, and mixtures of polysaccharides, with properties which indicate a microbial origin, have been obtained from soils. These preparations, and simpler, better defined polysaccharides from cultured organisms have interacted with clays and have stabilized aggregates. Numerous correlations between carbohydrate or polysaccharide contents of soils and aggregation have been obtained, but in many cases the correlation has been no better than with other organic materials. The most convincing evidence that polysaccharides function as glues in soil aggregates arose from the use of periodate as a selective oxidant for polysaccharides.

Periodate oxidation led to a decrease in water-stable aggregation of soils, not only

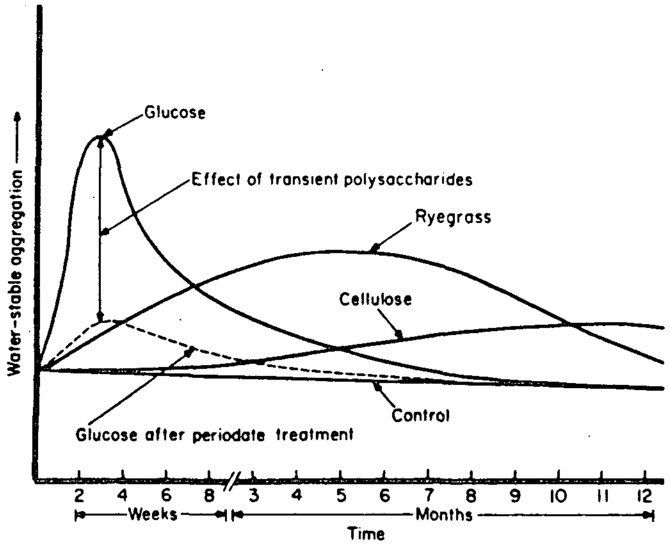

Fig. 4. Changes in water-stable aggregation after the addition of organic materials.

immediately after addition of organic materials to soils, but also on soils which were cultivated frequently and which had low contents of organic matter (Greenland *et al.*, 1962; Stefanson, 1971). However, it is clear that in some soils, other organic binding agents or inorganic cements are present so that removal or destruction of polysaccharides does not influence aggregation.

The association of polysaccharides (produced by bacteria, fungi and plant roots) with clay particles has been illustrated convincingly by electron microscopy (Jackson *et al.*,1946; Foster and Rovira, 1976; Marshall, 1976; Foster, 1978; Tisdall and Oades, 1979). This work shows clearly the attachment of fine clay particles to capsular or exuded polysaccharides.

It is important to consider the scale at which this association takes place. The polysaccharides bind together clay-sized particles into aggregates which are of the order of 10 μm diameter. It is unlikely that small quantities of polymers with chain lengths of a few hundred ångströms would be important in binding particles into aggregates with diameters of several millimetres.

Inconsistencies in the literature on the role of polysaccharides in binding water-stable aggregates can be explained when one considers the size of aggregates which have been investigated. The methods of assessing aggregation or 'structure' have varied; for example, Greenland *et al.* (1962) determined permeability and Stefanson (1971) used a 10 μm degree of aggregation. (Both these methods assess the effects of the treatment on small aggregates, i.e. those with diameters less than 50 μm. Disintegration of aggregates less than 50 μm, and release of clay and silt-sized material would decrease permeability.)

Tisdall and Oades (1980*b*) assessed the influence of periodate on aggregates with diameters up to 10 mm and found that aggregates with diameters greater than 50 μm were unaffected by treatment with periodate. Mehta *et al.* (1960) examined 2–4 mm aggregates and Webber (1965) > 250 μm aggregates, and both groups of workers found that periodate-sensitive materials were not responsible for stabilizing macroaggregates.

Thus the methods used to study aggregates or the water-stability of soil structure will influence the results obtained when using periodate. The integrity of large aggregates is not affected by treatment with periodate and it seems reasonable to conclude that polysaccharides are not involved in stabilizing aggregates with diameters of several millimetres. However, polysaccharides stabilize aggregates less than 50 μm diameter, and perhaps also floccules of clay. This is in keeping with the molecular size of exocellular polysaccharides and the size of the particles which the polysaccharides glue together. Polysaccharides thus have less relative importance in soils with high organic matter contents, e.g. after many years of pasture growth.

Temporary binding agents

Temporary binding agents are roots and hyphae, particularly vesicular–arbuscular (VA) mycorrhizal hyphae (Hubbell and Chapman, 1946; Bond and Harris, 1964; Tisdall and Oades, 1979). Such binding agents build up in the soil within a few weeks or months as the root systems and associated hyphae grow. They persist for months or perhaps years and are affected by management of the soil (Tisdall and Oades, 1979, 1980*a*, *b*). The temporary binding agents are probably associated with young macroaggregates and can be equated with the organic skeleton grains described by Bal (1973).

Roots. Roots not only supply decomposable organic residues to soil and support a large microbial population in the rhizosphere, but roots of some plants, especially grasses, themselves act as binding agents. They appear to enmesh fine particles of soil into stable macroaggregates, even when the root has died (Fig. 5) (Clarke *et al.*, 1967; Coughlan *et al.*, 1973; Forster, 1979).

Residues released into the soil by roots are in the form of fine lateral roots, root hairs, sloughed-off cells from the root-cap, dead cells, mucilages, lysates and volatile and water-soluble materials (Soper, 1959; Rovira and McDougall, 1967; Shamoot *et al.*, 1968; Martin, J. K., 1971; Dickinson, 1974; Oades, 1978). The amount of organic carbon released by roots is related to the total length of root; Shamoot *et al.* (1968) found that, regardless of species, plants released 20–49 g organic material per 100 g harvested root. The root systems and associated fungal hyphae of pasture plants, especially grasses, are extensive and the upper layer of the soil under pasture is probably all rhizosphere, i.e. the roots are less than 3 mm apart (Thornton, 1958; Barley, 1970).

Part of the effect of plants on water-stable aggregates is also due to localized drying around roots (Allison, 1968). Electron micrographs of the rhizosphere show that particles of clay close to a root tend to be oriented almost parallel to the axis of the root; the percentage of oriented particles increases with the age of the root and with decreasing radial distance from the root (Blevins *et al.*, 1970; Greaves and Darbyshire, 1972; Foster and Rovira, 1976). The particles of clay had probably been reoriented by the expanding roots and by localized drying around the roots, from

Fig. 5. Particles of soil held together by plant roots.

randomly dispersed positions to positions of minimal energy (Aylmore and Quirk, 1959).

Plants may also increase water-stable aggregation of soils indirectly by providing food for soil animals, such as earthworms and the mesofauna, enabling large populations to build up. Soil under 3-year-old pasture had few earthworms but after 8 years' pasture there were more than 1.5×10^6 ha^{-1} (Low, 1955). Earthworm casts generally contain more organic matter than the surrounding soil and the casts from soil under pasture were more stable than the surrounding soil (Swaby, 1950). The earthworm may stabilize structure by ingesting soil and mixing it intimately with humified organic materials in its gut (Swaby, 1950; Barley, 1959; Greenland, 1965). In a non-cultivated peach orchard where adequate food and water were present throughout the year, earthworm populations increased in 3 years to 2000 m^{-2}, compared with 150 m^{-2} where food and water were scarce, and infiltration of water was increased over 80-fold (Tisdall, 1978).

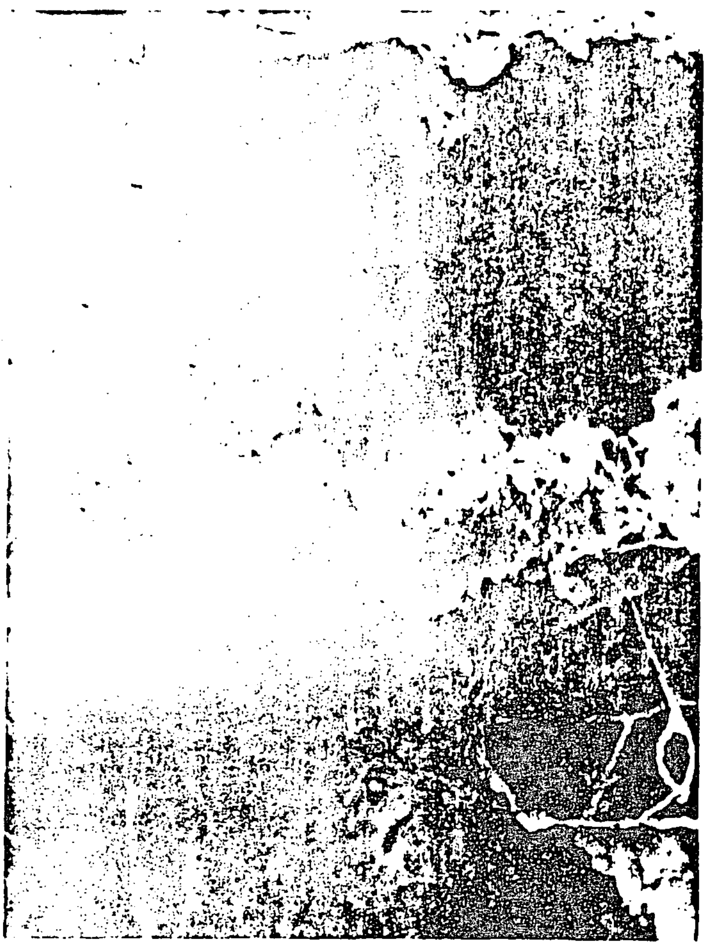

Fig. 6. Scanning electron micrograph of hyphae of VA mycorrhizal fungi binding soil particles into water-stable aggregates.

Hyphae. Hyphae, not necessarily viable, are sticky and encrusted with fine particles of clay and retain their strength when stable, wet aggregates from the field are dissected (Hubbell and Chapman, 1946; Bond and Harris, 1964; Tisdall and Oades, 1979). Water-stable aggregates in sand-dune soils also may be held together by fungal hyphae (Koske *et al.*, 1975; Forster, 1979). Although individual hyphae are not strong, the combined strength of all hyphae and fine roots, especially in a three-dimensional network, holds particles more or less equally in all directions so that aggregates do not slake when wetted rapidly.

Temporary binding agents stabilize macroaggregates, i.e. > 250 μm diameter (Hubbell and Chapman, 1946; Harris *et al.*, 1966; Tisdall and Oades, 1980*b*). This is probably because roots and fungal hyphae are relatively large and because they can grow in large pores in soil (Jackson, 1975; Marshall, 1976) which, in well-drained soils, are likely to contain air even during wet weather. Fungi have been shown to grow mainly in the outer parts of aggregates (Hattori, 1973).

It is believed that stabilization of aggregates by fungi in the field is limited to periods when readily decomposable material has been added to the soil in large amounts leading to a flush of hyphal growth (Martin *et al.*, 1955; McGill *et al.*, 1973; Low and Stuart, 1974). This may be true of the fungal species which most workers have studied. Such species produce characteristic spores, are isolated easily from soil and grow readily on dilution plates. However, fungal hyphae in the field have been shown to be associated with water-stable aggregates of a red-brown earth, with little seasonal variation; unstable aggregates contained few hyphae (Bond and Harris, 1964). Most of the microbial filaments which have been reported to stabilize aggregates in the field in the presence of plants were probably VA mycorrhizal fungi (Mosse, 1959; Koske *et al.*, 1975; Tisdall and Oades, 1979) (Fig. 6). The water-stability of aggregates of a red-brown earth was related directly to the length of external hyphae of these fungi associated with unit weight of aggregates or soil.

Saprophytic fungi. Saprophytic fungi which remain sterile in culture and which are rare or absent from dilution plates may also be included in temporary binding agents, since some of these sterile species could be isolated from soil in the field throughout the year (Warcup, 1967). This group includes dark-coloured fungi which tend to persist in soil for longer periods than hyaline fungi (Martin *et al.*, 1959; Hurst and Wagner, 1969). These melanic fungi occur widely in soils (Warcup, 1967) but tend to be less conspicuous than sporing fungi so that their importance in aggregation may have been overlooked; yet Martin *et al.* (1959) showed that some melanic fungi stabilized aggregates as effectively as did hyaline fungi.

Vesicular–arbuscular mycorrhizal fungi. Vesicular–arbuscular mycorrhizal fungi are widespread in soils, are obligate symbionts, and so far have not been cultured on artificial media (Mosse, 1973, 1975). Only recently have they been implicated in the water-stability of aggregates of soil. It is believed that VA mycorrhizal fungi tend to be most abundant in soils with low or unbalanced levels of nutrients; however, some plants are mycorrhizal even in fertile soils (Mosse, 1973; Sanders *et al.*, 1975). It is not known how long these fungi persist in soil once the host has died, but hyphae were still present in soil several months after the plants were killed although the hyphae may not have been viable (Tisdall and Oades, 1980*a*).

Little is known of the factors which affect the growth of external hyphae in soil, yet the water-stability of macroaggregates depends on hyphal length. However, the fungi produce extensive hyphae in soil and have been reported to extend 10 mm from the surface of the root (Mosse, 1959; Sanders and Tinker, 1973; Tisdall and Oades, 1979). They extended 30 mm (Hattingh *et al.*, 1973) and 80 mm (Rhodes and Gerdemann, 1975) from the root in soil in modified petri dishes; however, the hyphae may have grown preferentially along the soil plane in the petri dishes so the distances quoted may not represent growth in natural soil.

Other temporary binding agents

Although fungi constitute more than 50 per cent of the microbial biomass in soil and probably contribute more than bacteria to the organic matter in soil (Wagner, 1975; Paul and van Veen, 1978), organic bonds probably develop also from degraded bacterial cells in the rhizosphere or around decaying organic residues (Marshall, 1976; Foster, 1978), i.e. develop from bacterial cells which form transient binding agents.

In desert soils, filaments of blue-green algae formed a solid and mechanically strong net which bound particles of soil or sand into a tough layer on the surface of the soil (Bond and Harris, 1964; Went and Stark, 1968). This layer may become leathery in water and even then may be difficult to break. Algae and lichens or algae and fungal hyphae may also form crusts in desert soils which stabilize the soils against erosion (Fletcher and Martin, 1948; Shields *et al.*, 1957).

Persistent binding agents

Persistent binding agents consist of degraded, aromatic humic material associated with amorphous iron, aluminium and aluminosilicates to form the large organo-mineral fraction of soil which constitutes 52–98 per cent of the total organic matter in

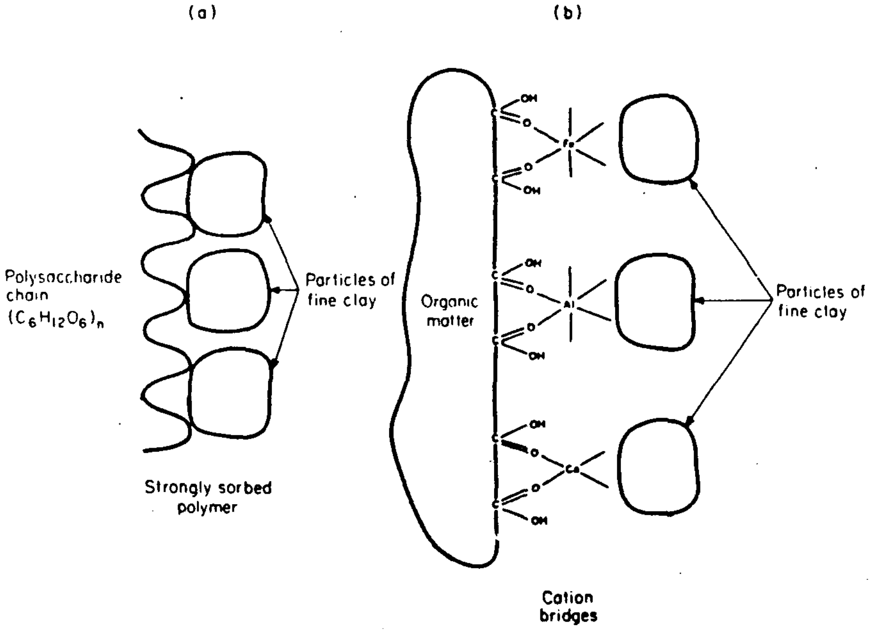

Fig. 7. Interaction of persistent binding agents with the surfaces of clays. (a) Organic polymer sorbed directly to clay surface, (b) humic material associated with clay through di- and trivalent metal cations.

soils (Greenland, 1965; Hamblin, 1977; Tate and Churchman, 1978; Turchenek and Oades, 1978). The persistent binding agents probably include complexes of clay–polyvalent metal–organic matter, C–P–OM and $(C–P–OM)_x$, both of which are $< 250\ \mu m$ diameter, as described by Edwards and Bremner (1967), and are probably included in the skeleton grains described by Bal (1973).

Persistent binding agents are probably derived from the resistant fragments of roots, hyphae, bacterial cells and colonies (i.e. temporary binding agents) developed in the rhizosphere; the organic matter is believed to be the centre of the aggregate with particles of fine clay sorbed onto it (Marshall, 1976; Foster, 1978; Turchenek and Oades, 1978) rather than the organic matter sorbed onto clay surfaces (Emerson, 1959; Greenland, 1965). However, persistent binding agents have not yet been defined chemically. It is likely that a precise chemical formula cannot be defined in the same way that a formula for humic acid cannot be defined. Although some of the binding by persistent materials can be broken with ultrasonic vibration (Edwards and Bremner, 1967), in some soils, especially those with a high percentage of total carbon, organo-mineral complexes within particles 1–20 μm diameter resist limited ultrasonic vibration (Hamblin, 1977; Tate and Churchman, 1978; Turchenek and Oades, 1978).

Also included in this group are strongly sorbed polymers such as some polysaccharides and organic materials stabilized by association with metals (Fig. 7). Multifunctional organic anions associated with di- and trivalent metal cations will act as stabilizing agents, although as mentioned earlier, they may also aid dispersion.

Conclusions

From the pragmatic point of view, it seems reasonable to consider micro- and macroaggregates defined as less than and greater than 250 μm diameter. The microaggregates are stabilized against disruption by rapid wetting and mechanical disturbance, including cultivation, by several mechanisms in which organo-mineral complexes play a dominant role. Polysaccharides are also involved. The

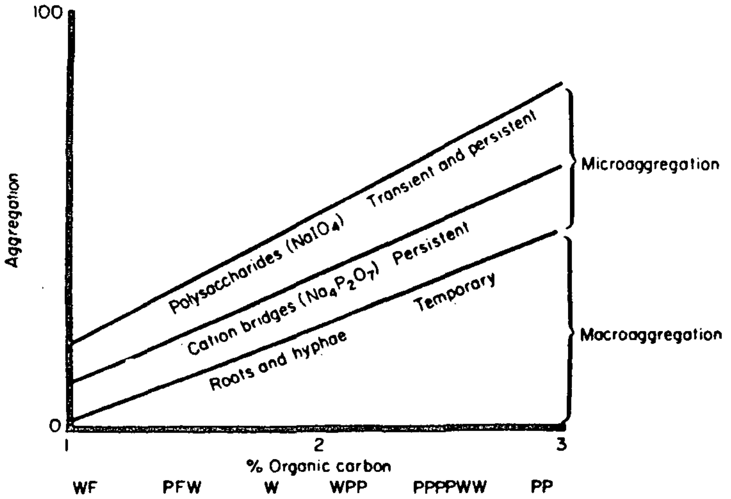

Fig. 8. Effect of crop-rotation on stable macroaggregation. W = wheat, F = fallow, P = pasture.

binding of microaggregates appears to be relatively permanent and is not influenced by changes in the organic matter content of the soil caused by different management, e.g. arable versus ley farming (Fig. 8).

On the other hand, the water-stability of macroaggregates depends largely on roots and hyphae, and thus on growing root systems. Numbers of stable macroaggregates decline with organic matter content as the roots and hyphae are decomposed and are not replaced. The stabilization of macroaggregates is controlled by management, and is increased under pasture and declines when arable cropping is practised, particularly fallow.

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WATER FLOW IN SOIL MACROPORES
I. AN EXPERIMENTAL APPROACH

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Summary

A method is proposed by which the volume of the macropore system and its effect on the infiltration capacity can be estimated using a soil water potential concept. The macropore systems of two large and undisturbed soil samples were investigated. The volumes of macropores were 0.01 and 0.045 of the sample volumes, respectively. When the samples were drained from full saturation to the point where it may be assumed that there was no more water in the macropore system, the hydraulic conductivity decreased by factors of 18 and 4.3 respectively.

Introduction

ALTHOUGH soil water flow is usually described by the equation given by Richards (1931) or its equivalent, there is little doubt that in field soils water can also infiltrate under conditions other than those described by these equations. A number of studies have demonstrated that water may flow in large pores, partially independent of the hydraulic conditions in the smaller pores. Ehlers (1975) studied water flow in single worm holes; Bouma *et al.* (1977, 1978, 1979) described the geometry and spatial distribution of large pores and also estimated the hydraulic conductivity from this information.

The minimum dimensions of macropores, as these large pores will be called, can be estimated from the relationship between the radius R of a cylindrical pore and the capillary potential ψ with which water is held in it. Thus

$$\psi = -\frac{2\sigma}{R\rho_w g} \qquad (1)$$

where σ is the surface tension at the air-water interface,

ρ_w is the density of water,

g is the acceleration due to gravity, and

ψ is in units of length, equivalent to energy per unit weight.

From Equation (1) a pore radius corresponding to a capillary potential of zero is undefined and an arbitrary value of $\psi = -1.0$ cm will be used to

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indicate a boundary between macropores and micropores. The equivalent radius is about 0.15 cm.

The data given by Brülhart (1969, see Fig. 1) show a difference of about two orders of magnitude between the hydraulic conductivity at full saturation and that at a capillary potential of −10 cm. The first value was derived from a throughflow experiment using a falling head device; the second by use of a pressure plate apparatus which maintained constant flow and constant hydraulic gradient across the sample at a constant water potential. From this experiment two modes of water flow may be distinguished. In mode 1 water moves in the absence of capillary forces. The change of water content, $\Delta\theta$, during this phase is about 0.01 of the sample volume. If it can be assumed that the drop in hydraulic conductivity from the saturated value takes place during this phase, then the functional relationship between hydraulic conductivity will be similar to the dotted line of Fig. 1.

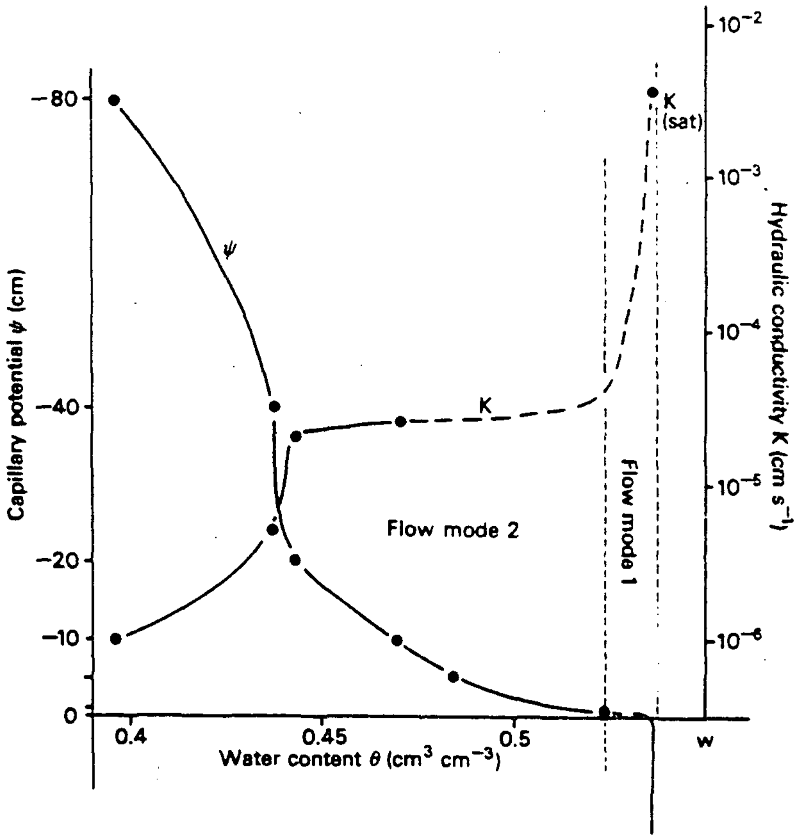

FIG. 1. The two proposed modes of water flow in a soil:
Flow mode 1: water flow in the macropore system (upper limit: hydraulic conductivity at saturation. K_{sat}; lower limit: water held by capillary forces; the macropore system is assumed to be 0.01 $cm^3 cm^{-3}$).
Flow mode 2: water flow in the micropore system. ● data given by Brülhart. 1969. ---- function assumed.

In mode 2 the water flow is not independent of capillary forces. At high capillary potentials, the hydraulic conductivity is close to a constant. but once the air phase in the micropores becomes continuous, conductivity again decreases with soil water potential.

In this interpretation, the porosity of the soil is viewed as a two component system, with a macropore component superimposed on the micropore component. The two components are coupled in that water may be exchanged between them. We recognize that this classification of the soil cavities is highly simplified, and that the criterion for the classification specified above is arbitrary, but the concept will serve as a first model for the interpretation of the experimental results described below. In this study we do not emphasize the effects of single macropores but rather the effect of a complex distribution of macropores as a whole on water flow in large undisturbed soil samples.

Experimental Method

The water flow of the non-saturated, non-capillary zone (flow mode 1 above) is of particular interest. The threshold between micropores and macropores is a matter of convention rather than physical principle. Therefore, the soil water properties of both the macropores and the micropores should be determined on the same sample, with the same equipment and without any interruption between the two modes of flow. The results may then be interpreted in terms of the two flow modes, using tensiometer data to separate them, on the basis of soil water potential, as demonstrated by Anderson and Bouma (1977*a*, *b*). It is possible to fulfil these requirements using a drainage experiment starting with a fully saturated sample. This also avoids the drawbacks of through-flow experiments. Germann (1976), for example, observed a big variation of the hydraulic conductivity at saturation on samples from a loess soil, determined with a falling-head device. Also, Aubertin (1971) reported a rapid decrease of hydraulic conductivity during a through-flow experiment.

The drainage method used here is based on descriptions by Benecke *et al.* (1976) and by Germann *et al.* (1978).

Theory

A large undisturbed soil sample, sealed with polyester resin, is put on a porous ceramic plate, through which the sample may saturate or drain by lifting or lowering the level of the outflow. Tensiometers measure the soil water potential at different heights. They are connected to water column manometers. The hydraulic potentials ϕ_u and ϕ_l of the upper and the lower tensiometers and the total amount of drainage, Q, are recorded over time. During the drainage experiment the outflow has to be placed so as to ensure that a hydraulic gradient of about unity is maintained. The hydraulic properties of the soil system for relatively short time steps, Δt_i, are calculated according to Equations (2) to (4) (see also Fig. 2).

$$\overline{K_i} = \frac{\Delta Q\, \Delta z}{A\, \Delta t_i\, \Delta\phi_i} \qquad (2)$$

where $\bar{K}_i$ (cm s^{-1}) is hydraulic conductivity during the period Δt_i.

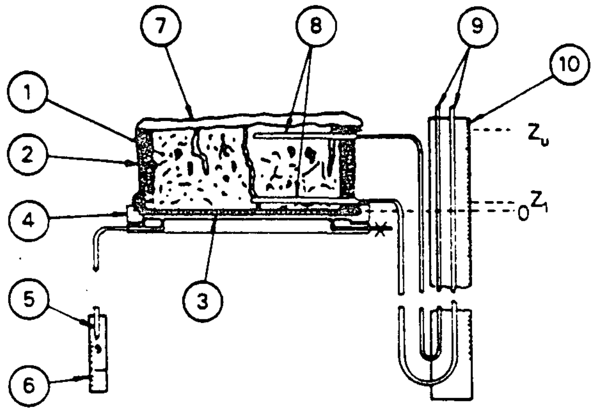

FIG. 2. Design of the outflow method: 1 large undisturbed soil sample; 2 wall of polyester resin and glass fibre; 3 porous ceramic plate; 4 support ring in aluminum; 5 outflow (level can be varied); 6 burette; 7 polyethylene sheet (preventing evaporation); 8 upper and lower tensiometer; 9 manometer tubes (glass); 10 manometer scale, adjusted to the bottom of the sample; z_u and z_l level of the upper and the lower tensiometer respectively.

$\Delta t_i = t_{i+1} - t_i$ (s) where t_{i+1} and t_i are times of readings,

$\Delta Q = Q_{i+1} - Q_i$ (cm^3) where Q_{i+1} and Q_i are the amounts of total outflow from the beginning of the drainage experiments until t_{i+1} and t_i respectively,

A (cm^2) is the cross sectional area of the sample,

$\Delta z = z_u - z_l$ (cm) where z_u and z_l are the heights of the upper and lower tensiometers above some datum,

$\Delta\phi_i = [\phi_{u,i+1} + \phi_{u,i} - \phi_{l,i+1} - \phi_{l,i}]/2$ (cm)

where $\phi_{u,i}$ and $\phi_{l,i}$ are the hydraulic potentials at the upper and lower teniometers respectively at time t_i.

$$\bar{\psi}_i = [\psi_{u,i+1} + \psi_{u,i} + \psi_{l,i+1} + \psi_{l,i}]/4 \tag{3}$$

where $\bar{\psi}_i$ (cm) is the average capillary potential within the sample during the period Δt_i, and

$\psi_{l,i} = \phi_{l,i} - z_l$,
$\psi_{u,i} = \phi_{u,i} - z_u$.

$$\bar{\theta}_i = \theta_f + [Q_f - (Q_{i+1} + Q_i)/2]/V \tag{4}$$

where $\bar{\theta}_i$ (cm^3 cm^{-3}) is average water content during the period Δt_i.
θ_f is the final water content at the end of the drainage experiment,
Q_f (cm^3) is the final amount of outflow at the end of the drainage experiment, and
V (cm^3) is the volume of the sample.

$\bar{K}_i$, $\bar{\psi}$, and $\bar{\theta}$ are then corresponding points on the soil property curves $K(\psi)$, $\psi(\theta)$ and $K(\theta)$. Because the drainage experiments in this study are concerned only with the range of soil water potentials close to saturation, the final water content θ_f is unknown. If the total porosity of the sample e. is given by

$$e = 1 - \frac{\rho}{\rho_r}$$

where ρ is the dry bulk density of the sample, and
ρ_r is the density of the soil material

then θ_f may be estimated by

$$\theta_f = e - Q_f/V$$

and the volume fraction of air filled pores, ε_i, at time t_i by

$$\varepsilon_i = e - \overline{\theta}_i$$

At the threshold between the two modes of flow as indicated by the value of ψ_i, ε_i will be equal to the volume fraction of the macropore system.

If the hydraulic potentials in Equation (2) are expressed with reference to a datum at the base of the sample (as shown in Fig. 2), then a potential $\phi > 0$ indicates a 'water table' or partially saturated conditions within the sample, and $\phi < 0$ indicates unsaturated flow conditions. There is no restriction on the number of tensiometers used for measuring the water potential profile. Where more than two tensiometers are used an average hydraulic gradient can be calculated by taking the first derivative of a smoothed potential profile. It should be noted that drainage experiments where potentials change rapidly over time may show a dynamic potential effect as reported by Vachaud *et al.* (1972), who found a maximum difference in potential at a given water content of about 10 cm between measurements made under continuous drainage (dynamic) conditions and stepwise drainage (static) conditions.

Preparation of a large undisturbed soil sample

A circular block of soil from the chosen soil horizon is carefully excavated by taking away the surrounding soil. In this study the diameter of the block was of the order of 25 cm and the length was at least 20 cm to allow for the preparation of a final length of 10 to 15 cm. The sides of the samples block are sealed *in situ* with polyester resin B and then with two layers of glass fibre mat and polyester resin A. When the walls have set hard, the sample is removed and transported to the laboratory.

Description of the outflow apparatus

The apparatus is shown in Fig. 2 and consists of a high flow porous ceramic plate (air entry value 1.5 bar, hydraulic conductivity 2.5×10^{-6} cm s^{-1}, diameter 27.5 cm, thickness 0.9 cm) sealed into an aluminum support. The sample is sealed to the top of the plate by filling the space between the polyester sample wall and the support ring with a silicon rubber sealant. The bottom of the sample should be a plane surface and care must be taken in cutting the sample not to block any macropores. Fine sand is used to give a good contact between the sample and the plate which should be fully saturated with air-free water prior to mounting the sample. At least two tensiometers are installed in the sample from the side (length 8.4 cm, diameter 0.6 cm, air entry value 1 bar, hydraulic conductivity 10^{-6} cm s^{-1}). The tensiometers are connected to water column manometers. An outflow tube conducts water draining from the sample to a burette. The level of the outflow and the burette can be moved vertically either stepwise or continuously. At the start of an experiment the sample is slowly saturated from the bottom by lifting the level of a water reservoir connected to the outflow. The top of the sample is covered with a sheet of polythene to prevent evaporation.

Results

The soil water properties of two samples have been investigated as follows.

Sample A

This sample was taken from an A_0 horizon at the site of a former hedge at a depth of 0 to 15 cm. The sample had a high content of organic matter with a bulk density of 1.09 g cm^{-3} and many cylindrical worm holes were present. Two tensiometers were installed 1.9 cm and 10.7 cm above the bottom of the sample. The cross-sectional area was 565 cm^2, the height 11.8 cm and the volume 6480 cm^3 (the cross-sectional area at the top was slightly smaller than at the bottom). Two runs were carried out on this sample.

Run A1: the sample was saturated to its upper surface and then the outflow was lowered to level to the bottom of the sample. Thus the bulk of the flow

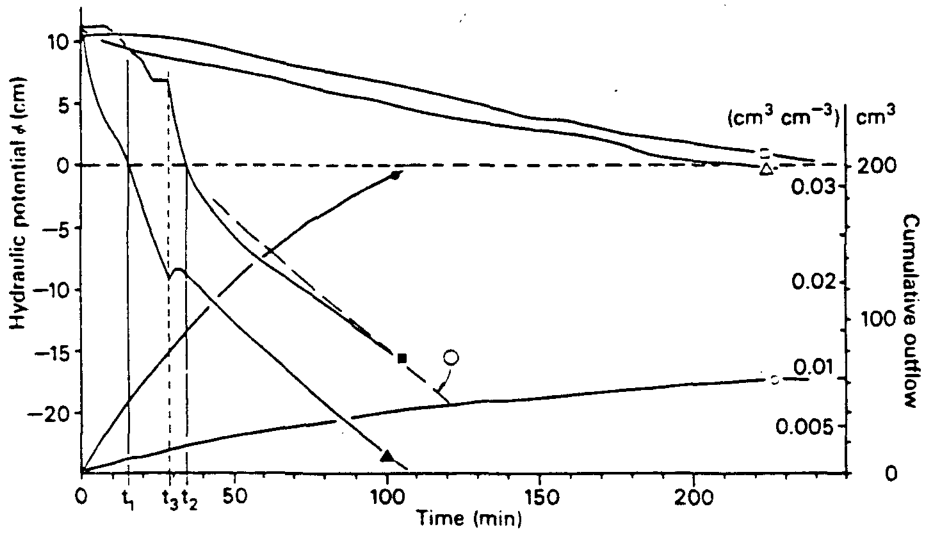

FIG. 3. Potentials from the upper and lower tensiometer and cumulative outflow as a function of time from run A1 and A2. The broken line indicates a gradient of unity; during the period $t_1 < t < t_2$ saturated and unsaturated parts within the soil sample are expected, demonstrated by particular development of the potentials shortly before and after time t_3. ■□ potential of the upper tensiometer (cm); ▲△ potential of the lower tensiometer (cm); ●○ cumulative outflow (cm^3 cm^{-3}); ○△□ run A1; ●▲■ run A2.

should be within the macropores (flow mode 1). Fig. 3 shows the cumulative outflow and soil water potentials during the experiment. If the total outflow at the end of the experiment, 65 cm^3, is taken as an estimate of the volume of the macropore system, the macroporosity is 0.01 of the sample volume.

Run A2: the sample was again saturated to its upper surface, then the outflow was lowered to a level 66 cm below the base of the sample. In this case both modes of flow will be reflected in the drainage from the sample. The results are shown in Fig. 3. The pattern of change of the soil water potentials shows three segments. During the period $0 < t < t_1$ it is assumed

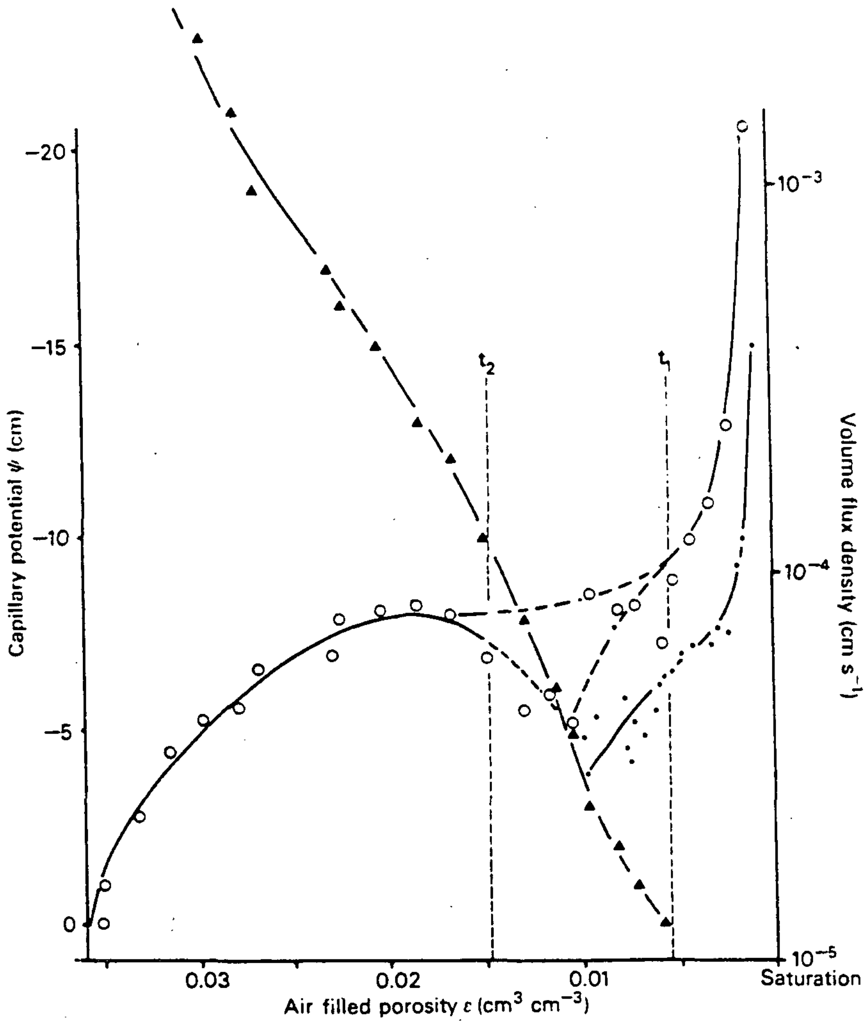

FIG. 4. Soil water properties, deduced from run A1 and A2 plotted against the drained amount of water. ● hydraulic conductivity from run A1; ○ hydraulic conductivity from run A2; ▲ retention curve from run A2; t_1 and t_2 are time when the lower and the upper tensiometer, respectively, indicated unsaturated conditions (t_1 and t_2 correspond with those in Fig. 3).

that the sample is fully saturated to a height indicated by the level of the upper tensiometer. During $t_1 \leq t \leq t_2$ there is a mixed saturated and unsaturated flow, depending on the instantaneous distribution of water within single macropores. The constant potential at the upper tensiometer just before $t = t_3$ and the rapid increase of the potential at the lower tensiometer just after this time suggests the rapid and irregular de-watering of large cavities. In the period $t > t_2$ the drainage is due to unsaturated flow, during which the condition of maintaining a hydraulic gradient close to unity is reasonably fulfilled. The air filled porosity, ε_i, at the time $(t_1 + t_2)/2$ is 0.011 cm^3 cm^{-3}, which may be taken as an estimate of the macroporosity.

Fig. 4 shows the calculated hydraulic conductivity and a part of the soil water retention curve for runs A1 and A2. The hydraulic conductivities deduced from run A1 are smaller than those of run A2. It is felt that due to the low hydraulic gradients during run A1, the resistance of the ceramic plate and the transition zone at the base of the sample have influenced the hydraulic conductivity calculated for run A1. Due to the length of the sample, the onset of fully unsaturated conditions is at an average soil water potential of -5 to -6 cm (approximately half the height of the sample), which differs from the definition of macropores based on Equation 1. However, the potential concept seems to produce consistent estimates of the total volume of the macropore system for both runs.

Sample B

This sample was taken from the transition zone between an A and a G_0 horizon of a soil developed on Oxford Clay at a depth of 20 to 35 cm. Both cylindrical worm holes and fine cracks were observed in the sample. The sample had a cross sectional area at the bottom of 431 cm^2, a height of 11.1 cm and a volume of 5090 cm^3. The dry bulk density of the sample was 1.12 g cm^{-3}. One run was carried out on this sample. The sample was saturated to a few millimeters above its surface so as to obtain a more precise estimate of the saturated hydraulic conductivity. The outflow was then lowered to a level 54.6 cm below the base of the sample. In this experiment pairs of tensiometers were installed on either side of the sample at depths of 1.8, 4.8, 7.8 and 10.5 cm above the base of the sample. Figs 5a and 5b show the development of the two hydraulic profiles. At the start of the experiment when there was a short period of through-flow, there was a hydraulic gradient of about unity within the sample. The calculated value of the saturated hydraulic conductivity was 1.3×10^{-4} cm s^{-1}. Drainage of the sample is expected to start when the falling water table reaches the upper surface of the sample. However, in this experiment this time could not be determined precisely due to the roughness of the upper surface, and the difference between the readings of the two upper tensiometers.

Later in the experiment, on side 2 at 21 minutes (Fig. 5b) and on side 1 at 39 minutes (Fig. 5a) after the start of drainage, the potentials at the upper level decreased faster than those at the second and third highest levels, but not much faster than those at the lowest level. Since evaporation from the sample is prevented this phenomenon may be explained as an effect of the macropores on the flow. If there is a significant decrease in the micropore hydraulic conductivity at the horizon break between the upper two

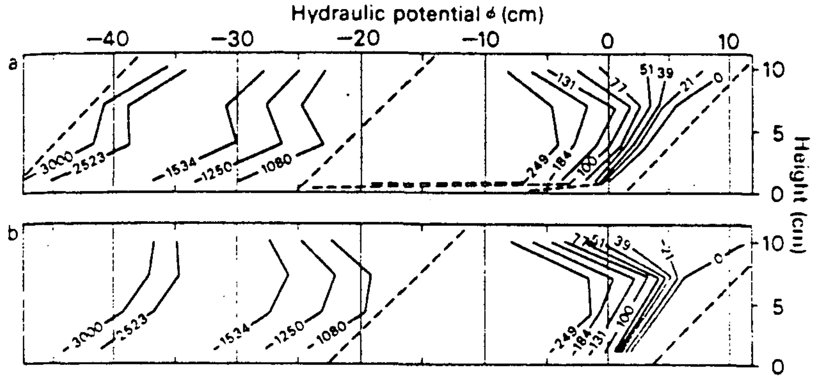

FIG. 5: The development of the potential profiles during different outflow experiments. a. run B, side 1: b. run B, side 2; —21– potential profile (time in minutes after the beginning); ---gradient of unity as a comparison; ------ leads to the potential at the upper side of the porous ceramic plate (note: After about 200 minutes the potential reached almost the final amount).

tensiometer levels, a restriction in the drainage of the upper portion of the sample would normally be expected. If, however, the macropores bypass this layer of reduced hydraulic conductivity the potentials at the upper level adjust to those at the bottom of the sample. The potential at the surface of the ceramic plate is shown on Fig. 5a by a broken line. This effect occurs on side 1 until 249 minutes and on side 2 until 1534 minutes after the beginning of the drainage. Later, the hydraulic gradient again begins to approach a value of unity. This example appears to demonstrate that the macropores have an effect on drainage down to a capillary potential of

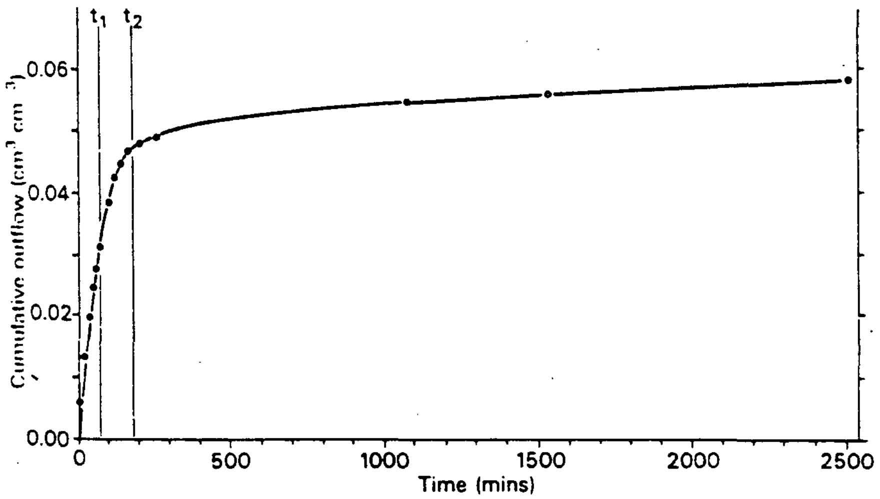

FIG. 6. Cumulative outflow of run B in $cm^3\,cm^{-3}$ of the volume of the sample versus time (minutes); t_1 indicates the time at which saturated and unsaturated (mixed) flow conditions during run B occur. t_2 indicates the time at which only unsaturated flow conditions during run B occur.

about −40 cm. This may be explained by the presence of a secondary soil matrix, superimposed on the low conductivity micropores, that provides lines of preferential movement of pore water. This secondary system must contain water held at high capillary potentials and probably comprises macropores loosely filled with eroded material and fine cracks in the sample. These are not macropores in the terms of the definition used at the start of this paper.

Fig. 6 shows the cumulative outflow derived from this run as a fraction of

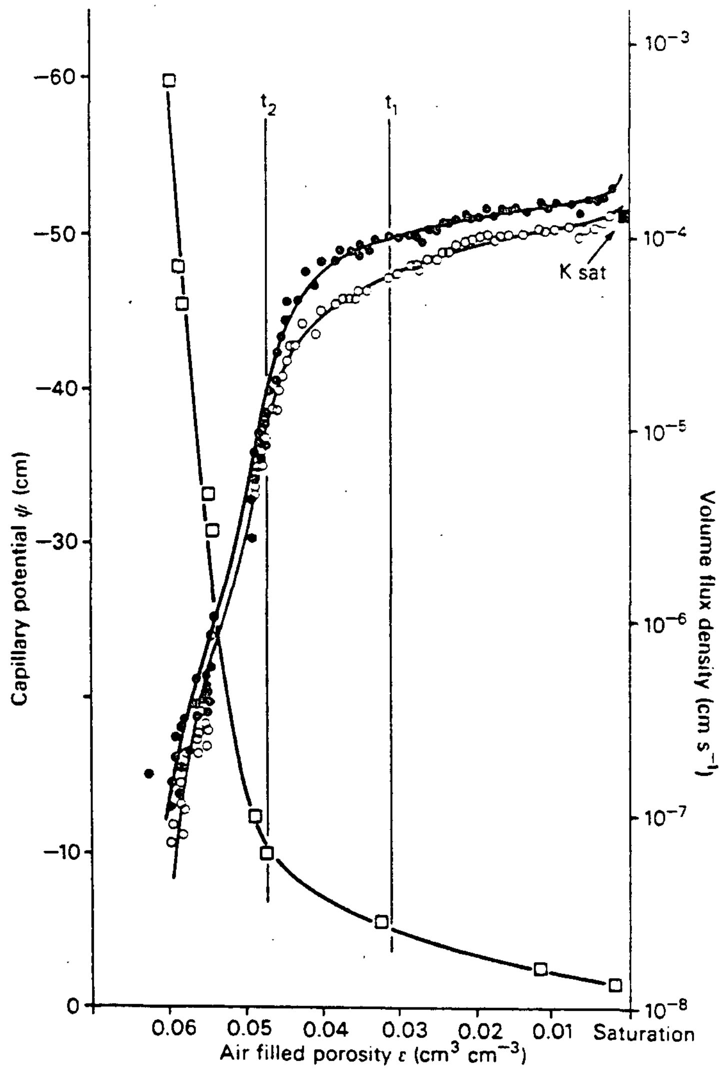

FIG. 7. Soil water properties of sample B versus drained amount of water: □ water retention curve from run B, side 1; ● hydraulic conductivity from run B, side 1; ○ hydraulic conductivity from run B, side 2; for t_1, t_2 see Fig. 6; ■ hydraulic conductivity at saturation (throughflow experiment).

the volume of the sample. The volume of the macropore system is estimated using a similar procedure to that outlined above. The period during which the sample remained partially saturated ($0 < t < t_2$) lasted about 70 minutes (Fig. 5a). From 70 to 148 minutes ($t_1 \leq t \leq t_2$) a mixed mode of saturated and unsaturated flow occurred (Fig. 5b). After that time only unsaturated flow took place. Fig. 6 shows that rapid drainage occurred as long as there was any macropore flow. The calculated air filled porosity at time $(t_1 + t_2)/2$ is 0.045 which may be taken as an estimate of the macroporosity.

The hydraulic conductivity of the sample was calculated using Equations (2) and (4) and a hydraulic gradient derived from the lower two tensiometer levels on each side. The two curves are shown in Fig. 7 and agree well. There is a rapid decrease in hydraulic conductivity at about $\varepsilon = 0.045$ when the macropore system is mostly drained.

A water retention curve is also shown in Fig. 7. The average capillary potential was calculated, although it is recognized that a range of potential is obtained for a given moisture content due to the irregularities down to a potential of about -40 cm.

Discussion and conclusions

A comparison of the results from the two runs on sample A suggests that the potential concept is a useful approach to estimate the volume of the macropore system of a soil, particularly where the cumulative outflow does not show any clear separation between the two modes of flow. The effect of macropores on the flow is clearly demonstrated in the evolution of the potential profile in the sample, with a hydraulic gradient of unity becoming established soon after the sample is fully unsaturated. In run B there was a more obvious influence of the macropores on the cumulative drainage curve. In this case the irregular soil water potential profiles down to about -40 cm leads to the conclusion that in addition to macropores as defined here, there is also a secondary soil matrix that is superimposed on the original

TABLE 1

The volume of the macropore system of two different soil samples and the hydraulic conductivity, K, as a function of the water content, θ (θ_1: full saturated soil sample; θ_2: water content when the macropores are completely drained; $\theta_3 = (\theta_2 - 0.01)$ cm^3 cm^{-3})

	Sample A	*Sample B*
Volume of the macropore system (cm^3 cm^{-3})	0.01	0.045
$K(\theta_1)$(cm s^{-1})	$1.5 \cdot 10^{-3}$	$1.3 \cdot 10^{-4}$
$K(\theta_2)$(cm s^{-1})	$8.3 \cdot 10^{-5}$	$3.0 \cdot 10^{-5}$
$K(\theta_3)$(cm s^{-1})	$3.5 \cdot 10^{-5}$	$4.0 \cdot 10^{-7}$
$K(\theta_1)/K(\theta_2)$	18	4.3
$K(\theta_2)/K(\theta_3)$	2.4	75
$K(\theta_1)/K(\theta_3)$	43.2	325

micropore system. This secondary matrix also allows preferential movement of water through the sample but does not have the same distinct effect on the outflow curve as the macropore system.

The main results of these experiments are summarized in Table 1. It is clear that macropores have an important effect on water flow through field soils when conditions are such as to maintain a supply of water to the macropores. This may occur either when the micropore system approaches saturation or when vertical flow velocities are such as to exceed the infiltration capacity of the micropores, either at the surface due to rainfall, or at a permeability break within the soil. Under these conditions there may be an immediate and dramatic change in the magnitude of the hydraulic conductivity. Whether these conditions are often satisfied, or whether there are other restrictions on the occurrence of macropore flow is the subject of further research.

Acknowledgments

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Chiseling Influences on Soil Hydraulic Properties[1]

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ABSTRACT

Chiseling is now more frequently used for primary tillage in the drylands of eastern Oregon and Washington. Improved measures of chiseling effects on soil water relations are needed to evaluate water intake and infiltration benefits, especially as related to depth of chiseling. Hydraulic conductivity (*K*) and soil water desorption characteristic (SWDC) were field measured in the 120-cm soil profile of a Walla Walla (mesic typic Haploxeroll) silt loam before and after chiseling 43-cm deep.

The test Walla Walla soil is layered. Cation exchange capacity, exchangeable Ca^{2+}, clay content, and organic matter all changed at the 30-cm depth; dry bulk density decreased with depth above 45 cm and was constant below 45 cm; *K* was 10 to 1,000-fold lower in depths above 30 cm; water contents in the SWDC (−50 to −200 mbar range) were lower in upper 30-cm layer.

Chiseling affected both the SWDC and *K* in the upper 30 cm, especially at 10 and 20-cm depths, but had no influence on these measurements at 40 cm. Both water potential at constant water content in the SWDC and *K* were increased especially in the −50 to −300 mbar range. Failure of chiseling to improve water relations in the mild duripan extending from 30 to 45 cm suggests the need for addition of plant residue or chemical amendments into the chisel slots.

Water contents and hydraulic heads during drainage showed that chiseling could reduce evaporation by reducing water content and diffusivity. Overall soil profile hydraulic resistances showed relative average *K* up to 15 times greater as a result of chiseling 43 cm deep, but nearly similar accelerated internal drainages were projected for simulated chiseling to 25-cm depth vs. chiseling to 43 cm.

Additional Index Words: **hydraulic conductivity, soil water characteristic.**

CHISEL PLOWS are now more frequently utilized for primary tillage in eastern Oregon and Washington. The operational component of these chisel plows is a shank, either solidly mounted or spring loaded, to which is attached a twisted or straight chisel point. Often, these chisel points rupture soil layers as deep as 10 cm below the normal depth of moldboard plowing. Oschwald (1973) describes a similar usage trend and operational depth in the Corn Belt.

Even though there is more use of chiseling and significant water intake benefits have been observed, the internal drainage and soil hydraulic properties are not well understood, especially as related to depth of chiseling. Massee and Siddoway (1969) and Lindstrom et al. (1974) showed improved overwinter soil water storage when deep loessial soils (mixed pachic Cryoboroll and mesic Calciorthidic Haploxeroll, respectively) were chiseled 25 to 30 cm deep in the fall. Comparisons were made with no tillage or shallow disking after cereal harvest. Water storage increases were attributed to improved intake from snowmelt or prevention of runoff, an expectation consistent with the observed surface roughness, trashy surface, and improved water intake, shown by Burwell et al. (1968), when chiseling is performed at the same depth as moldboard plowing.

Many indexes (like pore-size distribution, saturated permeability of cores, or infiltration rate) have been used to qualitatively evaluate subsoiling influences on soil water relations. Soil layers below the depth of moldboard plowing will be called subsoil layers consistent with the definition (Soil Sci. Soc. Am., 1973) that *subsoiling* is "any treatment to loosen soil with narrow tools below the normal tillage." Improved infiltration was inferred from increased proportion of large pores and permeability of saturated soil cores taken from the problem subsoil layer (Saveson and Lund, 1958). Increases of infiltration were observed (Campbell et al. 1974; Swain, 1975); when rupture of the

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problem subsoil layer was verified, and changes in surface roughness were not great enough to affect surface detention or water intake. Saveson and Lund (1958) observed an increased water holding capacity, while Savage et al (1968) noted a greater downward distribution of water in the profile due to subsoiling. Swain (1975), Oschwald (1973), and Duley (1957) cited many instances in which subsoiling has not improved or produced any significant changes of soil water indexes. In most cases, it was not determined that water relations of the treated subsoil layer remained unchanged or that changes in profile water relations were unaffected by changes of water relations in the treated layer.

Shallow chiseling undoubtedly improves water intake, soil water storage, and reduces soil erosion (Oschwald, 1973; Wischmeier, 1973) as compared to moldboard plowing, a primary tillage having similar energy requirements. Meanwhile, the value of deep chiseling for improved subsoil water relations is unresolved, because of both poor descriptions of changes in soil water relations and increased energy consumption for deep chiseling. Cooper (1971) showed that draft force on a chisel point can increase threefold for each 5-cm increase of operational depth. Furthermore, Cooper (1971) cited studies by Trouse and Humbert showing that the depth of loosened soil decreased from 0.75 to 0.5 of operational depths when the operational depths were increased from 30 to 90 cm.

Walla Walla (mesic typic Haploxeroll) soils have a slow intake rate typically < 0.7 cm/hour, but little is known about their layered characteristic and associated internal water transmission rates. Runoff and soil erosion are serious management problems, while crop yield increases commonly result from additional stored water.

Our objectives were to measure unsaturated hydraulic conductivities of the various layers in a Walla Walla silt loam before and after chiseling. Such hydraulic properties in a simulated water flow are required ultimately to project chiseling influences on wintertime water intake, water erosion, and soil storage. The influence of chiseling depth on internal water flow was projected provisionally based on additivity of hydraulic resistance and progressive substitution of hydraulic conductivity of the untilled treatment to simulate shallower chiseling depths.

METHODS AND MATERIALS

The experimental field site was located near Pendleton, Oregon in a field alternately cropped to peas (*Pisum sativum* L.) and wheat (*Triticum aestivum* L.). Annual precipitation at this site is about 42 cm with nearly 70% occurring during the winter (November-to-April) period. The test Walla Walla silt loam is underlaid by basalt at about 220 cm.

After wheat harvest in August 1972, an area about 30 by 100 m was divided into two plots each 30 by 50 m. While the soil profile was still dry (soil water contents in the upper 120 cm corresponding to soil water potentials of −15 to −30 bar), one of the 30 by 50-m plots was chiseled three times. Each new pass was made at a 90° angle to the previous pass; chiseling depth was determined by observing the depth of loosened soil after the third pass with the chisel plow. Lateral spacing of chisel points on the chisel plow was 35 cm. Springloaded shanks were used with straight chisel points about 6 cm wide. About 25% of the 4.4-metric ton/ha wheat straw yield remained on the surface after chiseling. The remaining 30 by 50-m plot, designated as untilled, was untreated except that about 75% of the wheat straw residue was removed. Both plots were maintained weed free and untrampled until September 1973, when monoliths were isolated for study of the hydraulic properties. Duplicate monoliths were isolated for each of the two treatments, untilled and chiseled.

Soil hydraulic properties were measured using a modified instantaneous profile method (Klute, 1972) and were developed independently from each monolith. After trenching at least 160 cm deep to expose a freestanding soil monolith (122 by 183 by 160 cm deep), the sides of the monolith were lined with plastic film and backfilled to assure one-directional water flow independent of soil water conditions on the outside of the plastic lining. A surface dike was provided for water ponding by attaching the plastic film to a wooden frame with inside dimensions 122 by 183 cm. Inside the monolith, duplicate tensiometers (1.9-cm diameter cups, 7 cm long) were placed at the 10, 20, 30, 40, 60, 75, 90, 105, and 120-cm depths. Mercury (Hg) manometers were assembled, using Hg reservoirs as described by Doering and Harms (1972). Duplicate neutron probe access tubes were installed to be read at the 15-and 23-cm depths and at each 15-cm interval between 23 and 145 cm. The neutron probe was calibrated earlier in the test Walla Walla silt loam.

To initiate a series of measurements, a constant head (about 5 cm) of water was applied until tensiometer readings stabilized; then the constant water head was removed after which hydraulic heads (h) and volumetric water contents (θ) were measured for 45 days beginning from 2 to 16 October 1973. Hydraulic heads were referenced to the soil surface plane. Soil temperatures at the 10-cm depth ranged from 6 to 14° C. Measurement frequency ranged from 90-min intervals during the first 6 hours to 3-day intervals after 20 days. During this soil drainage period, the soil surface was covered with plastic film to prevent evaporation, and an outer cover was attached to the wooden frame to protect the area from rainfall and sudden temperature changes. All manometer and nylon connecting tubes were sheltered; corrections were made for surface tension at the Hg-nylon interface relative to that at the interface of Hg and glass.

Water intake was measured during surface flooding just before unsaturated drainage. A water stage recorder was used to measure water height in the center drum of a group of three interconnected 208-liter drums, used as a reservoir for each soil monolith, and when water intake was constant and hydraulic heads remained unchanged, infiltration was steady state. Hydraulic conductivity and associated water contents and soil water potential estimated from this water intake will be identified as "steady infiltration."

For each depth, time (t) descriptions of h or θ were smoothed using a spline-fitting technique (Kimball, 1976); from the fitted spline functions, values of h, θ, or $\partial\theta/\partial t$ were calculated for 0.25, 0.5, 1, 2, 4, 8, 16, 24, 32; and 42 days. For a given day these calculated values were then fitted vs. depth (z) using the same spline technique. These second sets of spline functions were used to calculate h, θ, $\partial\theta/\partial t$, $\partial h/\partial z$, or τ ($h = \tau + z$), each as a function of depth. The final depths used were 10, 20, 30, 40, 60, 75, 90, 105, and 120 cm for all five parameters.

In some instances when slope was estimated inaccurately from spline function fits to the observations of h vs. z, $\partial h/\partial z$ was determined directly from h vs. z by averaging pairs of slopes. Each pair of slopes was described by a tensiometer observation at the test and either a shallower or deeper tensiometer depth.

Hydraulic conductivity, K_i, for the i^{th} depth increment was determined as follows:

$$½\left(z\frac{\partial\theta}{\partial t}\right)_{i=1} + \sum_{l=1}^{i}\left\{\left(\frac{\partial\theta}{\partial t}\right)_l(z_{l+1/2} - z_{l-1/2})\right\} = K_i\left(\frac{\partial h}{\partial z}\right)_i \qquad [1]$$

based on the definite depth integral of the equation describing vertical water flow in soil:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left\{K(\theta)\frac{\partial h}{\partial z}\right\} \qquad [2]$$

In Eq. [1], i or l = 1, 2, . . . , 9 indexes the values at depths 10, 20,

Table 1—Some chemical and mechanical properties of the test Walla Walla silt loam.†

Depth increment	pH	CEC	Extractable cations				Mechanical composition		
			Ca^{2+}	Mg^{2+}	K^+	Na^+	Sand	Silt	Clay
cm		meq/100 g	meq/100 g				g/100 g		
0-15	5.8	16.8	9.8	3.5	1.4	0.1	12.4	68.8	18.8
15-23	5.8	17.2	10.6	3.9	1.3	0.1	12.0	68.4	19.6
23-30	5.8	17.0	10.4	3.7	1.5	0.1	11.5	70.0	18.5
30-38	6.7	18.6	12.7	4.3	1.3	0.1	11.5	70.0	18.5
38-46	7.0	17.9	13.1	4.1	1.1	0.1	12.0	71.3	16.7
46-53	--	--	--	--	--	--	12.4	70.8	16.8
53-61	7.2	18.8	13.0	4.2	0.9	0.1	12.3	74.0	13.7
61-76	7.3	19.2	14.0	4.3	0.9	0.2	12.1	72.0	15.9
76-91	7.8	18.8	14.3	4.5	0.9	0.2	11.2	74.3	14.5
91-122	8.3	17.6	31.0	6.0	0.8	0.3	10.1	77.0	12.9

† Free lime concentrations were <0.05 g/100 g at depths <90 cm, but increased from 0.42 at 99 cm to 1.72 g/100 g at 150 cm.

. . ., 120 cm. Depths midway between those shown by integral i subscripts are designated by $z_{i\pm 1/2}$. For $i = 9$, $z_{i\pm 1/2}$ would be 127.5 cm. Hydraulic conductivities using Eq. [1], and associated water contents (soil water potentials) will be identified as "unsaturated drainage."

Some chemical and physical properties of the test Walla Walla soil were measured at 7.6-cm depth increments. Cation exchange capacity (CEC) was determined with a 1*N* NH_4OAc (pH 7) extracting solution (Schollenberger and Simon, 1945). Extractable cations were determined from a single extraction with a 1/20 (soil/neutral 1*N* NH_4OAc) solution (Pratt, 1965). In noncalcareous soils, a single extraction accounts for about 95% of that obtained with multiple extractions. The pH was determined using a glass electrode inserted into the supernatant of a soil/water (½) mixture. Mechanical analysis was determined using a combination of sieve separation of fractions greater than fine silt and pipette analysis for the fine silt and clay fractions. Field bulk density was determined using either a Washington Dens-o-meter[3] or a Utah core (1.87-cm diameter) sampler; the Washington Dens-o-meter is a highly accurate method utilizing the principle of soil excavation and in situ estimation of the volume of the excavation.

RESULTS

Layered Characteristic of the Test Walla Walla Soil

Selected chemical and mechanical characteristics (Table 1 and Fig. 1) show that the test Walla Walla silt loam is layered. At the 30-cm depth, pH, CEC, and extractable Ca^{2+} or Mg^{2+} notably increased with only small additional increases in the 30 to 90-cm depth. Soluble salts were always < 0.7 mmhos/cm, so that extractable Ca^{2+} or Mg^{2+} in Table 1 are good estimates of exchangeable Ca^{2+} or Mg^{2+}. Thus, exchangeable Ca^{2+} was $< 61\%$ above 30 cm, but $> 68\%$ below 30 cm. Exchangeable Ca/Mg ratios ranged from 2.8 above 30 cm to > 3.1 below the 30-cm depth. These chemical characteristics apparently distinguished the plow layer and subsoil.

Dry bulk density measurements neither detected a compact layer nor distinguished the plow layer from the subsoil. Dry bulk density decreased from about 1.34 gm/cm³ at the 10-cm depth to < 1.15 below 45 cm (curve labeled 21 Oct 74 in Fig. 1); a nearly constant dry bulk density below 45 cm suggests a difference of soil characteristics at 45 cm. Associated particle density of 2.56 g/cm³ indicated sufficient total porosity to preclude significantly compact layers.

Clay percentages in Table 1 decreased below the 23-cm depth while CEC increased below 30 cm depth. Organic matter also decreased from 2.2% above 30 cm to 1.7% or less below 30 cm. These characteristics indicated formation of a mild duripan, according to criteria of Flach et al (1974).

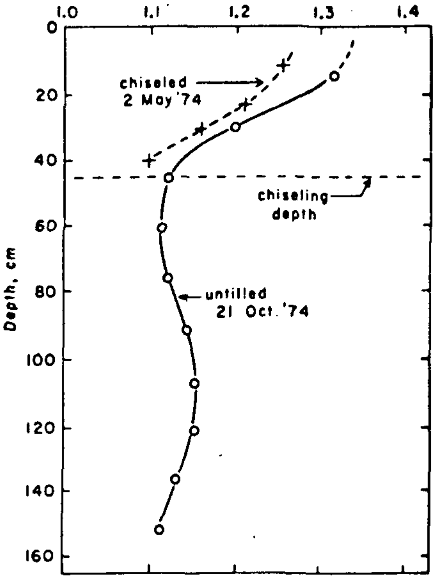

Fig. 1—Dry bulk density of the test Walla Walla soil before and after a chiseling treatment.

In late summer 1974, when the soil profile was dry, there was a high strength layer above 50 cm, even though dry bulk density measurements did not suggest compaction as a causative agent for high strength. Profiles in the untilled treatment, exposed in August 1972, showed three layers above 45 cm, i.e., two high strength layers at 10- to 15- and 30- to 45-cm depths, and a moderate-to-high strength layer containing partially decomposed small grain straw at the 15- to 25-cm depth. High strength was noted by resistance to penetration by a sharp instrument.

Slow internal drainage in the Walla Walla silt loam cannot be attributed to chemical or mechanical features below 45 cm (Table 1). Free-lime concentrations (not shown) were <0.05 g/100 g, and pH was consistently < 7.3 in the layers above 90 cm. At 90 cm, free lime content increased to 0.42, g/100 g. Exchangeable Na^+ remained $< 2\%$ throughout the profile above 120 cm.

Reduced dry bulk density of the chiseling treatment with no subsequent field traffic (Fig. 1) was still evident after the 1973 winter. Dry bulk density, with a standard error $< 2.2 \times 10^{-2}$ g/cm³, for the untilled treatment was obtained on 21 October 1974 using a Washington Dens-o-meter. Each mean for the 2 May 1974 curve shown in Fig. 1 had a standard error $< 3.6 \times 10^{-2}$ g/cm³. Thus, the change of dry bulk density due to chiseling shown in Fig. 1 was not the maximum change caused by chiseling, but was residual after exposure to a winter rainfall season.

Soil profiles, exposed just after chiseling August 1972, showed chiseling penetration to 43 cm and a loose mixture of clods ranging from 10 cm to 0.5 mm diameter over the whole 0-to 43-cm depth.

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[3] Trade names and company names are included for the benefit of the reader and do not infer any endorsement or preferential treatment of the product listed by the USDA.

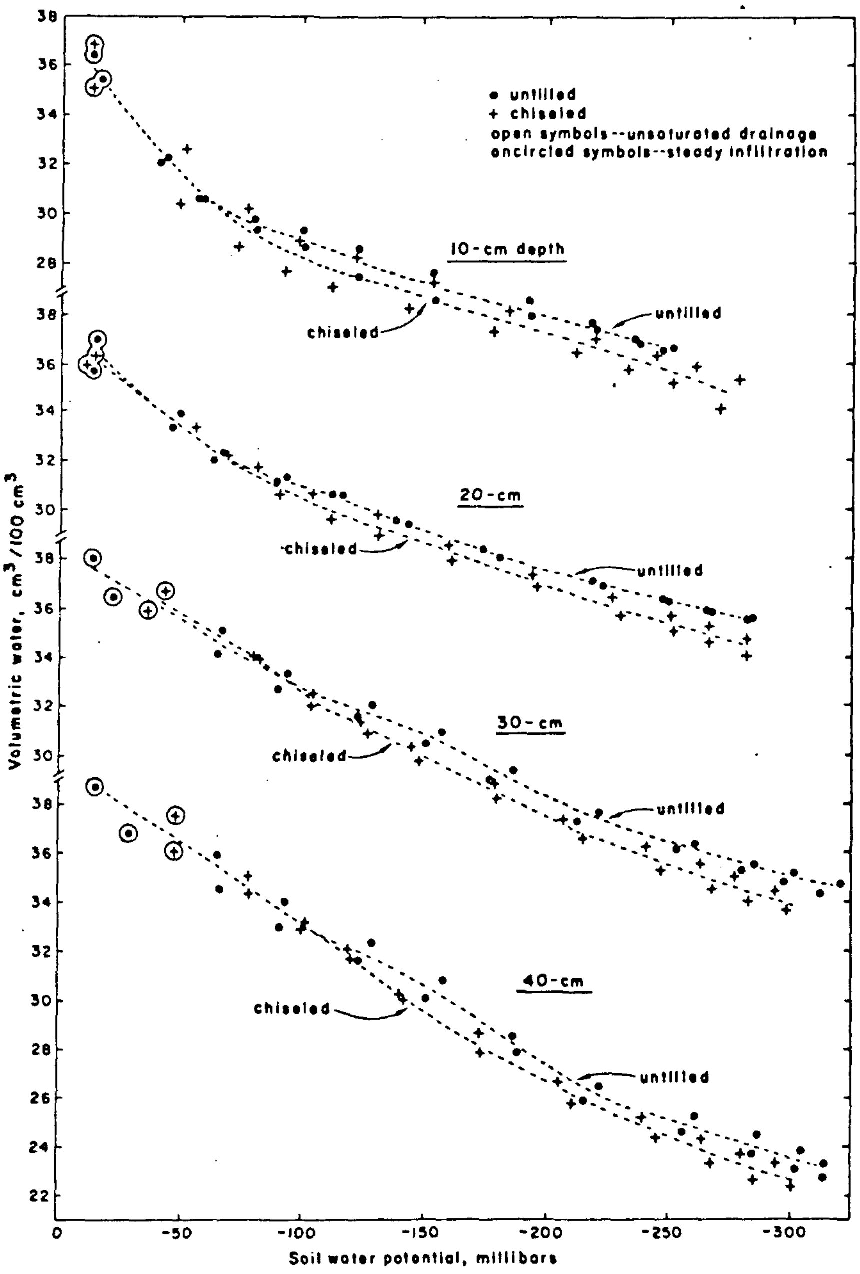

Fig. 4—Chiseling effects on soil water desorption characteristic at the 10, 20, 30, and 40-cm depths in the test Walla Walla soil.

depths ≤ 30 cm, both replications of the untilled treatment showed greater water contents than the two replications of the chiseled treatment over the whole potential range. This separation was less at 40 cm than at shallower depths, and disappeared below 40 cm (tillage treatments were not distinguished in Fig. 5). This systematically greater water content in the untilled treatment at depths shallower than 40 cm and at water potentials < −80 mbars is a true tillage effect, because if there were no treatment differences the probability of having two nearly equal untilled values greater than two nearly equal chiseled values is 0.15.

Hydraulic conductivity (K) of the untilled soil layers differed at depths shallower than 40 cm (Fig. 6 and 7), but all layers from 40 to 120 cm had similar hydraulic conductivity relationships. All layers had the same K at water potentials > −15 mbars, but at −300 mbar potential the K of the 40-cm layer was 100 times greater than that of the 10-cm layer. The K of the 20- and 30-cm layers at −300 mbar were about 10 and 20 times greater, respectively, than that of the 10-cm layer. Dry bulk density decreased linearly with depth to a constant value at 40 cm and below (Fig. 1). The uniform density below 40 cm corresponds with a single conductivity function for the same layers.

The K values in the 10-, 20-, and 30-cm layers were sensitive to the chiseling treatment. In Fig. 6, an approximate curve for each of the two treatments was drawn through the composite scatter of points provided from two instrumented monoliths. An unexplained discontinuity occurred at K of

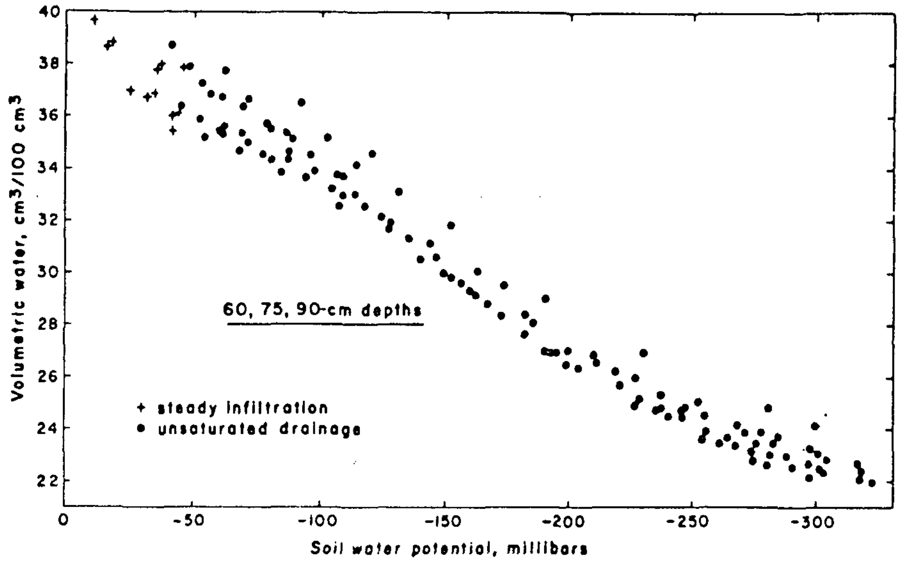

Fig. 5—Soil water desorption characteristic in the 50 to 97-cm layer of the test Walla Walla soil.

about 0.5 to 1 cm/day in the 10-, 20-, and 30-cm depths, which corresponded with the separation of treatments in the water characteristic curves of Fig. 4. Tillage treatment effects occurred in the 10-, 20-, and 30-cm layers, but not in the 40-cm layer. *Treatment effects in Fig.* 7 for the 60- through 90-cm depths should not be expected and in fact all four instrumented monoliths gave similar curves of *K* vs. water content. Surface layers in the chiseled treatment unexpectedly exhibited lower *K* than in the untilled treatment at water potentials > −15 mbar. At lower water potentials (−300 mbar), the *K* of the chiseled treatment was greater than that of the untilled treatment by a factor of 10, 5, and 2 for the 10-, 20-, and 30-cm layers, respectively. The crossover points, or water potentials providing equal *K* for both treatments, were −20, −25, and −60 mbars for the same three layers.

DISCUSSION

In this study, evaluations of chiseling effect on soil hydraulic properties were made after at least 25 cm of water had been continuously infiltrated through the surface soil layers. Other studies (Burwell et al., 1968; Burwell and Larson, 1969) showed that chiseling (or other treatment

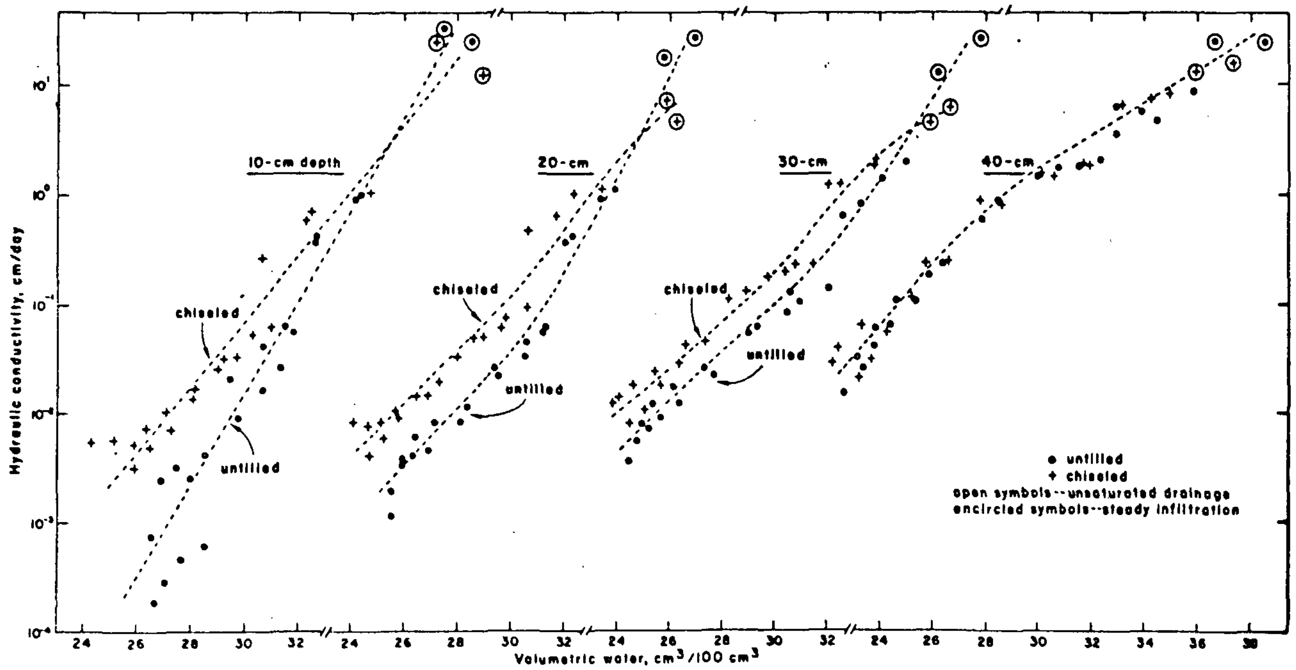

Fig. 6—Chiseling effects on hydraulic conductivity at the 10, 20, 30, and 40-cm depths of the test Walla Walla soil.

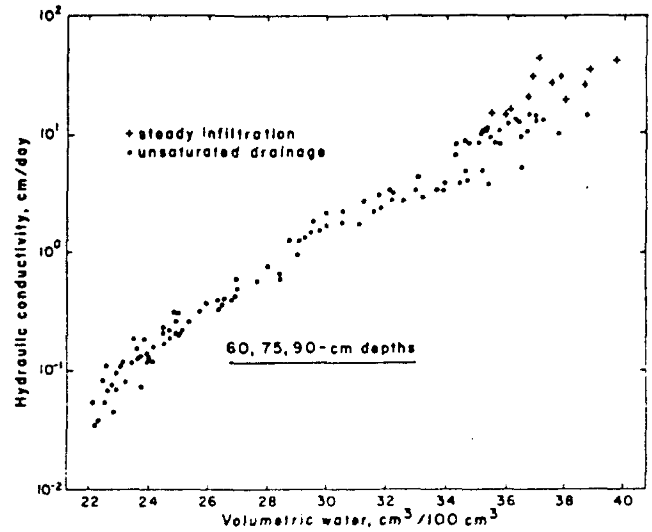

Fig. 7—Hydraulic conductivity in the 50 to 97-cm layer of the test Walla Walla soil.

providing a cloddy surface condition) infiltrated at least 50% more water than did the nonchiseled (packed and consolidated) counterpart before runoff occurred, but during the runoff phase (after about 10 cm of simulated rainfall), the intakes were often not affected by tillage treatment when there were no residues on the surface. Falayi and Bouma (1975) found similar results before runoff occurred, but little tillage effect during subsequent steady-state infiltration. Our lower steady-state infiltration rate (and associated lower *K* in surface soil layers) in the chiseled treatment did not agree with these studies on soils with greater stability (higher clay and organic matter contents). Surface layers of the test Walla Walla soil have relatively lower shear strength when nearly saturated (as expected from the lower water stable aggregation), particularly after the surface layer was pulverized by three chiseling passes. Greater slaking and fewer cracks occurred during ponding of the chiseled treatment, perhaps because plant rooting and wetting and drying had not yet stabilized the surface layers pulverized by chiseling.

After about 25 cm of water had been infiltrated through the surface soil layer, chiseling affected the SWDC and *K* over the potential range -50 to -300 mbar. At a given water content, chiseling increased both the potential and unsaturated *K*. Bulk density measurements and observed dry soil after chiseling indicated that the chiseled soil was an assemblage of aggregates. These observations agreed with those showing that *K* increased when aggregate size increased the water potential at a constant water content (Amemiya, 1965) which was true for assemblages of uniform or mixed diameter aggregates. Usually, higher water potential and *K* at constant water content were produced by decreasing aggregate diameter; an observation determined by aggregate diameter effects on pore (intra and interaggregate) diameter distribution. This latter finding of Amemiya (1965) cannot be applied to the chiseled vs. untilled comparison without more detailed information about the comparative soil structure.

Farrell (1972) deduced *K* vs. potential relations from the geometry of anchor rings of water in assemblages of solids. A lower theoretical *K* was predicted for an aggregated media as compared with a compacted soil slab. When the effects of aggregated media on the water potential at constant water content are considered, the results of Fig. 4 and 6 agree with Farrell's (1972) theoretical projections.

Table 2—Calculated average hydraulic conductivity of the 120-cm Walla Walla soil profile as related to chiseled depth.

	K_o, mm/day, at indicated time in days after removal of ponded water		
Profile treatment and (depth)	0.5	2	16
Untilled	0.96	0.27	0.016
Chiseling (43 cm)	4.2	1.6	0.20
Simulated chiseling (25 cm)	4.0	1.5	0.19
Simulated chiseling (15 cm)	3.6	1.3	0.15

The most useful projections about chiseling effects on intake and redistribution could be realized by soil water flow simulations using the measured hydraulic properties and intermittent rainfall. Meanwhile, several water conservation features can be projected even without considering runoff. When runoff is a part of the hydrologic system, these benefits have even greater importance.

The significant reduction in water content of the upper 40-cm layer of the chiseled treatment even after 2-days drainage and redistribution (Fig. 2) is expected to decrease surface evaporation which decreases as soil water content (water diffusivity) decreases (Hanks and Gardner, 1965). During long periods of intermittent, low-intensity rainfall and low potential evaporation (like that of Pacific Northwest winters) the increased drainage in the chiseled treatment is expected to facilitate soil-water storage accumulations, especially after the soil profile has been wetted to at least the 120-cm depth as was done to prepare the test monoliths for unsaturated drainage studies. The increased K at constant water content due to chiseling and also increased turbulent drying as the soil porosity is increased (Allmaras et al., 1977) are both nullifying influences that must be considered in any net soil water storage projections.

An average hydraulic conductivity, K_o, was obtained assuming that the hydraulic resistance of the 120-cm profile could be estimated as the sum of hydraulic resistances of individual layers in the profile (Swartzendruber, 1960). These K_o are shown in Table 2 for 3 different days after the beginning of unsaturated drainage, and for one observed and two simulated depths of chiseling. The estimated *K* for each soil layer was based on an average water content of the two tillage treatments in Fig. 2. Compared to the untilled soil, chiseling to 43 cm shows a relative soil drainage of 4.4 after 0.5 day of drainage, but which increases to 12.5 after 16 days of drainage. The greatest increase of K_o per unit of chiseling depth was projected from simulated chiseling at 15 cm while K_o increased only negligibly for chiseling at 43 cm as compared with that projected from a 25-cm depth of chiseling. The relative K_o increases for chiseling at 25 cm were 4.2 and 11.9 for 0.5 and 16 days, respectively, after water ponding. This small increase of internal drainage for chiseling deeper than 25 cm does not itself justify the associated energy expenditure. The small response of the 30-cm *K* to chiseling in Fig. 6 verifies this suggested 25-cm depth of chiseling. Yet, the *K* at 30 cm in Fig. 6 is low enough to impede soil drainage. Probably, chiseling deeper than 25 cm would be more beneficial if it were combined with residue placement or chemical amendment. These possibilities are currently being investigated.

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New Methods of Studying Soil Detachment due to Waterdrop Impact[1]

M. AL-DURRAH AND J. M. BRADFORD[2]

ABSTRACT

An improved and inexpensive raindrop tower 8.9 m in height was designed so that a single drop will hit a soil target area 1.6 cm in diameter. The soil used in this study was taken from the surface 15 cm of an Ida silt loam (mesic Typic Udorthents). The surface shear strength was altered by remolding the soil to three bulk densities and by equilibrating the cores to matric potentials of -5, -19, -38, and -62 mbars. The weight of soil detached from the impact of single waterdrops 3.0, 4.6, and 5.6 mm in diameter was closely correlated with the undrained soil shear strength as measured by the Swedish fall-cone device. A correlation coefficient of 0.97 was found between splash weight and a linear function of the ratio of waterdrop kinetic energy to the soil shear strength. The fall-cone method of determining soil shearing strength is rapid, inexpensive, and could be easily adapted to field use.

Additional Index Words: erosion mechanics, rainfall erosion, shear strength, soil splash.

Al-Durrah, M., and J. M. Bradford. 1981. New methods of studying soil detachment due to waterdrop impact. Soil Sci. Soc. Am. J. 45:949-953.

QUANTITATIVE MEASUREMENT of soil detachment due to raindrop impact is needed for a better understanding of soil erosion. Research of this nature began as early as 1944 by Ellison (Ellison, 1944). Since then, many studies on measuring soil splash have been conducted using different devices and techniques. In general, two problems restricted investigators from being able to directly measure the amount of soil splash from a single raindrop at terminal velocity. These were the horizontal drifting of a waterdrop at its terminal velocity and the difficulty in collecting the soil splash.

Since the kinetic energy of a raindrop depends upon the fall velocity and the fall velocity depends upon drop height, the tower height is critical to raindrop studies. A drop height of about 20 m is required for drops 2 to 6 mm in diameter to reach their terminal velocity; the fall distance, however, to reach 95% terminal velocity is only about 8 m. Thus, in order to obtain energies similar to those occurring in natural rainfall, drop towers 8 m or higher must be used. At these heights, the drift of free-falling waterdrops becomes a serious problem.

Mutchler (1965), using single drops 3.5, 4.2, and 5.6 mm in diameter freely falling 9.75 m, determined that about 10, 30, and 60% of the drops fell outside 5.0-, 3.8-, and 2.5-cm diameter circles, respectively. Cruse and Larson (1977) found that, even with a fall height of 177 cm, some drops fell outside a soil target 2.0 cm in diameter. To determine water splash amounts from waterdrops falling 9.75 m onto various depths of water over smooth glass, Mutchler and Larson (1971) used glass plate targets 7.65 cm in diameter. Sloneker et al. (1976) collected splash from sands with an annular splash cup fitted around a core 3.8 cm in diameter; the waterdrops, however, were dropped from a height of 3 m.

The possibility of collecting all the splash for a single drop impact decreases as both the target area and the splash angle with the horizon increases. A large splash angle causes the detached particles to fall relatively close to the point of impact. Mutchler and Larson (1971) determined water splash by weighing the portion of the waterdrop and target water that remained after impact. Because of the limitations in collecting splash from single drops, much of the raindrop splash research has been directed to multidrop experiments. The use of relatively large soil containers and multidrops, however, limits the collection of soil splash to the container edge.

In this study we present the design of a raindrop tower that reduces the variability of single drop impact points. The tower eliminated drifted waterdrops and allowed a single drop at near-terminal velocity to hit a soil target 1.6 cm in diameter. Splash was measured at several soil surface bulk densities and water potentials using three waterdrop diameters. Detached soil particles were caught using a newly designed splash collector.

In studying soil detachment due to raindrop impact, much work has been carried out on evaluating the effect of changing soil properties on soil detachment (Woodburn, 1948; Barnett and Rogers, 1966; Lyles et al., 1969; and Wischmeier and Mannering, 1969). Many relationships were developed for estimating the amount of splash as a function of some specific soil, raindrop property, or both. One relationship, developed by Cruse and Larson (1977), estimated splash as a function of soil shear strength. The relationship was in this form:

$$(D \times 10^{-4})^{1/2} = a + b\tau + c\tau^2,$$

where D is the amount of detached soil in grams, τ is the soil shear strength determined by the unconfined compression test, and a, b, and c, are constants. Soil shear strength was altered by varying soil bulk density and matric water potential and by adding polyvinyl alcohol. A close correlation between surface soil detachment by a single simulated 4.8-mm raindrop falling from a height of 177 cm onto remolded soil cores and soil shear strength was found.

The shear strength test procedures used by Cruse and Larson (1977), i.e., unconfined compression tests on soil samples 3.0 cm in length and 1.09 cm in diameter, were relatively time-consuming and required expensive equipment and complicated test procedures. The unconfined compression strength test requires a 2:1 length-to-diameter ratio, and a uniformly dense core of these dimensions is difficult to compact, especially for the low densities (ρ_b) such as we used in this study. Normally, minimum ρ_b is located at the core center, and since the failure plane passes through the center, some uncertainty exists concerning the magnitude of the ρ_b along the failure plane.

This investigation provides an alternative method for determining the soil shear strength using the Swedish

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[1] Contribution from USDA-SEA-AR in cooperation with the Purdue Agric. Exp. Stn. Journal Paper no. 8341. The Senior Author's salary was from the Ministry of Higher Ed. and Scientific Research, Baghdad, Iraq. Received 13 Mar. 1981. Approved 15 June 1981.

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Table 1—Properties of Ida silt loam.

Property	Quantity
Sand	1.7%
Silt	75.3%
Clay	23.0%
Organic matter	3.3%
Cation exchange capacity	28.7 meq/100 g
Total surface area	93 m^2/g

fall-cone test (Hansbo, 1957) and evaluates the relationship determined by Cruse and Larson (1977) with a newly developed raindrop tower, a different splash collector, and the fall-cone shear strength device.

MATERIALS AND METHODS

Soil Material

The soil used in this study was from the surface 15 cm of an Ida silt loam, a fine-silty, mixed (calcareous), mesic Typic Udorthent. Selected soil properties are given in Table 1. Organic matter was determined by the Walkey-Black method; cation exchange capacity (CEC) by the ammonium acetate method; sand, silt, and clay fractions by the hydrometer method (Day, 1965); and total surface area by the ethlyene glycol monoethyl ether method (Cihacek and Bremner, 1979).

The soil was air-dried, ground, sieved through a 1-mm screen, moistened by spraying water, and mixed until the water content was about 15%. The moist soil was then compressed into acrylic rings 5.7 cm in length and 7.6 cm in diameter. A 0.5-cm thick porous disk, having the same diameter as the ring, was pushed into one end of the ring. The soil was then trimmed from the other end. The compressed bulk densities were 1.03, 1.14, and 1.31 g/cm^3. The soil cores were placed on glass bead tension tables and allowed to become saturated. During saturation, the soil swelled to dry bulk densities of 1.00, 1.10, and 1.20 g/cm^3, respectively. After saturation, matric potentials of -5, -19, -38, and -62 mbars at the soil surface were applied to each bulk density level. Since a decrease in pore water potential changed the density of each core differently, the three bulk densities were then designated as levels low, medium, and high, respectively. Three replicate cores were formed for each of the three bulk densities, four matric potentials, and three raindrop sizes. The same soil core was used for soil detachment and falling cone penetration measurements.

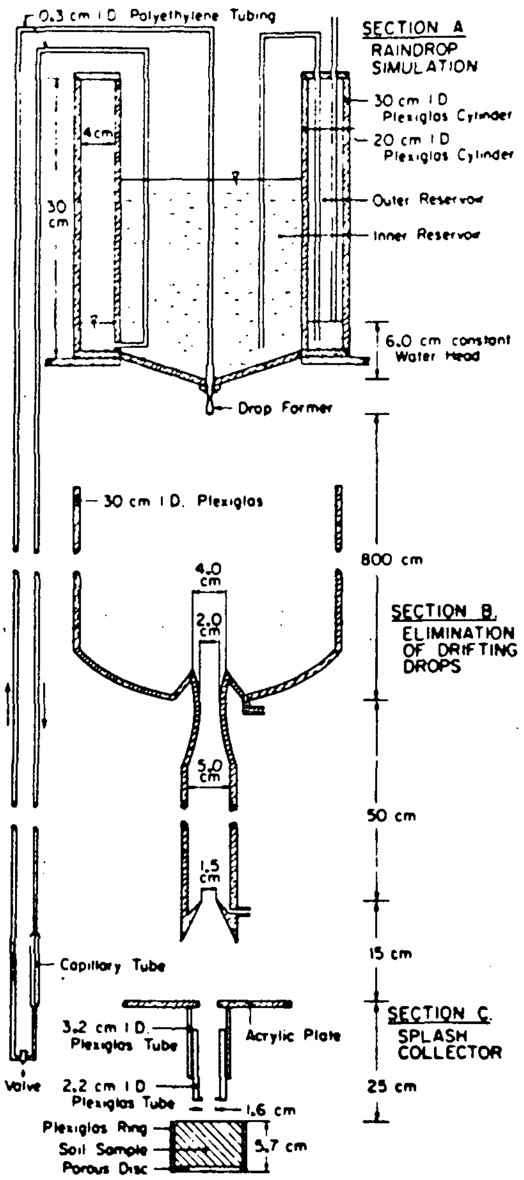

Fig. 1—Schematic diagram of the raindrop tower.

Splash Measurement

Figure 1 shows the design of the new raindrop tower. The tower frame was constructed using Unistrut,[1] 41- by 41-mm 12-gauge channel iron, and had a horizontal cross section of about 1 by 1 m^2. The raindrop simulator was fixed onto a wooden board resting on the tower top (Fig. 1, section A) and had two cylindrical reservoirs. The outer was air-tight and was connected to the waterdrop former through polyethylene tubing that extended to the bottom of the tower at the target area. This arrangement allowed control of the water supply to the dropper from the target area. The inner reservoir was connected to the outer reservoir through a Marriott-type arrangement so that a constant hydraulic head of 6.0 cm was maintained over the drop former throughout an experiment. The temperature of water ranged from 27 to 30°C. Three sizes of drop formers built to specifications by Mutchler and Moldenhauer (1963) were used to produce 3.0-, 4.6-, and 5.6-mm drops.

The outer path of the falling drop was shielded by means of a polyethylene sheet to reduce drifting of drops caused by air currents. In addition, drifting was further controlled by using the two-stage system shown in Fig. 1, section B. The first stage, 800 cm below the drop former, was made from a sharp-edged, 4.0-cm i.d. tube that nar-

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[1] Trade names and company names, included for the benefit of the reader, do not imply endorsement or preferential treatment of the product listed by the USDA.

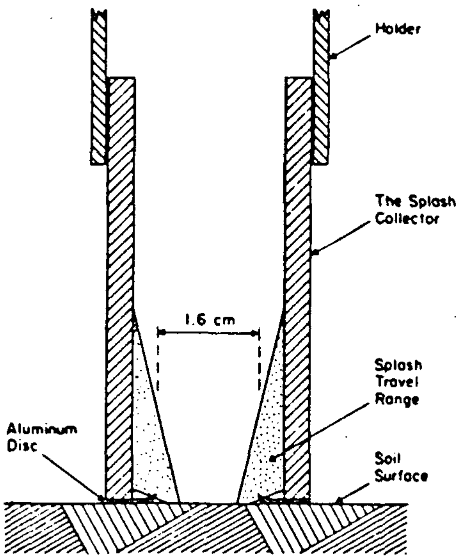

Fig. 2—Schematic design of the splash collector.

rowed to a minimum of 2.0 cm and gradually increased again to 5.0 cm. The second stage, located about 50 cm further down, was a sharp-edged cone with an upper i.d. of 1.5 cm and lower i.d. of 6.0 cm. All drops falling outside the 4.0-cm diam opening were eliminated. Those striking the inner wall or the sharp edge flowed along the inner walls of the tube as a result of surface tension. The same process was repeated at the 1.5-cm opening; only those drops not touching the opening passed. All drops which passed through section B of the tower fell onto a 1.6-cm diam target located 40 cm further down.

The splash collector (Fig. 1, section C) consisted of two cylinders. The upper cylinder was attached to a stationary acrylic plate 15 cm below the second stage of the drift control. The plate protected the soil sample from the splash of drops which occasionally might still hit the upper edge to the cone in the second stage. The upper cylinder also served to hold the lower cylinder, which was the actual splash collector, and allowed it to move up and down along a vertical axis. An aluminum disk with a hole 1.6 cm in diameter in the center was attached to the bottom of the lower cylinder. A 1-mm beveled edge around the hole prevented the soil - water mixture from flowing back onto the sample.

Figure 2 shows the splash collector lowered to contact the soil surface. Observations from high speed photography showed that the splash angles ranged from about 15 to >40 degrees. The splash travel range is indicated by the shaded area in Fig. 2. Most of the soil and water splashed onto the sides of the container.

When the system was tested, we found that, under conditions of the experiment, the percentages of drops which passed through the splash collector hole were 50, 40, and 10% for drops 5.6, 4.6, and 3.0 mm in diameter, respectively. The rate of drop formation was controlled either by altering the hydraulic head above the drop former or by changing the diameter and length of the capillary tube between the constant head reservoir and the drop former. The latter procedure was used in this experiment. A capillary tube 7.0 cm in length and 1.0 mm in diameter controlled the rate of flow at 5.0, 4.0, and 1.0 cm^3/min for the 3.0-, 4.6-, and 5.6-mm diam drop formers, respectively.

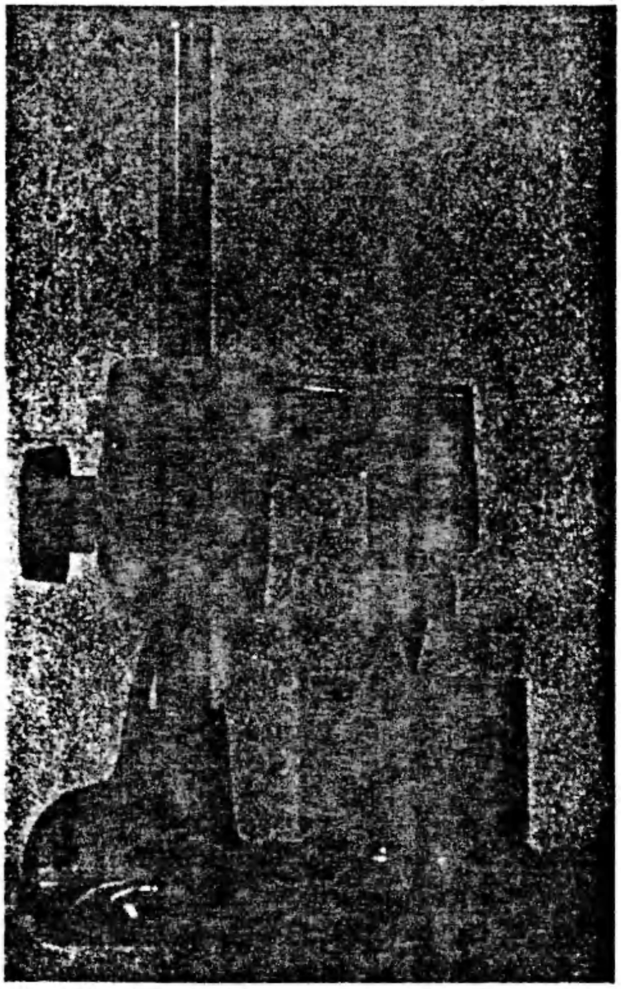

Fig. 3—The Swedish fall-cone apparatus for determining the undrained shear strength of soils.

The procedure for soil splash measurement was accomplished by first lowering the splash collector to just contact the soil surface. When a drop struck the soil surface, a shutter above the acrylic plate was closed to prevent more drops from striking the soil surface. The splash collector was then removed; the soil was washed with distilled water into a previously weighed aluminum pan, dried at 105 °C, and reweighed to determine the detached soil weight to the nearest 0.1 mg. Six measurements were made on each soil sample at different locations on the surface so that splash was not affected by previous impacts on the soil target.

FALLING CONE MEASUREMENT

The soil surface shear strength was determined with a Geonor[1] model g-200 Laboratory Cone Penetration Apparatus (Fig 3). The cone was placed vertically with its apex just in contact with the soil surface. It was then released freely into the soil and the depth of penetration measured. The undrained soil shear strength was then

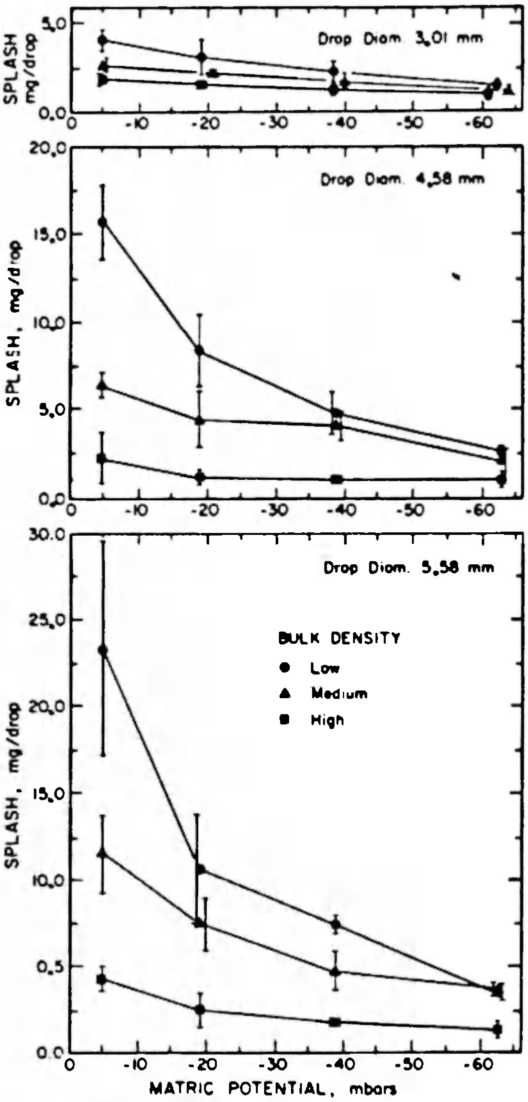

Fig. 4—The effect of bulk density and matric potential on splash weights due to an impact of drops 3.01, 4.58, and 5.58 mm in diameter (bars represent standard deviations).

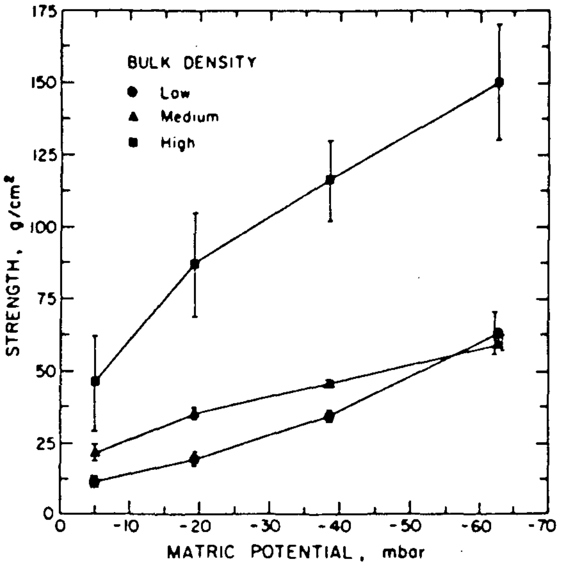

Fig. 5—The effect of bulk density and matric potential on soil shear strength as determined by the fall-cone method (bars represent standard deviations).

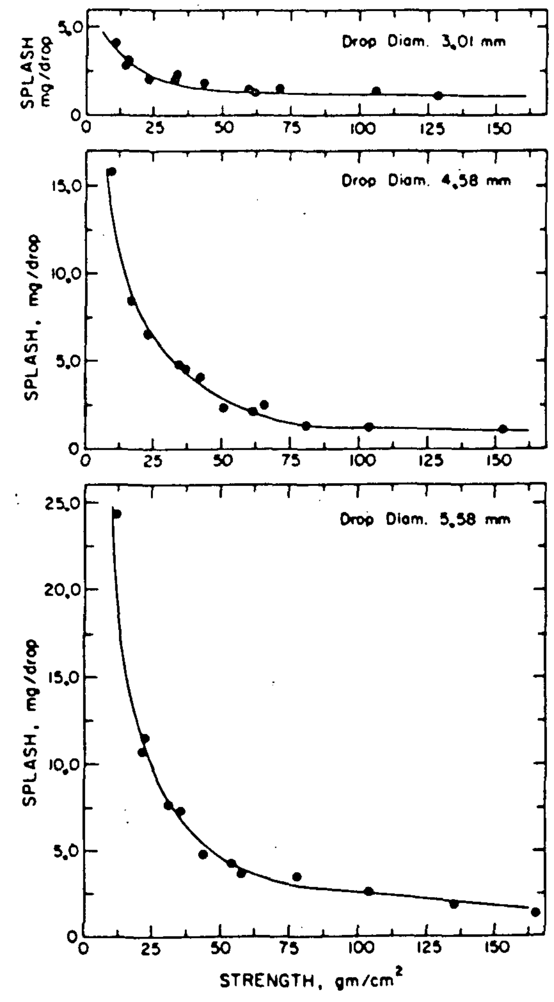

Fig. 6—The relation between shear strength and splash weight due to an impact of drops 3.01, 4.58, and 5.58 mm in diameter.

determined from tables presented by Hansbo (1957). The depth of penetration (h) is related to the undrained shear strength (τ) by

$$\tau = K\,(Q/h^2),$$

where K is a factor of proportionality assumed to be a constant at the different bulk densities and matric potentials (Towner, 1973), and Q is the weight of the cone. Theory and procedural details can be found in Hansbo (1957). In this experiment, three falling cone penetration measurements were made on each soil sample.

RESULTS AND DISCUSSION

The effect of soil bulk density (ρ_b) and matric potential (ψ_m) on soil splash is shown in Fig. 4. For all drop sizes, the weight of soil splash was reduced as ρ_b increased and ψ_m decreased. The differences in soil splash weight between the three ρ_b levels, however, became smaller as ψ_m decreased. Relatively small differences in splash weights occurred for the 3.0-mm diam drops. Splash weights declined sharply with increasing ρ_b, especially at the higher ψ_m levels, for the 5.6-mm diam drops. For similar drop sizes, the splash weights at each ρ_b level were also greatly reduced by decreasing ψ_m from -5 to -38 mbars.

Figure 5 shows the effect of ρ_b and ψ_m on the shear strength of the soil as measured by the falling cone method. Near-surface shear strength increased as ρ_b increased and ψ_m decreased, except for ρ_b levels low and medium at ψ_m equal to -62 mbars. An unequal volume change occurred in each sample when ψ_m decreased. At -62 mbars, the final ρ_b of the 1.00 g/cm³ samples was greater than the 1.10 g/cm³ samples. Therefore, the estimated shear strength was also greater at ρ_b level low than at ρ_b level medium.

The relationship was then plotted between near-surface shear strength and the amount of soil detached (Fig. 6), using shear strength values for each treatment (Fig. 5) and the average amount of soil detachment for that treatment (Fig. 4). The results in Fig. 6 show a curvilinear relationship between soil splash and near-surface shear strength and that the relationship depends on raindrop size.

We found, for any particular soil strength value, greater splash weights from our 4.6-mm diam drop study when compared to the data of Cruse and Larson (1977), who used a 4.8-mm diam drop falling 177 cm. Unfortunately, a complete comparison between our

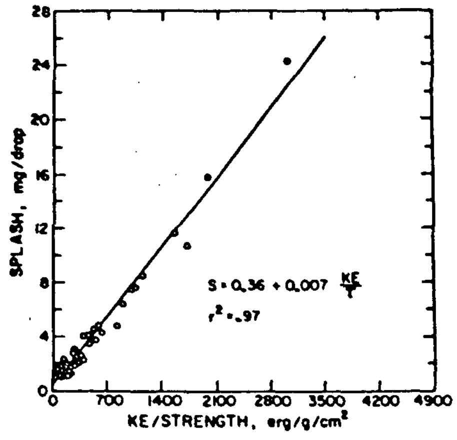

Fig. 7—The relation between splash weight and the ratio of kinetic energy of a raindrop to the soil shear strength.

data and those of Cruse and Larson (1977) cannot be made because of the differences in measuring the shear strength of soil. Our results, however, support their general relationship between soil detached and shear strength.

The results in Fig. 6 indicate that the amount of soil splash from drop impact depends upon forces which tend to detach material and opposing forces which resist particle movement. Soil resistance to detachment is controlled by soil shear strength. Shear strength is defined as the maximum resistance a soil can offer under certain stress conditions before its particles start to slide over each other (Baver et al., 1972). The data in Fig. 6 was recalculated for a force-resistance type relationship and plotted in Fig. 7 as soil splash vs. the ratio of the drop kinetic energy to soil shearing strength. A linear regression analysis of the data gave the relation

$$S = 0.36 + 0.007\ \mathrm{KE}/\tau,$$

where S is soil splash in mg per drop; KE, the kinetic energy; and τ, the soil shearing strength, both in cgs units. A very high correlation coefficient ($r^2 = 0.97$) was found.

The fall-cone device provides a rapid and inexpensive method of determining the soil undrained shear strength. It overcomes the problem of nonuniform core density common in the unconfined compression test cores since penetration depths range from 0.5 to 1.5 cm, and relatively homogeneous cores with length-to-diameter ratios < 1 can be tested. The fall-cone also can easily be adapted for in situ shear strength measurements.

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APPENDIX 2a

Highlights of the "Notice to Contributors" of journal articles to the Journal of Soil Science

(1) A summary, consisting of no more than 150 words, should precede the body of the article itself.

(2) Visual aids, such as tables and illustrations, should be designed to fit specific page dimensions.

(3) References should give all authors' names, the periodical name and the page numbers in full.

(5) Units, symbols and abbreviations should comply with the SI system (Le Systeme International d"Unites).

APPENDIX 2b

Highlights of the manuscript format for journal articles submitted to the Soil Science Society of America Journal

(1) The Title and author(s) should appear in first place. The title should not only identify the subject to be treated in the article and indicate the purpose of the study, it should also "give important high impact words early" (p. 22).

(2) An Abstract, consisting of a maximum of 250 words, should supply enough information to those readers who will read the entire paper as well as those who will not read any further than the abstract. It should include (i) a justification for the research, (ii) objectives and topics covered, (iii) a brief description of the methodology used, (iv) results, and (v) conclusions. In this section the authors are advised to avoid expressions such as "is discussed" or "is described" so as to allow the limited space to be used with relevant information.

(3) Additional words are to appear immediately after the Abtract. Along with the Title and the Abstract, these words - mostly key words, noun phrases and noun clusters - comprise most of the content of the article. Among other purposes, the availability of the index allows the reader to choose whether to read the article as a whole or not.

(4) An Introduction should provide (i) a brief, but clear, statement of the problem along with a justification for the research or the hypothesis upon which the study is

based, (ii) a short review of previous work on the topic (authors are advised to cite only published, significant and up-to-date publications), and (iii) a clarification of the general approach and objectives.

(5) A Materials and Methods section should provide enough detail so as to allow the scientific community to repeat and verify the experiment(s). For materials, the autho(s) should supply the appropriate technical specifications and quantities as well as source or method of preparation. As for the methods, they should be cited by a reference or, if widely known, by their name. Details of unusual experimental designs should also be supplied as well as statistical methods.

(6) The Results section should present (i) the major generalization(s) made about the data, and (ii) the data supporting the generalization(s). These data should be given by tables, graphs, and other illustrations as much as possible. Such information should not be repeated in prose. Finally, the author(s) may choose to discuss the results as they present them. In this case, the Results section would be combined with the Discussion section.

(7) A Discussion section should explain the implications of the results obtained. It should consider (i) principles, relationships and generalizations that can be supported by the results, (ii) exceptions, lack of correlation or areas needing further investigation, and

(iii) results and conclusions that correspond or not with those of other work.

(8) A References section should be prepared according to the instructions established by the Handbook (pp. 28-33).

(9) Tables, figures and illustrations should be used to support conclusions or illustrate concepts. They should be entirely informative in themselves as no text is expected to be appended to them.

APPENDIX 3

Instances of the modal *can* as an indicator of a degree of ability and probability

I. *Ability*

Article 1:

(1) "The management of a soil *can* change the content of organic matter ..." (p. 143)

(2) "However, aggregates 20 - 250 m diameter *can* be destroyed by ultrasonic vibration" (p. 146).

(3) "This organic matter *can* be seen in the transmission electron micrograph of a thin section of soil ..." (p.148)

(4) "... they *can* grow in large pores ..." (p. 155)

(5) "Although some of the binding by persistent materials *can* be broken with ultrasonic vibration ..." (p. 157)

Article 2:

(1) "There is little doubt that in field soils water *can* also infiltrate under conditions other than ..." (p. 1)

II. *Probability*

Article 1:

(1) "...this change *can* occur under different climates" (p. 143).

(2) "... the remains of the colony with its capsule *cannot* be identified as such ..." (p. 148)

(3) "An idealized model *can* be drawn to scale showing that an aggregate ..." (p. 149)

(4) "Inconsistencies in the literature ... can be exolained when one considers the size of aggregates ..." (p. 152)

(5) "The temporary binding agents ... can be equated with the organic skeleton grains ..." (p. 152)

(6) "It is likely that a precise chemical formula cannot be defined in the same way that a formula for humic acid cannot be defined ..." (p. 157)

Article 2:

(1) "If it can be assumed that the drop in hydraulic conductivity ..." (p.2)

Article 3:

(1) "This latter finding of Amemiya (1965) cannot be applied to the chiseled ...without more detailed information..." (p. 802)

(2) "... several water conservation features can be projected even without considering runoff" (p. 802).

Article 4:

(1) The fall-cone also can easily be adapted for in situ shear strength measurements" (p. 953).

APPENDIX 4

Explanations of specialized terminology given by the informant

(1) vesicular-arbuscular mycorrhizal fungi are fungi that grow in symbiosis with roots (article 1, p. 155).

(2) hydraulic conductivity is the measure of the ease at which water flows through soil (article 2, p. 1).

(3) falling head device is an apparatus used to determine saturated hydraulic conductivity in which the water level (head) on top of the soil surface progressively decreases as the experiment advances (article 2, p. 2).

(4) problem subsoil layer refers to compaction of soil, a common fact which occurs in the layer immediately below the plow layer, resulting in slow internal drainage, and decreasing, therefore, water infiltration (article 3, p. 796).

(5) unsaturated drainage (= unsaturated flow) refers to the movement of water in a soil which is not completely filled with water (article 3, p. 797).

(6) hydraulic head refers to the elevation with respect to a specified reference (usually the soil surface), at which water would stand in a vertical pipe (piezometer) connected to the point in question in the soil (article 3, p. 799 and article 4, p. 950).

(7) zero drainage time refers to the time at which the soil monolith is completely filled with water and tensiometer readings become stable. At this time no more water is added

to the monolith, and the drying process starts (article 3, p. 799).

(8) *zero matric potential* refers to complete saturation of the soil profile (article 3, p. 799).

APPENDIX 5

List of key words for each of the four articles

Article 1:

organic matter
dispersion
flocculation
slaking
organic polymer
polyvalent metal cations
pore-size distribution
aluminosilicates
water-stable aggregates
vesicular-arbuscular mycorrhizal fungi
domain
quasi-crystal
periodate oxidation
binding agents (temporary, transient and persistent)
polysaccharides
hyphae
saprophytic fungi

Article 2

hydraulic conductivity
pore size-distribution
soil water potential
infiltration capacity
macropore(s)
falling head device
saturated hydraulic conductivity
hydraulic gradient
drainage
throughflow experiment

Article 3

chiseling
hydraulic conductivity
soil water potential
unsaturated drainage
steady-state infiltration
soilwater desorption characteristic (SWDC)
hydraulic head
instantaneous profile method

Article 4

shear strength
soil splash
fall-cone device
terminal velocity

splash collector
matric potential
bulk density
raindrop tower