MAGNITUDE, MODELING AND SIGNIFICANCE OF SWELLING AND SHRINKAGE PROCESSES IN CLAY SOILS

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Proefschrift
ter verkrijging van de graad van doctor
in de landbouw- en milieuwetenschappen
op gezag van de rector magnificus,
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van de Landbouwuniversiteit te Wageningen.

"Klein vee kan verloren gaan, doordat de dieren in een diepe scheur terecht komen. Onlangs zakte zelfs een boer, hoewel beter dan iemand anders bedacht op de gevaren, door de grasmat heen en verdween tot aan de oksels in zulk een scheur."

(J.S. Veenenbos. 1950. De Bodemkartering van Nederland, deel V. De bodemgesteldheid van het gebied tussen Lemmer en Blokzijl in het randgebied van de Noordoostpolder)

Aan mijn ouders

STELLINGEN

1. Maaiveldsdaling en scheurvorming als gevolg van uitdroging van kleigronden zijn op eenvoudige wijze te voorspellen.
   Dit proefschrift

2. Door naast de waterretentie- en de doorlatendheidskarakteristiek ook de krimpkarakteristiek en een krimp-geometriefactor als bodemfysische invoer in simulatiemodellen op te nemen, kunnen water-, stof- en gastransport in kleigronden realistischer worden berekend dan met bestaande modellen voor rigide gronden.
   Dit proefschrift

3. Preferente stroming van water en stoffen in de bodem: meer regel dan uitzondering!

4. Het feit dat kleigronden in Nederland vaak worden beschouwd als weinig zwellend en krimpend zegt meer over het Nederlandse klimaat dan over de Nederlandse bodem.
   Dit proefschrift

5. Bestaande theorieën, waarin aan de belastingspotentiaal een grote invloed op waterstroming in kleigronden wordt toegeschreven, zijn te veel gebaseerd op ongerijpte "pasta-achtige" kleiën en daardoor niet goed bruikbaar in gerijpte kleigronden.

6. Het is onjuist om bij het modelleren van infiltratie in gescheurde kleigronden het deel van de neerslag dat rechtstreeks in de scheuren valt, te verwaarlozen.
   Ross, P.J. and B.J. Bridge. 1984. The properties and utilization of cracking clay soils: 155-163.
   Kihupi, N. 1990. PhD thesis. University of Leuven, Belgium.
   Dit proefschrift

7. De verdampingsmethode van Wind, voor het bepalen van de waterretentie- en doorlatendheidskarateristiek van een bodem, verdient een brede toepassing.
   Wind, G.P. 1966. Proc. Symp. Water in the unsaturated zone, UNESCO/IASH: 181-191.

8. Als de verzadigde doorlatendheid van een grond, gemeten met de "Double ring infiltration method", hoger is dan optredende neerslagintensiteiten, mag daaruit niet worden geconcludeerd dat preferente stroming in de desbetreffende grond niet voorkomt. Het tegenovergestelde is waarschijnlijker.
   Seyfried, M.S. and P.S.C. Rao. 1987. Soil Sci. Soc. Am. J. 51: 1434-1444.

9. Veel wetenschappers zijn niet werkelijk geinteresseerd in de statistiek achter hun onderzoekswerk. Ze gebruiken haar slechts als vijgeblad om hun conclusies mooier te laten lijken.
   Nienhuys, J.W. 1991. Intermediair 4: 47-51.

10. Het leuke van bodemnatuurkunde is de combinatie van vieze handen en hogere wiskunde.

11. Bij fusies van instellingen als scholen en ziekenhuizen, zou per stad of regio in ieder geval één instelling met een algemeen karakter over moeten blijven.

12. Het populair worden van de vacaturestop en de kaasschaafmethode als bezuinigingsmaatregel bij de overheid duidt op gemakzucht onder politici.

Stellingen behorende bij het proefschrift van J.J.B. Bronswijk
Magnitude, modeling and significance of swelling and shrinkage processes in clay soils
Wageningen, 17 mei 1991.

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ABSTRACT

Bronswijk, J.J.B. 1991. Magnitude, modeling and significance of swelling and shrinkage processes in clay soils. Doctoral thesis. Wageningen Agricultural University, Wageningen, The Netherlands, (IX) + 145 pp.

The dynamic process of swelling and shrinkage in clay soils has significant practical consequences, such as the rapid transport of water and solutes via shrinkage cracks to the subsoil, and the destruction of buildings and roads on clay soils. In order to develop measuring methods and computer simulation models to take swelling and shrinkage processes into account in agricultural and environmental studies, experiments were conducted on soil aggregates, small soil cores, with a lysimeter, and in the field.

Determination of shrinkage characteristics of soil aggregates revealed some clay soils from the Netherlands to be among the strongest swelling and shrinking soils of the world with a maximum volume decreases upon drying of 49 %. Normal shrinkage and residual shrinkage are significant within pressure head ranges occurring in field conditions. Shrinkage was isotropic for all horizons of a heavy clay soil, at overburden pressures corresponding to field loads.

The shrinkage behaviour of a clay soil in a lysimeter may be explained by the occurrence of structural shrinkage, normal isotropic shrinkage and residual isotropic shrinkage. Field experiments confirmed this picture. A newly developed equation to relate vertical soil movements to water content changes during structural, normal, residual and zero shrinkage, for any shrinkage geometry, was successfully applied in the field.

The obtained knowledge about the swelling and shrinkage process was used to develop a computer simulation model, FLOCR, to calculate the water balance of a clay soil, including preferential flow through shrinkage cracks, on a daily basis. Besides, crack volume and surface subsidence are computed. Model calculations for a heavy clay soil during 1985 were in good agreement with field observations. Comparing FLOCR with a rigid-soil model showed a considerable influence of shrinkage cracks on the soil water balance, on the groundwater level and on the topsoil bearing capacity. The simulation model was also applied to predict the effect of drainage on actual swelling and shrinkage processes in a heavy clay soil profile.

Finally, the principles of incorporating evaporation from shrinkage cracks, oxygen diffusion in cracking clay soils, and lateral infiltration during preferential flow into the present model approach are presented.

Additional index words: volume changes, cracking, surface subsidence, simulation model, water balance, preferential flow, bypass flow, shrinkage characteristic, shrinkage geometry, oxygen diffusion, evaporation.

CONTENTS

1. INTRODUCTION

1.1. General

The soil has many valuable functions. It supplies agricultural crops with water and nutrients, and offers a firm medium for plant roots. Buildings, roads and other constructions also derive solidity from the soil. It also acts as a filter that adsorbs harmful substances, thus minimizing or preventing the transport of pollutants from the soil surface to groundwater. Soil material is used in various civil engineering applications, for example in dams and dikes, as a basis for roads, or as an isolating liner on top or below waste disposal sites. To optimize the various uses of soil, as well as to conserve its quality, knowledge of soil properties and soil behaviour is essential.

In this thesis the properties and behaviour of one specific group of soils, the clay soils, are investigated. Clay soils show a very distinct feature: when they are drying, the volume of the soil decreases. In the field this process becomes visible by the appearance of shrinkage cracks and the occurrence of surface subsidence. Upon wetting, the cracks close again, and the soil surface rises. This dynamic process of swelling and shrinkage in clay soils has significant consequences.

In some situations, the consequences of swelling and shrinkage are mainly *unfavourable*.

In the non-agricultural use of clay soils, an example of such unfavourable consequences is the destruction of buildings, roads and pipelines (McCormack and Wilding, 1975; Gillot, 1984). Jones and Holtz (1973) estimated that the total damage in the USA resulting from the swelling and shrinkage of soils amounted to over two billion US dollars per year. This is more than twice the annual damage from floods, hurricanes, tornadoes and earthquakes. When applying clayey materials to isolate waste disposal sites from the environment, the process of cracking is very undesirable, because it may induce leakage of toxic compounds into the subsoil (Miller and Mishra, 1990).

In agricultural land use, the rapid transport of water and nutrients via shrinkage cracks to the subsoil, where they become inaccessible to shallow rooting crops, is unwelcome. This phenomenon is called preferential flow, bypass flow or short-circuiting (Bouma and Dekker, 1978). Preferential flow may result in water and nutrient shortage to crops (Belmans et al., 1982). Another unfavourable consequence of preferential flow is the rapid pollution of the groundwater, for example when fertilizers or liquid manure are applied to a cracked clay soil (Thomas and Phillips, 1979; Dekker and Bouma, 1984). Via the saturated zone, pollutants may also reach surface waters relatively quickly. This is especially true when tile drains or mole drains are present in the soil (Smettem et al., 1983; Coles and Trudgill, 1985). In the case of preferential flow, the contact between dissolved matter and the soil matrix is only limited. Therefore, substances that would normally be adsorbed in the topsoil, such as heavy metals or various pesticides and herbicides, will be able to reach the subsoil. Besides vertical shrinkage cracks, horizontal cracks may also be formed upon drying. The horizontal cracks restrict capillary rise from the groundwater and therefore reduce water availability to crops (Kooistra et al., 1987).

In many situations, however, swelling and shrinkage has *favourable* effects. One example from civil engineering practice is the application of clay as an isolation layer below or on top of waste disposal sites. After construction of a layer of dry clayey material, wetting and swelling in situ makes the layer impermeable.

In agricultural land-use, the saturated hydraulic conductivity of clay soils, and therefore their drainage potential, is positively affected by cracking (Van Hoorn, 1960; Dekker and Bouma, 1978). In arid regions, basin irrigation of deep rooting crops on vertisols is positively influenced by soil cracks promoting the infiltration of water (Swartz, 1966; Farbrother, 1972). Furthermore, when shrinkage cracks are present, surface runoff and erosion are unlikely to occur. Swelling and shrinkage is also a natural process for restoring soil compaction. Finally, swelling and shrinkage improves soil structure (Wilding and Hallmark, 1984).

1.2. Previous investigations

From the above, it is clear that cracking and surface subsidence have many significant consequences. It is, therefore, not surprising that scientists have long been interested in the *process of swelling and shrinkage.*

Shrinkage of clods and small cores has been studied by the simultaneous measurement of water content changes and volume changes, sometimes accompanied by measurements of soil water pressure heads. Studies of this kind were conducted by Tempany (1917), Haines (1923), Lauritzen and Stewart (1941), Johnston and Hill (1944), Stirk (1954), Holmes (1955), Grossman et al. (1968), Franzmeier and Ross (1968), Perroux et al. (1974), Reeve and Hall (1978), Newman and Thomasson (1979), Yule and Ritchie (1980a), Reeve et al. (1980), Chan (1982), Jayawardane and Greachen (1987) and Dasog et al. (1988).

Of more practical applicability are studies on the behaviour of large undisturbed clay soil cores, for instance by allowing such a large core to evaporate while measuring the resulting shrinkage (Yule and Ritchie, 1980b).

Field studies on swelling and shrinkage of clay soils by measuring the subsidence of the soil surface have been carried out by Yaalon and Kalmar (1972). Woodruff (1936), Aitchison and Holmes (1953) and Jamison and

Thompson (1967) installed benchmarks at several depths in the soil and measured vertical shrinkage and swelling. Zein el Abedine and Robinson (1971), Yaalon and Kalmar (1984), Dasog et al. (1988) and Hormann and Widmoser (1990) measured crack volume directly, using thin needles. Field research has also been conducted by taking samples in the field at different times of the year to determine bulk density and water content (Fox, 1964; Perroux et al, 1974; Berndt and Coughlan, 1977; Hallaire, 1984).

The various investigations have increased our understanding of physical processes in clay soils. The application of soil physical knowledge nowadays often involves the development of *computer simulation models*, which can compute the transport of water and solutes through the soil.

Simulation models for water transport in the unsatured zone offer the opportunity to asses relatively quickly and cheaply the effects of (changes in) water management on behaviour and quality of soils. For example, when relations between transpiration and crop production are known, then the effects of water management on crop production can be evaluated quantitatively by applying a model that computes transpiration in dependance of water management (e.g. Feddes et al., 1988). Another important soil quality is the topsoil's workability. When relations between the soil water pressure head in the topsoil and the workability are known, then a simulation model that computes the topsoil pressure head in dependance of water management can be applied to quantify the effects of changes in water management on soil workability (Van Wijk, 1985).

Furthermore, models have been developed that compute solute transport in the soil. These models are widely used to predict transport of contaminants to subsoil, groundwater and surface waters.

Existing simulation models, however, cannot be applied to clay soils, because in most of these models, water flow is supposed to follow Darcy's law, which is not a valid assumption for preferential flow through non-capillary sized shrinkage cracks. Besides, often the volume change of the clay soil itself is of importance, which is evidently not calculated in 'rigid soil models'. Therefore, various researchers have developed new simulation models, or adapted existing ones, with the aim of incorporating volume changes and/or macropore flow in the computation of water and solute transport in soils.

Some of these models simulate only part of the physical processes in cracking clay soils. For example, models to simulate infiltration at the surface of soils with macropores have been developed by Edwards et al. (1979), Hoogmoed and Bouma (1980) and Ross and Bridge (1984).

Other models are aimed at describing macropore flow in rigid soils, and do not consider dynamic volume changes. An example is the model described by Beven and Germann (1984), based on kinematic wave theory.

Jarvis and Leeds-Harrison (1987, 1990) developed a macropore-flow model, which includes volume changes of the soil matrix. The model yielded good agreement between predicted and measured drain outflow and soil water content. A shortcoming of this model, however, is that it is essentially a macropore-flow model and that transport processes inside the soil matrix are not considered.

Only very few attempts have been published to model the complete water balance of a cracking clay soil. Bouma and De Laat (1981) have accounted for the effect of vertical cracks on water balance simulations by reducing the effective rainfall that infiltrates into the soil by 10-20% depending on the time of year. Van Aelst et al. (1986) adapted the SWATRE model (Belmans et al., 1983) for use in cracking clays by calculating a quantity of crack flow dependent on the water content of the topsoil. Kihupi (1990) also incorporated subroutines to compute macropore flow in the SWATRE model. The disadvantage of these approaches is that they are not easily transferable to situations different from those in the considered studies, because they have poor physical background and lack sufficient field validation. Furthermore, the process of cracking and subsidence is not incorporated in the models, so they cannot be used in situations where the change in soil volume itself is of importance.

So far, a generally valid simulation model for water transport in cracking clay soils, that takes into account dynamic cracking and surface subsidence, transport processes in the soil matrix, and preferential flow through shrinkage cracks, does not exist.

1.3. Scope of present investigations

The objective of this thesis is to describe swelling and shrinkage processes in clay soils, and to develop measuring methods and computer simulation models in order to incorporate swelling and shrinkage and its consequences in agricultural and environmental studies.

The thesis is divided into two parts. The *first part* contains Chapters 2 to 5 in which the process of swelling and shrinkage is analysed on an increasing scale starting with natural aggregates and ending with a field soil. In Chapter 2, the basic parameter describing the magnitude of shrinkage in soils is introduced: the shrinkage characteristic of soil aggregates. This shrinkage characteristic has been determined for the various soil horizons in seven representative clay soil profiles from the Netherlands. Not only the magnitude of swelling and shrinkage is of importance, the question how far volume changes of the soil matrix occur either as cracking or as surface subsidence is of equal importance. Therefore, in Chapter 3 the geometry of shrinkage of a clay soil is analysed. With the conclusions on magnitude and geometry of shrinkage from the first two chapters in mind, an experiment was conducted in which drying and shrinkage of a clay soil lysimeter was investigated, under well-defined laboratory conditions (Chapter 4). The evident next step was the execution of a field experiment in a heavy clay soil. This experiment is reported in Chapter 5.

In the *second part* of the thesis, consisting of Chapters 6 to 9, the results obtained in the first part are made applicable by developing a simulation model for water transport in clay soils in which swelling and shrinkage are incorporated. The principles of this simulation model are outlined in Chapter 6. In Chapter 7 some results obtained with this model are compared with field observations and with calculations of validated models for rigid soils, in order to assess the neccessity of incorporating swelling and shrinkage in simulation models. Chapter 8 presents an example of a model application, in which the volume change itself of the soil is important. In Chapter 9, some possible alternative applications of the developed approach to model volume changes in clay soils, are discussed.

Finally, in Chapter 10, the possibilities and limitations of the developed model approach are discussed.

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2. SHRINKAGE OF DUTCH CLAY SOIL AGGREGATES

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Shrinkage of Dutch clay soil aggregates

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Abstract

Shrinkage processes in clay soils are important because surface subsidence and shrinkage cracks have a large impact on transport processes in these soils and on their use potential. Of seven representative clay soil profiles from the Netherlands, shrinkage characteristics and COLE and PLE values were measured, using undisturbed natural aggregates. It appeared that the course of the shrinkage process upon drying varied strongly from one soil to another, and very often the measured shrinkage characteristics deflected from the theoretical curve. Some Dutch heavy clay soils belong to the strongest swelling and shrinking soils of the world, with volume decreases of aggregates being maximally 49 % between saturation and oven-dryness, and maximally 42 % between saturation and a pressure head of − 16 000 cm. Potential surface subsidence of a Dutch field soil due to shrinkage is maximally 15 cm. Under Dutch climatic circumstances, in some heavy clay soils, as a result of normal shrinkage, the aggregates remain saturated throughout the whole year. Only inter-aggregate pores like shrinkage cracks, contain air.

Keywords: clay soils, shrinkage, swelling, aggregates, drying, COLE, PLE

Introduction

Clay soils distinguish themselves from other soils by the presence of certain amounts of clay minerals like kaolinite, illite and montmorillonite. Clay minerals occur in plate-shaped crystals. These crystals are build up of small platelets, consisting of silicium oxides and aluminium hydroxides. The thickness of each platelet is about 5-10 Å. The number of platelets within one clay crystal depends on the configuration of the silicium oxides and the aluminium hydroxides in the platelet, but may vary from 1 (Na-montmorillonite) to almost infinite (Kaolinite). Due to the special structure of clay minerals, platelets or packets of platelets are surrounded by water layers (Bolt & Bruggenwert, 1978). Upon drying, the platelets approach each other (Fig. 1). This process causes shrinkage of soil aggregates. Upon wetting, the distance between the platelets increases again, through which the aggregates regain their original volume. The volume decrease of soil aggregates upon drying can be divided into three shrinkage phases (Haines, 1923):

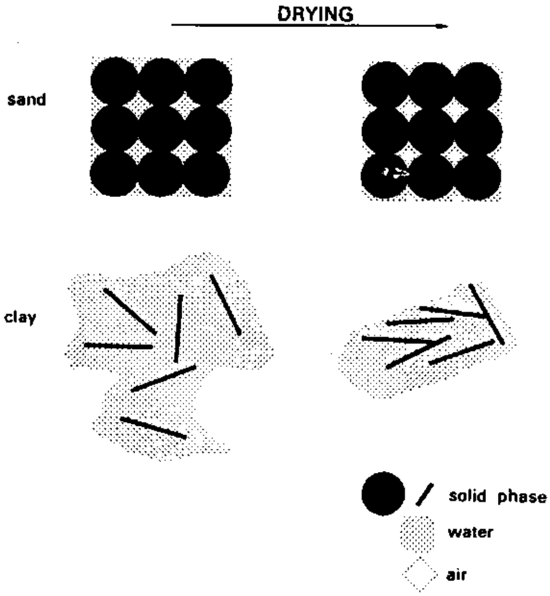


Fig. 1. Schematic representation of the process of drying and air entry in sandy soils and clay soils.

– Normal shrinkage. Volume decrease of clay aggregates is equal to water loss. The aggregates remain fully saturated.
– Residual shrinkage. Upon drying the volume of the aggregates still decreases, but water loss is greater than volume decrease. Air enters the pores of the aggregates.
– Zero shrinkage. The soil particles have reached their densest configuration. Upon further water extraction, the volume of aggregates stays constant. Water loss is equal to increase of air volume in the aggregates.

The three shrinkage phases are pictured schematically in Figure 2.

Course and magnitude of the shrinkage process of soil aggregates upon drying are determined by clay content, clay mineralogy, capacity and composition of the cation exchange complex and organic matter content. (Greene-Kelly, 1974; Schafer & Singer, 1976; Murray & Quirk, 1980; Parker et al., 1982; Tessier, 1984).

In large samples, containing more than one structural unit, sometimes a fourth shrinkage phase can be distinguished: structural shrinkage (Stirk, 1954; Yule & Ritchie, 1980). Structural shrinkage occurs in saturated soils. When saturated soils dry, large water-filled pores may be emptied. Due to this, aggregates can get a somewhat denser packing. Structural shrinkage falls outside the scope of this article because the volume changes in this shrinkage phase are negligible and furthermore the magnitude of this phase is not a soil constant but varies strongly with land use and soil management (Reeve & Hall, 1978).

In studies on swelling and shrinkage of clay soils, the shrinkage characteristic is

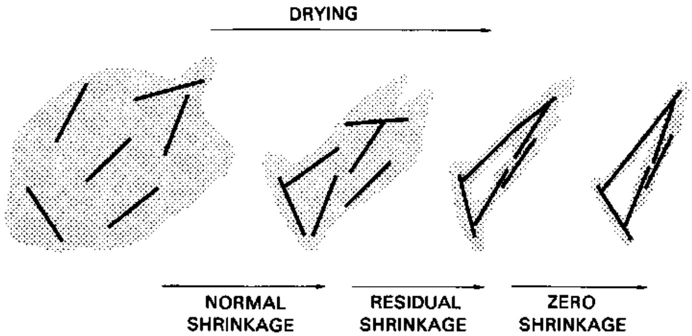


Fig. 2. The three shrinkage phases of clay soil aggregates upon drying.

often used. This characteristic has been defined in many ways but is essentially always the relation between soil volume and soil water content. One of the most-used forms of the shrinkage characteristic is the relation between moisture ratio and void ratio of soil aggregates. Moisture ratio ϑ and void ratio e are defined as:

$$\vartheta = \text{volume of water/volume of solids} \tag{1}$$

$$e = \text{volume of pores/volume of solids} \tag{2}$$

Because of volume changes of aggregates, the use of moisture ratio ϑ and void ratio e is preferred to water content θ and porosity ϵ. ϑ and e can simply be converted into θ and ϵ:

$$\epsilon = \frac{e}{1 + e} \tag{3}$$

$$\theta = \frac{\vartheta}{1 + e} \tag{4}$$

The general form of the shrinkage characteristic, including the three shrinkage phases, is shown in Figure 3.

The relation between volume and void ratio of soil aggregates is:

$$V = V_s(1 + e) \tag{5}$$

in which:
V = volume of soil aggregates (m^3)
V_s = volume of solids (m^3)

Any change in void ratio, derived from the shrinkage characteristic, can simply be

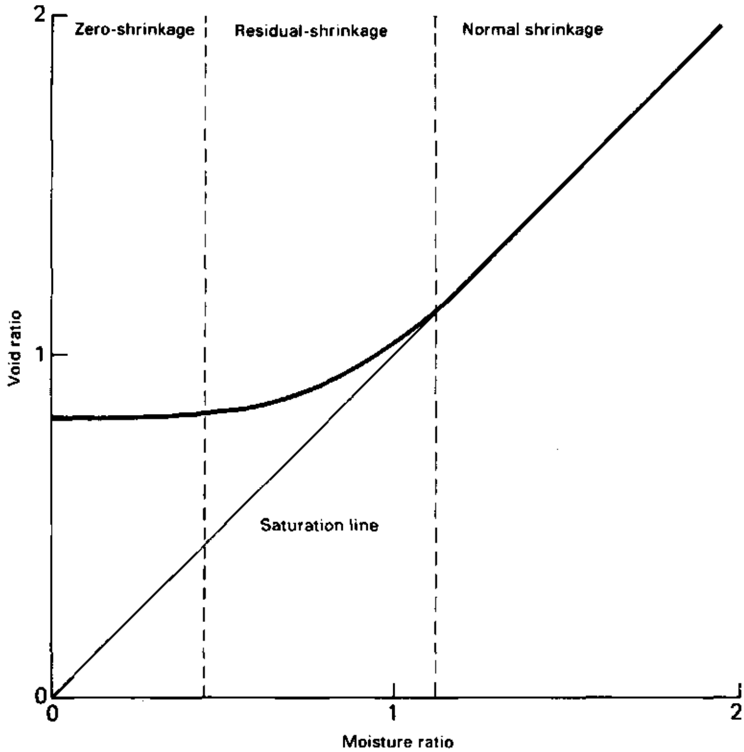


Fig. 3. General form of the shrinkage characteristic with three shrinkage phases; void ratio = volume of pores/volume of solids; moisture ratio = volume of water/volume of solids.

converted into change of volume of soil aggregates:

$$\frac{V_2}{V_1} = \frac{1 + e_2}{1 + e_1} \qquad (6)$$

in which:

V_1, e_1 = volume and void ratio, respectively, of soil aggregates at moisture content 1

V_2, e_2 = volume and ratio, respectively, of soil aggregates at moisture content 2

On a macroscopic level, volume changes of soil aggregates result in the occurence of shrinkage cracks and surface subsidence. This has important consequences for both agricultural and non-agricultural users of a soil. In some cases, these consequences are mainly unwanted. An example is the transport of water and solutes via shrinkage cracks to the subsoil, bypassing the root zone. This may result in inefficient sprinkler irrigation and water and nutrient shortage of plants, but also in rapid pollution of groundwater (Thomas & Phillips, 1979; Coles & Trudgill, 1985; Bronswijk, 1988). Other unwanted consequences of soil shrinkage are the destruction of buildings, pavements and pipelines in or on heavy clay soils (McCormack & Wilding, 1975; Gillot, 1984). Jones & Holtz (1973) estimated that the total damage in the USA resulting from swelling and shrinkage of soils amounted to $ 2 255 000 000 per year, more than twice the damage from floods, hurricanes, tornadoes and earthquakes.

In many cases, soil shrinkage has positive effects as well. Examples are the drainage of some heavy clay soils, where the hydraulic conductivity of the soil increases by cracking (Bouma et al, 1979). In arid regions, basin irrigation of vertisols is positively influenced by soil cracks promoting a deep infiltration of water (Swartz, 1966; Farbrother, 1972). Swelling and shrinkage is also a natural process to restore soil compaction. Finally, swelling and shrinkage improves soil structure (Wilding & Hallmark, 1984; Bronswijk, 1989). The mentioned examples illustrate the large impact of swelling and shrinkage on behaviour of clay soils, both in a positive and a negative way.

Studies of Berndt & Coughlan (1977) and Yule & Ritchie (1980) have demonstrated that the behaviour of aggregates and small soil cores can be used to explain and predict field soil behaviour. Moreover, simulation models have been developed recently that calculate transient water transport in cracking clay soils (Bronswijk, 1988). In these models the shrinkage characteristic plays an important role, comparable with the water retention curve and the hydraulic conductivity curve. Because of this, knowledge about course and magnitude of shrinkage of soil aggregates becomes increasingly important.

In the Netherlands, large areas of clay soils occur (Fig. 4). Little is known about swelling and shrinkage processes in these soils. In this article the magnitude of potential swelling and shrinkage in Dutch clay soils is determined. Seven soils with various texture, location, parent material and land use were selected. In the laboratory the shrinkage characteristics of these soils were determined. Parameters like COLE (Coefficient Of Linear Extensibility) and PLE (Potential Linear Extensibility), which quantify the shrinkage of a soil upon drying, were measured as well. The consequences of the obtained results for field behaviour of clay soils in the Netherlands are discussed.

Materials and methods

Soil properties

Seven soils with various texture, location, parent material and land use were selected. These seven soil profiles are considered representative for the holocene clay soils that occur in the Netherlands. Their location is pictured in Figure 4. Of each soil horizon the following properties were determined:
- texture,
- $CaCO_3$ and organic matter content,
- density of the solid phase,

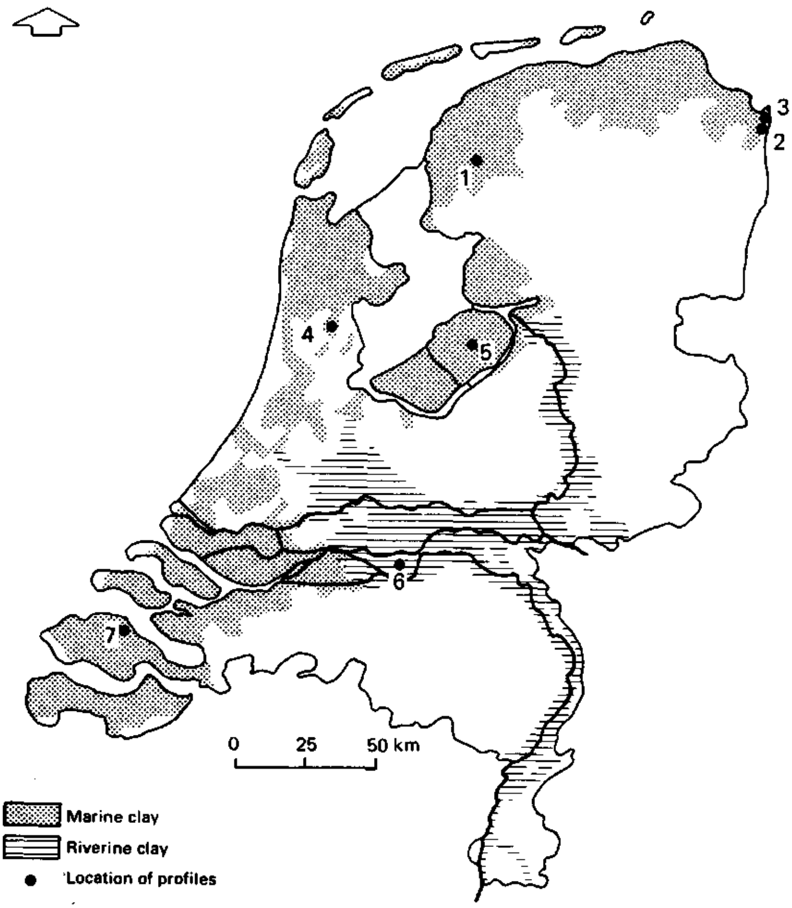


Fig. 4. Clay soil areas in the Netherlands. Locations of the seven profiles selected in this paper are marked. Numbers correspond with Tables 1 and 2.

– shrinkage characteristics,
– COLE and PLE values,
– water retention curve.

In the early spring of 1986, on each site about ten natural clods of sizes ranging from 7 to 34 cm^3 were taken from each soil horizon, in wet conditions. In the laboratory these clods were saturated for another two weeks. Three clods were used for determination of shrinkage characteristics and three clods were used for measurement of water retention curves. The remaining four clods were used to determine texture (by the Pipet method of Gee & Bauder, 1986), organic matter content (by ignition loss at 500 °C), $CaCO_3$ content (with Scheibler apparatus), and density of the solid phase (by the Pycnometer method of Blake & Hartge, 1986). The clay minerals of the seven selected profiles consist mainly of illite (30-40 %) and smectite

(20-40 %) (Breeuwsma, pers. comm.). Water retention curves were determined on a sand box and with pressure membrane apparatus. The characterization of the seven soil profiles is given in Table 1.

Table 1. Brief description and composition of seven selected clay soils in the Netherlands of which the shrinkage behaviour was determined. Numbers before location names correspond with Fig. 2. ϱ_s = density of the solid phase.

Location	Depth (cm)	Horizon	ϱ_s (g/cm³)	Composition					
				in weight % of the soil		in weight % of mineral parts			
				$CaCO_3$	organic matter	<2	2-16	16-50	>50 μm
1. Oosterend	0- 22	A11	2.52	0.0	10.3	39.9	20.9	33.4	5.8
	22- 42	ACg	2.60	0.0	6.9	40.7	25.9	28.3	5.1
	42- 78	C1g	2.66	2.5	4.5	58.1	24.7	16.2	1.1
	78-120	C2g	2.68	6.9	2.2	24.1	14.3	53.5	8.1
2. Nieuw Beerta	0- 26	Ap	2.64	1.4	4.8	45.4	27.8	16.6	10.2
	26- 34	A12	2.61	0.8	3.9	45.9	27.4	18.9	6.8
	34- 56	C11g	2.62	1.7	2.2	51.6	29.2	15.4	3.8
	56- 75	C12g	2.68	3.3	1.9	39.1	24.1	32.8	4.0
	75-107	C13g	2.69	0.3	3.0	59.3	31.7	6.9	2.1
3. Nieuw Statenzijl	0- 29	Ap	2.65	9.0	3.3	52.0	24.2	20.4	3.4
	29- 40	AC	2.67	10.6	2.9	62.9	17.0	17.7	2.4
	40- 63	C21	2.69	11.3	2.7	52.4	25.3	18.3	4.0
	63- 80	C22g	2.66	9.8	2.8	55.8	24.1	16.7	3.4
	80-100	C23g	2.69	11.6	2.2	59.6	26.4	12.2	1.8
4. Schermerhorn	0- 21	A11	2.59	11.7	5.9	34.8	17.9	27.9	19.5
	21- 52	A12	2.61	11.1	6.2	42.9	22.1	26.5	8.5
	52- 77	C21g	2.62	17.6	3.7	32.1	20.4	33.2	14.2
	77-100	C22g	2.63	18.8	3.1	16.2	10.1	37.8	36.0
5. Dronten	0- 22	Ap1	2.66	9.9	2.6	36.8	22.2	27.5	13.5
	22- 38	A12	2.66	8.1	2.2	45.6	27.2	22.9	4.3
	38- 60	C22g	2.63	6.6	7.6	35.3	43.9	19.7	1.1
	60- 90	C23g	2.59	5.8	7.0	15.9	23.9	58.2	2.0
	90-110	C24g	2.57	4.6	10.5	20.2	27.2	51.2	1.4
6. Bruchem	0- 18	A11	2.52	0.0	9.9	58.1	30.7	10.2	1.0
	18- 30	A12	2.60	0.0	7.5	55.8	35.5	8.1	0.6
	30- 58	C11g	2.64	0.0	3.7	59.6	29.5	10.1	0.8
	58- 85	C12g	2.59	0.0	3.8	51.7	37.0	9.6	1.7
7. Kats	0- 35	Ap	2.67	10.2	2.1	30.8	15.7	30.2	23.3
	35- 60	C21g	2.67	13.6	1.6	46.4	20.5	21.2	11.9
	60- 80	C22g	2.70	15.7	1.3	41.9	18.3	23.3	15.5
	80- 95	C23g	2.69	9.5	0.3	16.2	6.7	21.0	56.1

Shrinkage characteristics

In order to determine shrinkage characteristics, each clod was briefly immersed in SARAN-F310 resin (resin to solvent ratio 1:5, w/w) and allowed to dry in the laboratory. The applied SARAN-coating is very elastic, impermeable to water and permeable to water vapour (Brasher et al., 1966). As the clods dry and shrink, the elastic coating remains tightly fitted around the clods. By repeated weighing and under water weighing, both weight and volume of the clod can be determined at different stages of shrinkage, in a non-destructive way. After two to four weeks, weight losses became negligible. The SARAN-coated clods were oven-dried in order to measure final dry volume and dry weight.

Cole and PLE

The Coefficient Of Linear Extensibility (COLE) (Grossman et al., 1968) is a parameter that quantifies the swelling and shrinkage potential of a soil layer. COLE is defined as:

$$\text{COLE} = \left(\frac{V_{\text{wet}}}{V_{\text{dry}}} \right)^{1/3} - 1 \qquad (7)$$

in which:
V_{wet}, V_{dry} = volume of a soil aggregate in wet and dry state, respectively.

To quantify potential swelling and shrinkage of a soil in situ, the swelling and shrinkage potential of the different layers of that soil should be taken into account. With respect to this, the Potential Linear Extensibility (PLE) was defined:

$$\text{PLE} = \text{COLE}(1) \times z(1) + \text{COLE}(2) \times z(2) + \ldots + \text{COLE}(n) \times z(n) \text{ (cm)} \qquad (8)$$

in which:
$\text{COLE}(n)$ = COLE value of nth soil horizon (–)
$z(n)$ = thickness of nth soil horizon (cm)
$z(1) + z(2) + \ldots + z(n) = 100$ cm

For a given soil, values of COLE and PLE depend on definition of V_{wet} and V_{dry}. In the USA soil classification system (Soil Survey Staff, 1975), V_{wet} is defined as the volume of a soil aggregate at a pressure head of -333 cm. V_{dry} is the volume of an aggregate at air-dryness. In practice, air-dry sometimes is replaced by oven-dry. To quantify potential swelling and shrinkage in Dutch clay soils, this definition is not very suitable. In Dutch climatic circumstances, soils are often much wetter than moisture contents corresponding with a pressure head of -333 cm. At the same time they will never become as dry as 'air-dry' (except for a very thin surface layer). Because of this, a COLE calculated between $h = -333$ cm and air-dry does not give any information on the magnitude of swelling and shrinkage to be expected in Dutch field situations. Therefore in this article we first have calculated COLE and

PLE with V_{wet}, volume of an aggregate at saturation, and V_{dry}, volume of an aggregate at a pressure head of $-16\ 000$ cm. It should be kept in mind that, independant of the definition of V_{wet} and V_{dry}, both COLE and PLE are indicating *potential* swelling and shrinkage. If measured between saturation and $h = -16\ 000$ cm, COLE and PLE are upper limits for field shrinkage in the Netherlands, which will normally not be reached in the field in subsoils, except in special cases, like removal of the topsoil or planting of a deep-rooting crop. *Actual* swelling and shrinkage are determined not only by soil properties but also by the hydrology of the soil in situ. It can for instance easily happen in the field that a well-drained soil with low COLE and PLE exhibits far more cracking and subsidence than a poorly drained soil with high COLE and PLE.

For the sake of international comparison, COLE and PLE values have also been calculated over the range $h = -333$ cm to oven-dry.

Results and discussion

Shrinkage characteristics

The measured shrinkage characteristics are presented in Figure 5. The shapes of the shrinkage characteristics, with respect to magnitude of shrinkage, relation with pressure head values, air entry points, start and end of shrinkage phases etc. vary strongly from one soil to another. Only few curves, for instance Schermerhorn A12, resemble the theoretical picture, including a substantial normal shrinkage phase, of Figure 3. This can be ascribed to either the presence of small amounts of silt and sand particles which may locally restrict shrinkage and induce air entry, or to the development of micro-cracks inside of the soil clods during drying. Because in all cases the shape of the measured shrinkage characteristics was reproducable using clods of various size, the first explanation is the most likely.

Most of the selected soil horizons show large shrinkage, as is clearly visible from the large decrease of void ratio of the drying aggregates. In all aggregates, shrinkage starts immediately at the first water extraction at saturation. Moreover, shrinkage expressed as $de/d\vartheta$ is largest near saturation, and becomes smaller when the soil gets dryer. Because of the influence of clay content, clay mineralogy, cation exchange capacity and organic matter on the shrinkage process, there are also many differences in behaviour of the various soils. In some soil layers, like Schermerhorn C22g, shrinkage stops at pressure heads of minus a few hundred cm's. In other soils, shrinkage continues far below pressure heads of $-16\ 000$ cm, e.g. the subsoils of Nieuw Beerta and Bruchem and the whole Kats profile. Not only the magnitude but also the course of the shrinkage process differs from one soil horizon to another. In some horizons, the change from normal to residual shrinkage (the air-entry point) lies very close to saturation, as is the case in the complete Nieuw Statenzijl profile. In other soils, this point lies somewhere between a pressure head of -10 cm and $-16\ 000$ cm. An extreme case is the Bruchem C11g horizon, where normal shrinkage continues until pressure heads much lower than $-16\ 000$ cm.

Another special case is the Dronten subsoil. This subsoil is only half ripe, which

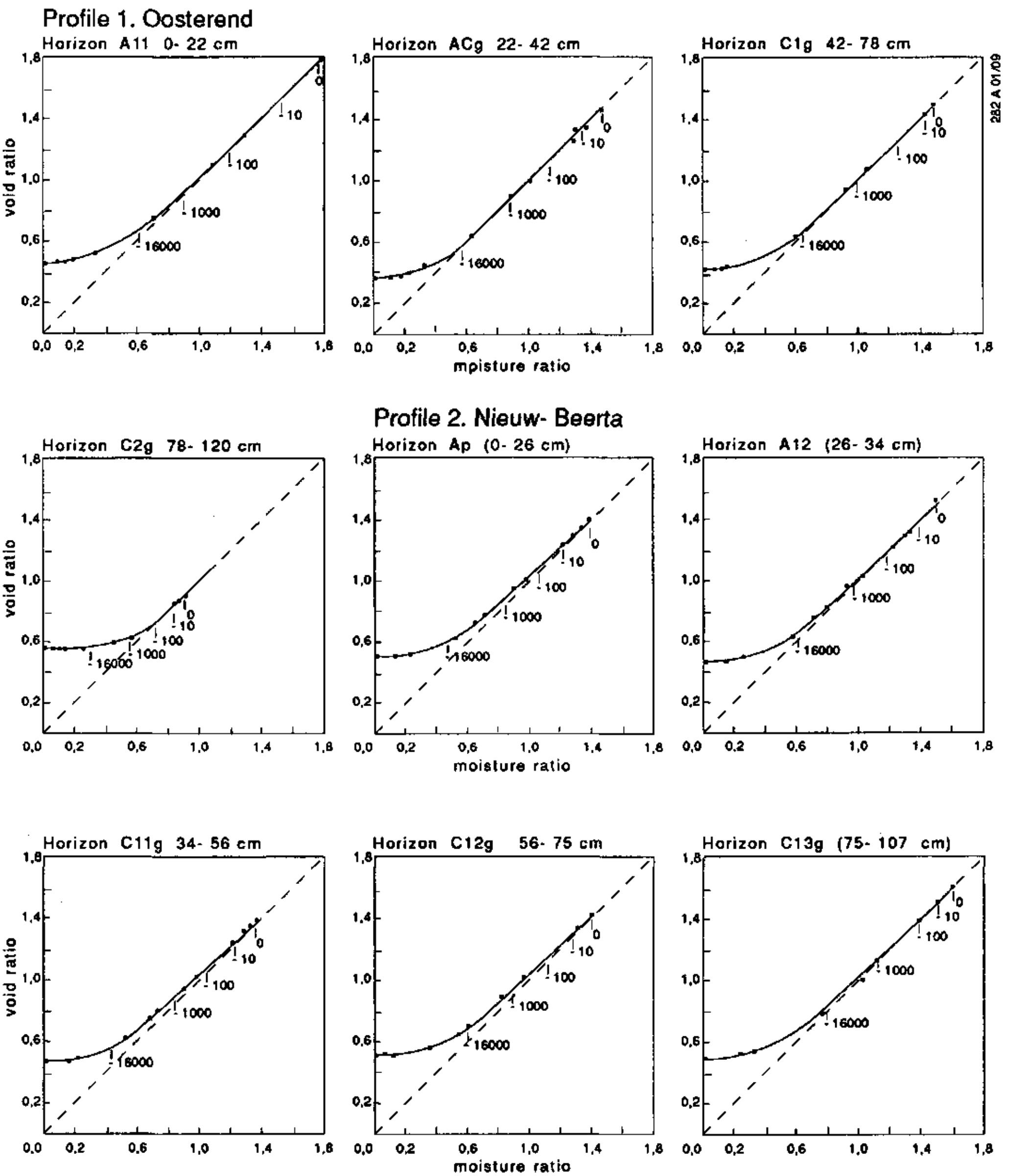


Fig. 5. Shrinkage characteristics of natural aggregates of seven clay soil profiles from the Netherlands; void ratio = volume of pores/volume of solids; moisture ratio = volume of water/volume of solids. Some values of pressure heads (cm) are also indicated.

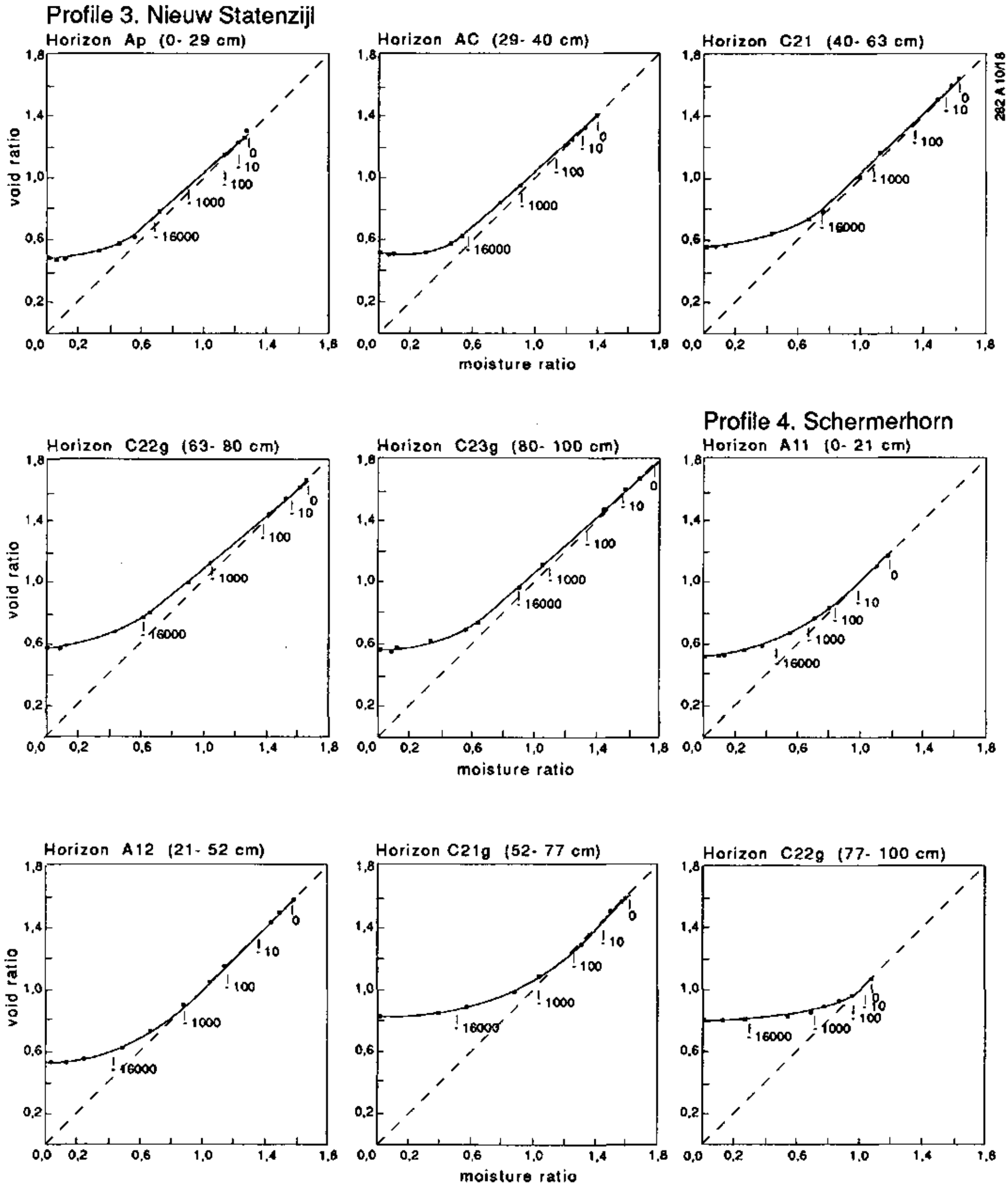
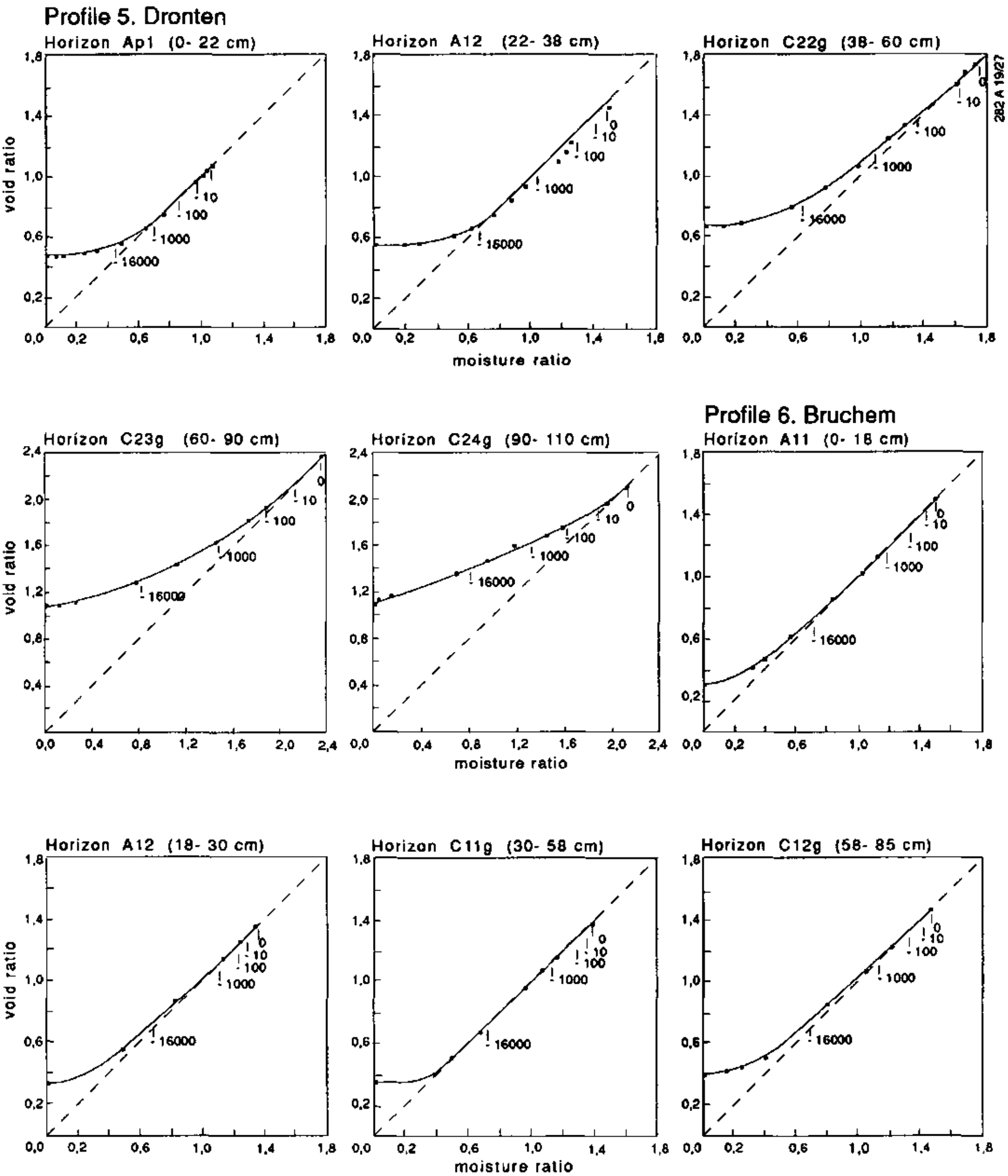


Fig. 5. Continued



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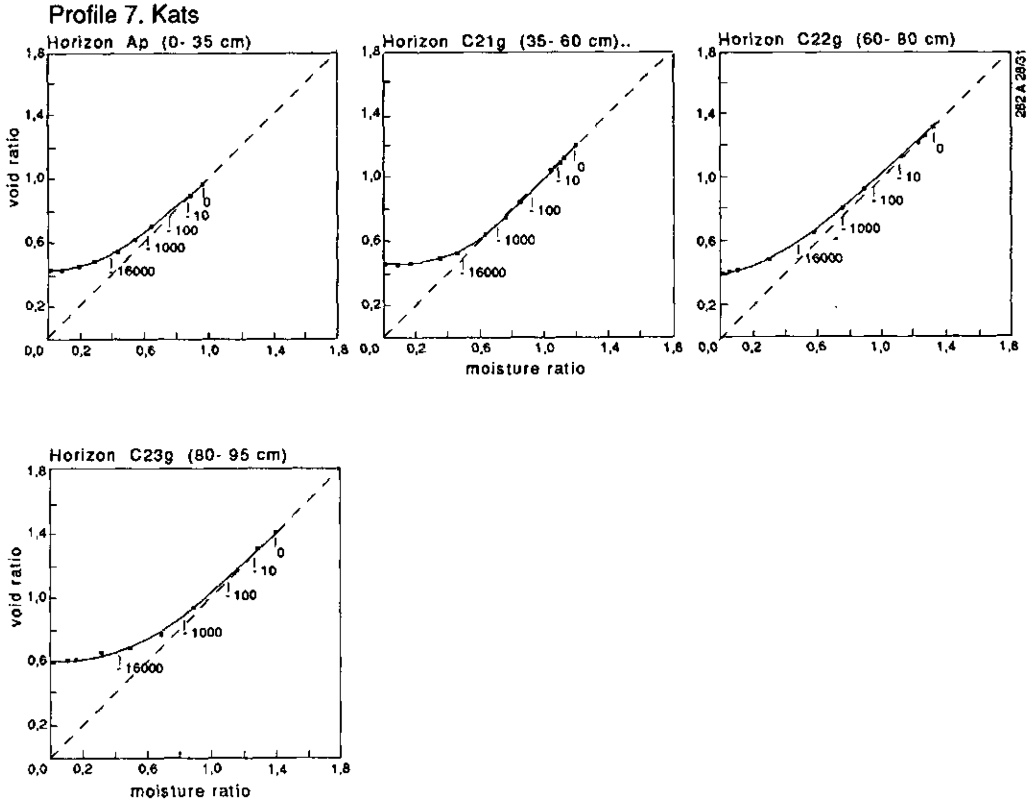

Fig. 5. Continued

results in a markedly different shape of the shrinkage characteristic. In this subsoil, total shrinkage is high, but air entry occurs much earlier and is much larger than in most of the other soils. It can be expected that, after a few wetting-drying cycles, total shrinkage will become smaller and the shrinkage curve will approach the saturation line, as a result of ripening. It is likely that some ripening also plays a role in the observed shrinkage of some fluvial soils. Miedema (1987) reported that aggregates of a holocene fluvial soil did not regain their original volume after extreme drying and rewetting. This effect will be most pronounced in poorly drained subsoils.

The observed course and magnitude of shrinkage upon drying has important consequences for the field behaviour of clay soils in the Netherlands. Some clay soils show normal shrinkage from saturation till a pressure head much lower than − 16 000 cm's. An extreme example of this is the Bruchem C11g horizon (Profile 6). This means that under Dutch climatic circumstances, the aggregates in this soil horizon always remain fully saturated. Air is only present in inter-aggregate pores like shrinkage cracks. Naturally, this strongly affects the air availability and root development in this type of soil. Soil structure becomes very important because to optimize root development, the distance between air-containing macropores should be minimized. Furthermore, phenomena like partial anaerobiosis (Leffelaar, 1987) are likely to occur in this type of heavy clay soils.

COLE and PLE

The values of volume decrease, COLE and PLE over three pressure head ranges are presented in Table 2. Volume decrease from saturation to oven-dry varies between 14 % for the Schermerhorn C22g horizon and 49 % for the Bruchem A11 horizon. Some horizons with relatively low clay contents of only 15-16 % show volume decreases of 15 to 20 %. Less than the heavy clay soils, but still considerable. Corresponding COLE values from saturation to oven-dry range from 0.052 to 0.248. The PLE values over the same range for the seven profiles corresponds with the clay contents of the soils. The light clay soils of Kats and Schermerhorn have PLE values of about 13 cm. The heavier clay soils of Nieuw Beerta and Nieuw Statenzijl have PLE values of about 17 cm and the soils traditional known as strong swelling and shrinking, indeed show the highest PLE values: 18.5 cm for Oosterend clay and 21.6 cm for Bruchem basin clay. The PLE value of 16.4 cm of the Dronten soil reflects partly the irreversible ripening proces upon oven-drying.

Volume changes between saturation and a pressure head of − 16 000 cm are of more practical importance in the Netherlands. In this pressure head range, volume decreases vary from 13 %, again for the Schermerhorn subsoil, to 42 % for the Nieuw Beerta C11g Horizon. Corresponding COLE values over this pressure head range are respectively 0.05 and 0.20. The PLE values from 0 to − 16 000 cm can be considered as the maximum surface subsidence that the considered soil can exhibit under Dutch climatic conditions. This maximum subsidence is about 11 cm for the light clay soils of Kats and Schermerhorn and also the heavy clay soil of Bruchem. The relatively low value of Bruchem is surprising but can be explained from the fact that in this soil shrinkage continues far below pressure heads of − 16 000 cm and shrinkage in the range saturation to − 16 000 cm is relatively small. The maximum subsidence of the soil surface is about 13 cm for the heavy clay soils of Oosterend, Nieuw Statenzijl and the partly unripe soil of Dronten. The heavy clay soil of Nieuw Beerta shows the largest maximum surface subsidence, namely 15 cm. Whether these potential maximum subsidences are really reached in the field depends on hydrology and actual water loss of the soil in situ, but is not likely.

Because determination of COLE values requires much effort, and clay and organic matter contents of Dutch clay soils are already available or easily measured, it is worthwhile to try to predict COLE from these two soil properties. The best fit of COLE (− 333 cm to oven-dry) against clay content (in weight % of the soil) is expressed by:

$$\text{COLE} = 0.002552 \text{ clay content} + 0.0118 \quad r^2 = 0.59$$

Table 2. Relative volume decrease ($\Delta v/v \times 100$), coefficient of linear extensibility (COLE) for equal individual soil horizon and potential linear extensibility (PLE) for the entire soil profile of seven clay soils from the Netherlands. Values are presented for three different pressure head ranges.

Location	Horizon	0 cm to-16 000 cm			−333 cm to oven-dry			0 cm to oven-dry		
		$\Delta v/v$ ×100 (%)	COLE (−)	PLE (cm)	$\Delta v/v$ ×100 (%)	COLE (−)	PLE (cm)	$\Delta v/v$ ×100 (%)	COLE (−)	PLE (cm)
1. Oosterend	A11	38.0	0.173		26.9	0.110		47.2	0.237	
	ACg	34.9	0.154	13.1	32.5	0.140	11.2	44.0	0.213	18.5
	C1g	31.4	0.134		33.7	0.147		42.9	0.205	
	C2g	17.9	0.068		9.3	0.030		19.3	0.074	
2. Nieuw Beerta	Ap	34.9	0.154		25.3	0.102		38.0	0.173	
	A12	34.1	0.149		29.0	0.121		41.2	0.194	
	C11g	42.0	0.199	15.3	30.9	0.131	11.9	44.6	0.218	16.9
	C12g	31.1	0.132		25.3	0.102		38.7	0.177	
	C13g	30.5	0.129		32.1	0.138		41.4	0.195	
3. Nieuw Statenzijl	Ap	25.5	0.103		29.2	0.122		37.2	0.168	
	AC	31.1	0.132		27.9	0.115		37.9	0.172	
	C21	32.0	0.137	13.3	30.9	0.131	12.6	41.8	0.198	17.0
	C22g	34.1	0.149		30.3	0.128		40.4	0.188	
	C23g	35.4	0.157		30.3	0.128		43.6	0.210	
4. Schermerhorn	A11	25.1	0.101		15.6	0.058		28.8	0.120	
	A12	38.0	0.173	11.3	25.3	0.102	6.3	40.5	0.189	13.2
	C21g	27.0	0.111		15.1	0.056		29.6	0.124	
	C22g	13.1	0.048		6.6	0.023		14.1	0.052	
5. Dronten	Ap1	25.5	0.103		17.4	0.066		29.2	0.122	
	A12	31.1	0.132		27.1	0.111		37.7	0.171	
	C22g	34.6	0.152	12.7	27.3	0.112	10.0	39.9	0.185	16.4
	C23g	32.0	0.137		28.6	0.119		40.2	0.187	
	C24g	21.5	0.084		20.4	0.079		30.1	0.127	
6. Bruchem	A11	30.5	0.129		42.8	0.205		48.6	0.248	
	A12	25.3	0.102	11.6	38.5	0.176	18.2	43.4	0.209	21.6
	C11g	28.1	0.116		40.4	0.188		44.1	0.214	
	C12g	28.1	0.116		37.6	0.170		42.8	0.205	
7. Kats	Ap	21.9	0.086		13.9	0.051		25.3	0.102	
	C21g	29.0	0.121	11.4	20.0	0.077	6.7	33.9	0.148	13.3
	C22g	32.0	0.137		21.1	0.082		35.9	0.160	
	C23g	31.1	0.132		18.4	0.070		32.9	0.142	

When the organic matter content (in weight % of the soil) is taken into the regression analysis, we get the following result:

$$\text{COLE} = 0.002636 \text{ clay content} + 0.006 \text{ organic matter content} - 0.171$$
$$r^2 = 0.71$$

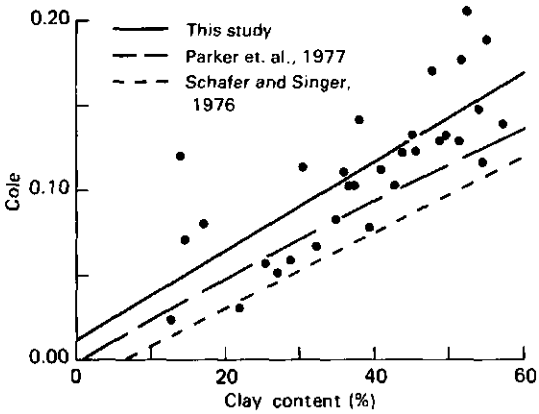

Fig. 6. Relation between clay content (weight percentage) and coefficient of linear extensibility (COLE) over the range $h = -333$ cm to oven-dry for aggregates of seven clay soil profiles from the Netherlands. The best fit is expressed by COLE = 0.002552 × clay content + 0.0118 with r^2 equal to 0.59. Relations between COLE and clay content of Parker et al. (1977), and Schafer & Singer (1976) are also presented.

Relations between total clay content and COLE of Schafer & Singer (1976), and Parker et al. (1977) for various clay soils from the USA, were compared with the results of the present study (Fig. 6). Over the whole range, COLE values of Dutch clay soils are somewhat higher, which is probably due to the presence of substantial amounts of organic matter.

Classification of shrinkage of Dutch clay soils

In order to evaluate whether the measured shrinkage in Dutch clay soils is small or large, we compared the presented results with data from other studies. A summary of studies from several countries in which COLE values (between oven-dry and $h = -333$ cm) of clay soils have been determined is presented in Table 3. The majority of Dutch clay soils have COLE values between 0.11 and 0.15(see Table 2). Compared with foreign soils, these values are neither very high nor very low. An exception is the Bruchem basin clay with a COLE value of 0.205 which belongs to the highest COLE values of the world. Due to the Dutch climate, however, actual field shrinkage will always be much smaller than for instance in arid Vertisols.

When we compare the presented measurements with an often used classification of swelling and shrinkage potential of a soil based on COLE values (Parker et al., 1977) we find that the heavy clay soils from Oosterend, Nieuw Beerta, Nieuw Statenzijl and Bruchem belong to the class of soils with very high shrink-swell potential. The soils from Schermerhorn and Kats show medium to high shrink-swell potential in the different horizons (Table 4).

Reeve et al. (1980) presented a classification of shrinkage for British soils based upon PLE values. In this classification the soil as a whole is considered and not the

Table 3. Comparison of measured minimum and maximum COLE-values (h = −333 cm to oven-dry) of Dutch clay soils with values of foreign clay soils.

Location	Number of samples	COLE range	Source
USA	30	0.004-0.181	Franzmeier & Ross (1968)
Yolo County, USA	16	0.001-0.118	Schafer & Singer (1976)
Ontario, USA	13	0 -0.088	Ross (1978)
Tanzania	6	0.037-0.230	Ross (1978)
Great Britain	20	0.049-0.232	Reeve et al. (1980)
Israel	67	0 -0.277	Smith et al. (1985)
Saskatchewan, Canada	33	0.021-0.168	Dasog et al. (1988)
Netherlands	31	0.023-0.205	This study

Table 4. Rating of shrink-swell potential of soil horizons based upon COLE values (Parker et al., 1977).

Shrink-swell potential	COLE (−333 cm to air-dry)	Horizons
Low	<0.03	Oosterend C2g Schermerhorn C22g
Medium	0.03-0.06	Schermerhorn A11, C21g Kats Ap
High	0.06-0.09	Dronten Ap1, C24g Kats C21g, C22g, C23g
Very high	>0.09	Nieuw Beerta Nieuw Statenzijl Bruchem Oosterend A11, ACg, C1g Schermerhorn A12 Dronten A12, C22g, C23g

different horizons separately. Reeve et al. distinguished three shrinkage categories:
- PLE >14: large shrinkage,
- 9 ≤PLE ≤14: moderate shrinkage,
- PLE <9: low shrinkage.

In the quoted paper, PLE was calculated between a pressure head of −333 cm and oven-dryness. As is explained above, in the Netherlands a definition of PLE between 0 cm and −16 000 cm is of more practical use. Therefore it is proposed to classify shrinkage of Dutch clay soils according to the PLE boundary values of Reeve et al., but between pressure heads of 0 and −16 000 cm. The resulting classification is presented in Table 5.

Table 5. Classification of shrink-swell potential of Dutch clay soils.

Shrink-swell potential	PLE (between $h = 0$ and $h = -16\,000$ cm) (cm)	Location
Low	<9	
Moderate	9-14	Oosterend, Nieuw Statenzijl, Kats, Schermerhorn, Dronten, Bruchem
Large	>14	Nieuw Beerta

Conclusions

Only few shrinkage characteristics of Dutch clay soils resemble the idealized picture of Figure 3. The measured shrinkage characteristics (Fig. 5) vary strongly with respect to magnitude of shrinkage, relation with pressure head values, air entry points, start and end of shrinkage phases etc.

Some heavy clay soils from the Netherlands belong to the strongest swelling-shrinking soils of the world, but also relatively light clay soils like Kats and Schermerhorn show considerable shrinkage indicating that even in these soils processes resulting from shrinkage, like bypass flow, may take place. (Fig. 5, Table 2, Table 4).

Volume decrease of Dutch clay soils aggregates that dry from saturation to oven-dryness is maximally 49 % (Table 2). In the Netherlands because of climatic conditions the range between saturation and a pressure head of $-16\,000$ cm is of more relevance. In this range the maximum volume decrease of a soil horizon is 42 % (Nieuw Beerta C11g) and the potential surface subsidence of a soil in situ is about 15 cm (Nieuw Beerta) (Table 2).

Some clay soils in the Netherlands show normal shrinkage from saturation to pressure heads much lower than $-16\,000$ cm (Fig. 5). This means that in the field, the aggregates of these soils will always remain saturated. Only inter-aggregate pores, which change their dimensions throughout the year, may contain air. This will have consequences for instance for root development and the occurrence of partial anaerobiosis.

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3. SHRINKAGE GEOMETRY OF A HEAVY CLAY SOIL AT VARIOUS STRESSES

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SHRINKAGE GEOMETRY OF A HEAVY CLAY SOIL AT VARIOUS STRESSES

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ABSTRACT

The shrinkage geometry of a clay soil upon drying from saturation to oven dryness was investigated. Undisturbed samples in rings measuring 232 cm^3 were taken in the field at depths of 0.0, 0.20, 0.40 and 0.60 meter. Overburden pressures at these four depths were determined by wet bulk density determination. Samples were oven dried with various loads applied on top. Surface subsidence and total volume decrease after drying were measured. It appeared that for each soil layer, shrinkage at overburden pressures equal to or larger than field pressures was isotropic. When the load was removed during drying, subsoil samples showed relatively large cracking in comparison with surface subsidence.

INTRODUCTION

The analysis of shrinkage processes in clay soils is important because of the large impact that shrinkage cracks and surface subsidence have on physical and chemical processes in clay soils and on the use potential of these soils. For example, water and solute transport in clay soils are largely determined by shrinkage cracks and other macropores, and buildings and pavements on clay soils may be destroyed by vertical soil movements. The question of how shrinkage processes in clay soils proceed upon drying can be divided into two parts:

i) The relation between water content changes and three dimensional volume changes of the clay soil matrix;
ii) The conversion of three dimensional volume changes of the clay soil matrix into cracking and surface subsidence of clay soils.

The first part can be dealt with by determining shrinkage characteristics of natural clods, as has been done by Franzmeier and Ross (1968), Schafer and Singer (1976), Ross (1978), Reeve et al. (1980), Smith et al. (1985), and Dasog et al. (1988). The second part of the question has received less attention. However, in order to completely describe the behaviour of clay soils upon drying, this second part is of equal importance because cracking and surface subsidence have different and sometimes contrasting effects on transport processes in soil. Moreover, recent simulation models for calculation of swelling and shrinkage processes and water balance in clay soils (Bronswijk, 1988), lack experimental support about geometry of cracking and subsidence.

Aitchinson and Holmes (1953), Berndt and Coughlan (1977), and Yule and Ritchie (1980) found volume changes in clay soils to be isotropic. Fox (1964) reported one dimensional subsidence in wet soils while Hallaire (1984) found volume changes in wet soils that were caused predominantly by cracking. One possible reason for the sometimes unclear and contradictory results of the aforementioned research is the effect of overburden on the geometry of shrinkage. In a field situation, the subsoil is subjected to an overburden pressure caused by the overlying soil. Theoretically, this could enhance vertical shrinkage and restrict vertical swelling. When sampling the subsoil, this natural load is removed, which could possibly influence the geometry of shrinkage. Detailed information on the effect of load on shrinkage geometry of clay is limited to very young, pedogenetically undeveloped marine soils (so-called 'unripened soils', Pons and Van der Molen, 1973) and clay pastes (Talsma, 1977; Rijniersce, 1983). Both these authors reported unidimensional shrinkage at high water contents and large loads and three dimensional isotropic shrinkage at low water contents and small or zero loads. It is likely, however, that their results are specific for clay pastes or paste-like soils with very high water contents.

The objective of this study was to assess the shrinkage geometry of a well developed, structured heavy clay soil. First, a simple general equation is presented which describes the conversion of three dimensional volume change into cracking and surface subsidence, using a dimensionless geometry factor r_s. Second, this r_s-factor is determined for a heavy clay soil at overburden pressures equal to field conditions. Finally, the dependance of r_s on overburden is investigated.

GEOMETRY OF SHRINKAGE OF A CLAY SOIL

Figure 1 shows a soil cube before and after isotropic shrinkage. From this figure, it can be seen that $V = z^3$, $V - \Delta V = (z - \Delta z)^3$ and $\Delta V = z^3 - (z - \Delta z)^3$. Therefore:

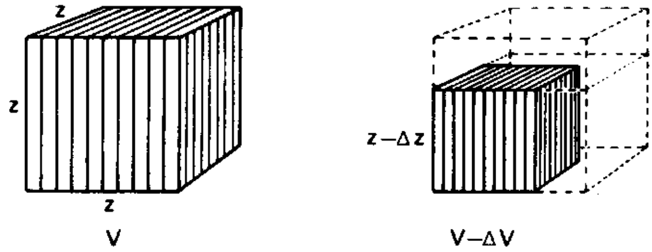

Fig. 1. A soil cube with initial layer thickness z (m) and volume V (m^3) shrinks isotropically into a cube with volume V-ΔV (m^3) and sides z-Δz (m)

$$1 - \frac{\Delta V}{V} = (1 - \frac{\Delta z}{z})^3 \tag{1}$$

in which V is the original volume of the soil cube (m^3), ΔV is the volume change upon shrinkage (m^3), z is the original height of the soil cube (m) and Δz is the surface subsidence upon shrinkage (m).

In the case of one dimensional subsidence without cracking, it can easily be shown that then:

$$1 - \frac{\Delta V}{V} = (1 - \frac{\Delta z}{z})^1 \tag{2}$$

In a study on unripened soils, Rijniersce (1983) named the exponent in Eq. [1] and [2] as the r_s-factor. We will adopt this terminology for developed soils as well and arrive at a general relation between volume change and subsidence of a soil volume:

$$1 - \frac{\Delta V}{V} = (1 - \frac{\Delta z}{z})^{r_s} \tag{3}$$

where r_s is a dimensionless geometry factor. From Figure 1 and Eq. [3], the possible values of r_s can be deduced. In case of subsidence without cracking: $r_s = 1$. In case of cracking without subsidence: $r_s \rightarrow \infty$. For all other r_s-values, both cracking and subsidence occur simultaneously with the following division:

$r_s = 3$: isotropic shrinkage; $1 < r_s < 3$: subsidence dominates cracking and $r_s > 3$: cracking dominates subsidence.

SOILS AND METHODS

The soil used in this study is located in a basin clay area in the central part of the Netherlands. The soil at the site can be classified as a typic Fluvaquent (very fine clayey, mixed, mesic) (Soil Survey Staff, 1975). The percentage of particles smaller than 2 μm ranges from 52 to 69%.

Horizontal and vertical components of shrinkage were measured on undisturbed cylindrical ring samples. The height of the rings was 5 cm and the inner diameter 7.69 cm giving a volume of 232 cm^3. The samples were taken in saturated conditions in the field at depths of 0.0-0.05 m, 0.20-0.25, 0.40-0.45 and 0.60-0.65 m.

Wet bulk densities of the whole soil profile were determined which yielded overburden pressures in situ of 0, 2.7, 5.8 and 9.2 kPa at depths of 0.0-0.05 m, 0.20-0.25, 0.40-0.45 and 0.60-0.65 m below soil surface, respectively.

In the laboratory, various loads were applied to the samples using lead discs. The following experiments were carried out:

i) From each depth, 25 samples were taken on which loads, corresponding with the field overburden were applied in the laboratory. This corresponds to loads of 0, 1253, 2641 and 4269 g at samples taken at 0.0, 0.20, 0.40, 0.60 m below soil surface. The loaded samples were dried in the oven at 103°C;

ii) At 0.20-0.25, 0.40-0.45 and 0.60-0.65 m below the soil surface, 25 samples were taken at each depth. The samples were oven dried without applying a stress;

iii) At 0.0-0.05 and 0.60-0.65 m below the soil surface, 25 samples were taken at each depth and oven dried with a stress equal to 5.8 kPa in addition to the existing overburden in the field. The applied stress of 5.8 kPa is equivalent to the weight of 40 cm of soil. Total stress on the 0.0-0.05 m and 0.60-0.65 m samples amounted to 5.8 and 15.0 kPa, respectively.

Subsidence of the soil surface in the ring after oven drying was measured at nine random positions using a dial gauge. The nine values were then averaged. The volume of the soil matrix in the rings after oven dring was determined by weighing the samples in oil. We have used a simple, high viscosity motor oil. This oil did not infiltrate in the oven-dried clay soil matrix, which was checked by weighing the dried soil cores before and after immersion. Therefore, the three-dimensional volume decrease, caused by cracking and subsidence, could be measured in this way. Measured values of subsidence Δz, and volume change ΔV, were introduced in Eq. [3] to yield an r_s-value for each sample. For each combination of depth and stress, the twenty five r_s-values were averaged and standard deviations calculated. A Student t-test (two-sided, significance level 5%) was run for the hypothesis that r_s was equal to three.

RESULTS AND DISCUSSION

Measured r_s-values at field overburden pressures were equal to three for all soil layers at a significance level of 5% (Table 1), indicating that shrinkage was isotropic. Increasing the stress on the soil samples did not alter the value of r_s. Decreasing the stress, however, resulted in r_s-values significantly larger than three thereby indicating that cracking dominated subsidence. This effect is probably caused by a small rise of the soil surface when the natural stress is removed. Shrinkage geometry of unloaded subsoil samples is therefore not representative for field behaviour. To extrapolate soil core shrinkage to field conditions, the natural overburden pressure should be maintained.

In the present clay soil, shrinkage in the field was found to be three dimensionally isotropic, from saturation to oven dryness.

Table 1. Measured values of the r_s-factor (Eq. 3), describing geometry of shrinkage, at various loads. Data are average values and standard deviation over 25 samples. $r_s = 3$ implicates three dimensional isotropic shrinkage

Depth	Natural stress in the field	r_s-factor under laboratory stress		
(m)	(kPa)	0 kPa	field stress	field stress +5.8 kPa
0.00-0.05	0		3.05 0.20	3.07 0.21
0.20-0.25	2.7	3.52 0.18	3.01 0.16	
0.40-0.45	5.8	3.61 0.14	2.96 0.14	
0.60-0.65	9.2	3.63 0.17	2.97 0.12	2.95 0.13

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4. DRYING, CRACKING AND SUBSIDENCE OF A CLAY SOIL IN A LYSIMETER

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DRYING, CRACKING AND SUBSIDENCE OF A CLAY SOIL IN A LYSIMETER

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ABSTRACT

The relation between changes in water content and swelling and shrinkage processes was studied by exposing an undisturbed heavy clay soil in a lysimeter to evaporation at controlled conditions in the laboratory, during a period of 82 days. Changes in water content were measured with tensiometers and by weighing the lysimeter. Swelling and shrinkage were determined by measuring the surface subsidence. The loss of water from the clay soil amounted to 45 mm, which was 40% less than the loss of water from a comparable silty soil lysimeter. Drying of the clay soil was restricted to the top 15 cm of the soil. As much as 67% of the water loss originated from the top 7.5 cm of the soil. Simultaneous shrinkage in the clay soil resulted in a three-dimensional decrease in volume of 34 mm, consisting of a crack volume of 22 mm and a surface subsidence of 12 mm. The clay soil exhibited the successive occurrence of structural shrinkage, isotropic normal shrinkage, isotropic residual shrinkage and isotropic normal shrinkage again. The occurrence of normal and residual shrinkage could be predicted by the water content changes in the soil and the shrinkage characteristics of soil aggregates. Water loss in the structural shrinkage phase occurred from interaggregate pores and could therefore only be quantified from the lysimeter experiment.

INTRODUCTION

Due to the presence of clay minerals, the volume of soil aggregates in clay soils changes as water content changes. In dry periods, the volume of individual aggregates decreases, which in the field becomes visible as shrinkage cracks and surface subsidence. In wet periods, swelling causes crack closure and upward movement of the soil surface. The physical behaviour of clay soils and their potential for agricultural production are determined by this alternating swelling and shrinkage.

When cracks are closed, infiltration of water into the soil is very slow, and ponding and surface runoff are likely to occur. In such a situation, crop growth may be hampered by oxygen deficiency and pasture may be destroyed by cattle hoofs. With respect to environmental consequences, the application of liquid manure in such periods may lead to rapid transport of pollutants to surface waters by runoff.

After a dry period the soil will be cracked, resulting in high potential infiltration rates and storage capacities. Capillary rise from the water table and evapotranspiration may then be hampered by low hydraulic conductivities. Resulting water shortage is enhanced by bypass flow: part of the precipitation flows through shrinkage cracks to subsoil layers, thus bypassing the relatively dry root zone. This process again has some important environmental effects. Pollutants may rapidly reach the water table or, when pipe drainage has been installed, travel through these drains to surface waters again.

Understanding and predicting transport processes in swelling clay soils require knowledge of the dynamic process of soil cracking and surface subsidence. Therefore, the relation between drying and shrinkage is of great importance.

Haines (1923) and Keen (1931) defined three shrinkage phases:

- normal shrinkage: the decrease in volume of clay aggregates is equal to the loss of water. The aggregates remain fully saturated;
- residual shrinkage: upon drying the volume of the aggregates still decreases, but the loss of water is greater than the decrease in volume. Air enters the pores of the aggregates;
- zero shrinkage: the soil particles have reached their densest configuration. Upon further water extraction, the volume of aggregates remains constant. The loss of water is equal to the increase in air volume in the aggregates.

In the field, sometimes a fourth shrinkage phase, preceding the three mentioned phases, can be distinguished: structural shrinkage (Stirk, 1954). Structural shrinkage occurs in very wet soils. When such soils dry, either by evaporation or drainage, large water-filled pores may be emptied. As a result, aggregates can get a somewhat denser packing. On the whole, the changes in volume in this shrinkage phase are negligible, but the loss of water can be considerable.

Studies on the relation between water content and swelling and shrinkage have been carried out on aggregates (e.g. Grossman et al., 1968; Franzmeier & Ross, 1968; Reeve & Hall, 1978; Reeve et al., 1980; Bronswijk & Evers-Vermeer, 1990), small cores (e.g. Perroux et al., 1974; Berndt & Coughlan, 1977; Yule & Ritchie, 1980a), large cores (Yule & Ritchie, 1980b), and in the field (Aitchison & Holmes, 1953; Jamison & Thompson, 1967; Yaalon & Kalmar, 1972; Yaalon & Kalmar, 1984; Hallaire, 1984; Bronswijk, in prep.). Different problems inhibit the analysis of the relation between changes in water content and changes in volume. Studies on aggregates and small cores generally do not yield the magnitude of water loss in the structural shrinkage phase, because structural shrinkage is strongly dependent on soil structure, and therefore large samples are required. Furthermore, the load of upper soil layers may influence the geometry of swelling and shrinkage in the field, and this effect is not taken into account when dealing with aggregates or small cores taken out of the field into the laboratory. In large cores and field situations, on the other hand, changes in volume are difficult to determine. Moreover, measuring water contents is difficult. Of the latter two, large cores have the advantage that they resemble a field situation and that the water balance can be determined rather accurately in a well-controlled laboratory environment.

The objective of this research was to predict the shrinkage of a clay soil from water content changes in the soil and easily measured physical properties of soil aggregates. Because of the advantages mentioned above, a lysimeter experiment was conducted. The undisturbed heavy clay soil inside the lysimeter was subjected to evaporation in the laboratory during a period of 82 days. During drying of the soil, the various terms of the water balance were determined, together with surface subsidence and crack volumes. In order to explain the observed phenomena in the clay soil in the lysimeter, water retention curves and shrinkage characteristics were determined using soil aggregates.

METHODS AND MATERIALS

Soil type

The investigated Bruchem heavy clay soil originates from the river district in the central part of the Netherlands. The soil is classified as a typic Fluvaquent, very fine clayey, mixed, illitic-montmorillonitic mesic (Soil Survey Staff, 1975). Its clay content ranges from 52 to 69%. The soil was in use as pasture.

Soil aggregates

In the early spring of 1985, when the soil was saturated, 7 natural aggregates of about 25 cm^3 were taken from each 20 cm layer of the soil at the sampling site. To ensure their complete saturation, the aggregates were placed on a saturated sand bed for another two weeks. From the seven aggregates per soil layer, three aggregates were used to determine water retention curves on a sand box and with pressure membrane apparatus. One aggregate was used to determine the density of the solid phase. The remaining three aggregates were used to determine shrinkage characteristics by immersing the aggregates briefly in Saran F310 Resin (resin to solvent ratio 1:5 by weight). The applied Saran coating is impermeable to liquid water, but permeable to water vapour (Brasher et al., 1966). The coated aggregates were dried in the laboratory. When the aggregates dry, the elastic coating remains tightly fitted around the aggregates. By weighing and water displacement, both volumes and weights of the aggregates were determined at different stages of drying. After about 3 weeks, weight losses became negligible and the resin-coated aggregates were dried in the oven at 103°C in order to measure their final dry volumes and dry weights. Void ratios (i.e. volume of pores divided by volume of solids) and moisture ratios (i.e. volume of water divided by volume of solids) were calculated, using the measured values of density of the solid phase.

Lysimeter

One large undisturbed soil core was sampled in the field in early spring when the soil was saturated. The height of the empty pvc core was 70 cm and the diameter 27.6 cm. The top 20 cm of the soil had been removed to eliminate the

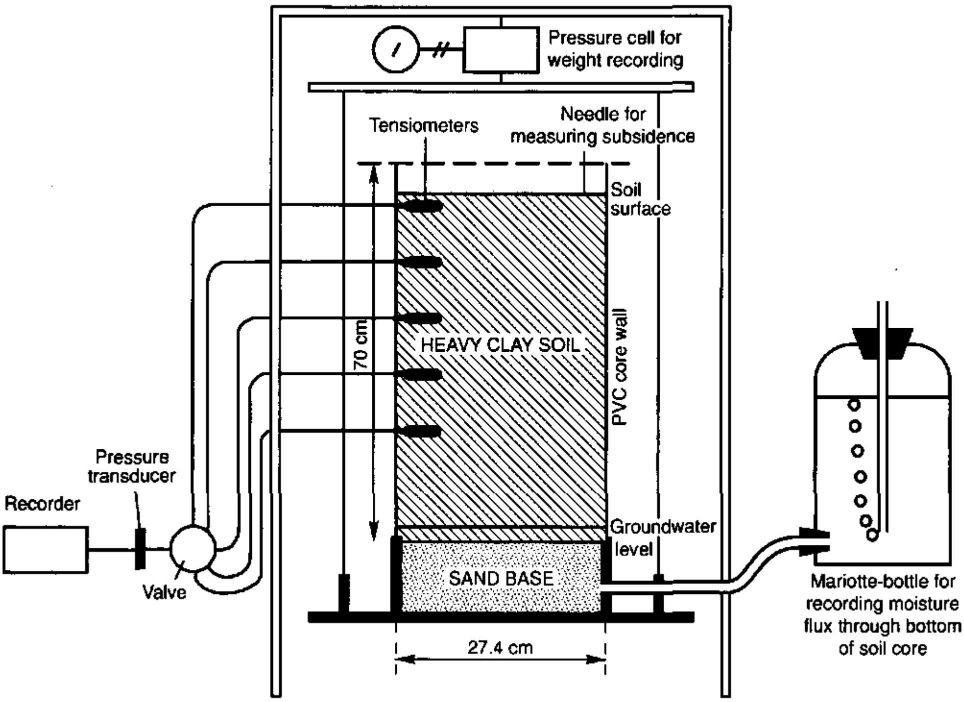

Fig. 1. Setup of the experiment

possible influence of grass roots on soil shrinkage. With a hydraulic pump and a cutting edge, the empty core was carefully pushed 60 cm into the soil, and dug out. Subsidence of the soil surface in the column during sampling was negligible. Thus, the upper 10 cm of the core remained empty and the lower 60 cm was filled with undisturbed soil from a depth of 20 to 80 cm.

In the laboratory, the core was placed on a sand base containing a drainage system, allowing water to flow into and out of the bottom of the lysimeter (Fig. 1). By using a Mariotte bottle setup, the groundwater level was kept constant at 50 cm below the soil surface during the experiment. The soil surface was kept bare. In the present experimental setup, the water balance of the clay soil over a certain time interval reads: $\Delta W = E - B$, in which ΔW is the decrease in water storage of the soil (mm), E is the cumulative actual evaporation (mm, positive) and B is the cumulative flow of water through the bottom of the lysimeter (mm, positive upwards). The quantity B was measured by weighing the Mariotte bottle, ΔW was determined by weighing the whole lysimeter, and E was calculated from the difference of B and ΔW. Ceramic cup tensiometers were installed at 3, 12, 22, 32 and 42 cm below the soil surface. The tensiometers were inserted through oval-shaped holes (2 cm height) in the lysimeter wall. Thus, tensiometers could freely move downward as the soil shrank. Tensiometers were recorded automatically, using a 5-way valve, a pressure transducer and a recorder. The average surface subsidence of the soil inside the lysimeter was measured using 9 thin needles that were lowered every other day onto the soil surface at varying randomly selected positions.

After 36 days of drying, the decrease in water storage in the soil became negligible. The potential evaporation demand was then increased using ventilators. The experiment was stopped after the tensiometer at a depth of 12 cm had exceeded its air-entry value. At that time, the experiment had lasted 82 days.

An estimation of crack volume in the lysimeter was made at the start and the end of the experiment as follows. At the time of taking the soil core in the field, 4 samples in rings of 30 cm x 5 cm (diameter x height) were taken at 5 depths in the surroundings of the sampling site of the lysimeter. Aggregate bulk density, derived from the shrinkage characteristics, was compared with ring-sample bulk density. Interaggregate porosity could thus be calculated. After concluding the lysimeter experiment, the interaggregate porosity was determined inside the lysimeter itself, again by comparing aggregate bulk density with soil bulk density.

Final gravimetric water contents (day 82) in the lysimeter were determined, as well as distribution of the weight of the solid phase in the column.

During the experiment, a similar experiment was conducted with an artificially packed soil column in order to compare the water balance of the cracking clay soil with a rigid soil. The rigid soil, 'Blokzijl silt', consists of 85% silt, 3% clay and 12% sand.

Data processing

Tensiometers at 3, 12, 22, 32 and 42 cm below soil surface were considered to represent the soil layers of 0-7.5 (layer 1), 7.5-17 (2). 17-27 (3), 27-37 (4), and 37-50 (5) cm depth respectively. The measured pressure heads in the lysimeter were converted into gravimetric water contents using the water retention curve determined on aggregates. Because the weight of the solid phase of each layer was determined, the total water storage in each layer could be calculated. Due to rapid drying of the topsoil, the tensiometer at 3 cm depth passed its air-entry value rather quickly, i.e. after 9 days. From then on, the water contents of layer 1 were calculated by subtracting the calculated cumulative changes in water storage of layers 2 to 5 from the measured change in water storage of the whole lysimeter (column weights).

Bronswijk (1990) concluded that shrinkage at natural loads occurring in Bruchem heavy clay soil was isotropic. Therefore, the measured one-dimensional soil surface subsidence of the soil was converted into a three-dimensional decrease in soil matrix volume and into crack volume by using the following equations (Bronswijk, 1989):

$$\Delta V = \{ 1 - (1 - \frac{\Delta z}{z})^3 \} V \tag{1}$$

$$V_{cr} = \Delta V - z^2 . \Delta z \tag{2}$$

with V = volume (m^3) of soil matrix at saturation
z = layer thickness (m) of soil matrix at saturation
ΔV, Δz = decrease in volume of soil matrix (m^3) and layer thickness (m) respectively as a result of shrinkage (both positive)
V_{cr} = change in crack volume (m^3)

The calculated change in crack volume of the soil, computed with Eq. (2), was compared with the measured value obtained with the core-sampling method outlined before.

RESULTS AND DISCUSSION

Aggregates

The shrinkage characteristic of the soil aggregates is shown in Figure 2A. The measured shrinkage characteristic shows the three classical shrinkage phases: normal shrinkage from ϑ = 1.15 to 0.5, residual shrinkage from ϑ = 0.5 to 0.18, and zero shrinkage from ϑ = 0.18 to 0. The water retention curve is pictured in Figure 2B. As is common in heavy clay soils, the water retention

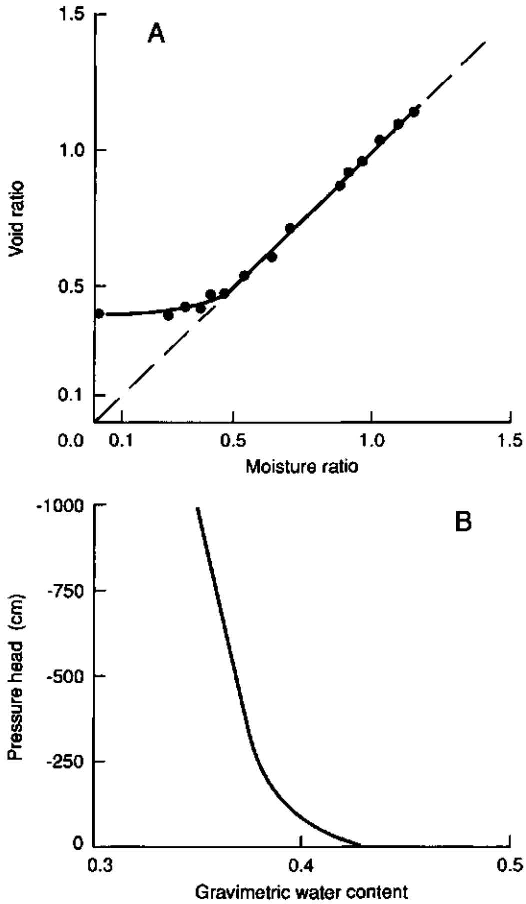

Fig. 2. Physical properties of the clay soil used in the experiment
A Shrinkage characteristic of soil aggregates
B Water retention curve

curve shows a very steep decrease in pressure head with decreasing water content. The greater and most important part of the shrinkage process in the considered soil can be regarded as normal shrinkage. The whole pressure head range in which water uptake by plant roots takes place, lies within the normal-shrinkage phase.

Lysimeter

The water balance of the clay soil is depicted in Figure 3A. During the first ten days of the experiment, the initially high evaporation rate decreased gradually until a more or less constant rate of 0.76 mm/d was reached. From day 36 on, when the potential evaporation demand was increased by ventilators, the evaporation rate was equal to about 0.83 mm/d. The upward flow through the bottom of the clay-soil lysimeter quickly became constant at a rate of about 0.37 mm/d. The water storage in the clay soil decreased rapidly during the first fifteen days. Thereafter, the evaporation became equal to the upward flow through the bottom of the lysimeter, so the water storage did not decrease anymore. After the potential evaporation demand had been increased at day 36, the evaporation rate increased, the upward flow of water through

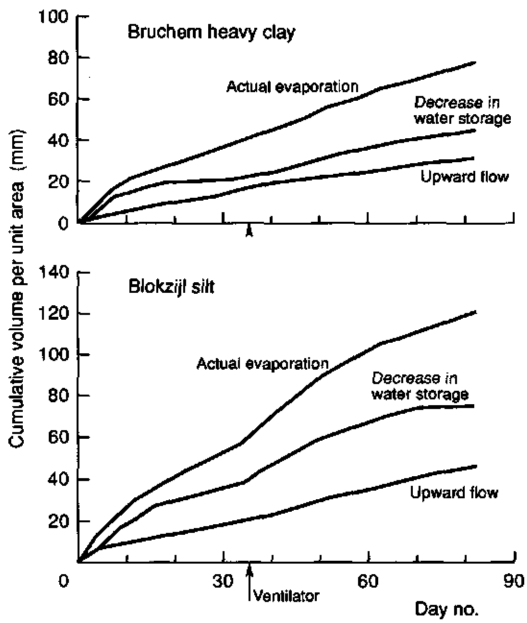

Fig. 3. Measured water balances of a lysimeter with Bruchem heavy clay and one with Blokzijl silt. The potential evaporation was the same for both lysimeters

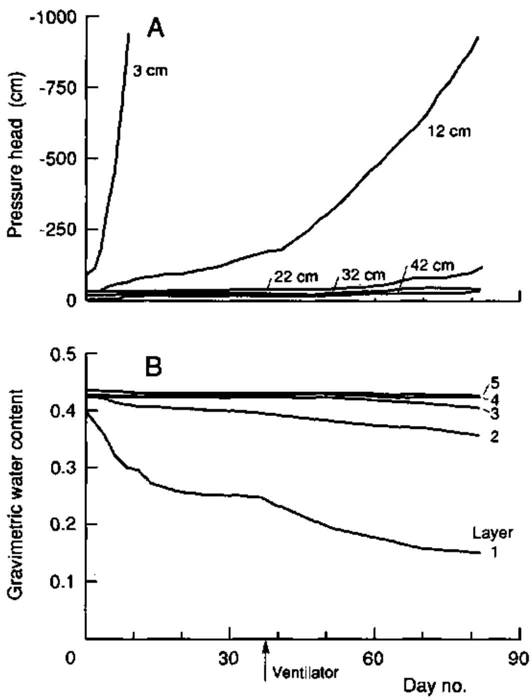

Fig. 4. Drying of Bruchem heavy clay at various depths
A Measured pressure head values (cm)
B Water contents. The water contents of layers 2-5 were derived from measured pressure head values and the water retention curve. The water content of layer 1 was calculated from the difference of the column weight and the water contents of layers 2-5

the bottom remained practically unaltered, and therefore the water storage in the soil decreased again. No equilibrium situation was attained again before the experiment was concluded. The cumulative evaporation of the Bruchem heavy clay soil was about 65%, the cumulative upward flow about 73%, and the decrease in water storage 58% of the values obtained for Blokzijl silt (Fig. 3).

The measured pressure head values in the clay soil showed a rapid decrease for the top tensiometer at 3 cm depth (Fig. 4A). The air-entry value of this tensiometer was already reached at day 9, due to the steepness of the water retention curve (Fig. 2B). The second tensiometer at 12 cm depth showed a gradual decrease in pressure head over the whole measuring period of 82 days. This indicates that, while the column weight implicated a steady state around day 30, the soil around the second tensiometer was still drying out and therefore water inside the core was still redistributing. The tensiometers at

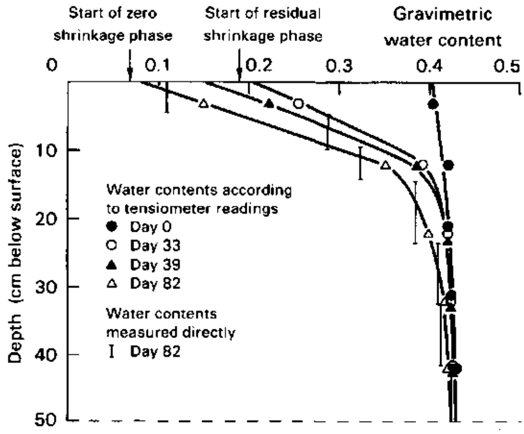

Fig. 5. Gravimetric water content profiles at various times during drying of Bruchem heavy clay soil. After conclusion of the experiment, the water content of the soil in the lysimeter was determined. These directly measured values are presented in the figure as well. Finally, the water contents where residual shrinkage and zero start according to the shrinkage characteristic (Fig. 2A) are indicated with ↓

depths of 22, 32 and 42 cm showed only very little drying.

The water contents of the various layers of the clay soil are pictured in Figure 4B. The course of the gravimetric water content of layer 1 (0-7.5 cm) clearly reflected the two different evaporation regimes. The water content of this layer reached a constant value of about 0.25 around day 22. When the potential evaporation demand was increased, the water content rapidly decreased, down to 0.15 at the end of the experiment. Only after about fifty days did the three lower soil layers begin to lose water.

In Figure 5, water-content profiles at various times during the experiment are compared. At the end of the experiment at day 82, a very steep water-content profile had developed with high water-content gradients in the upper 10 cm of the soil profile. From Figure 5 it follows that the directly measured gravimetric water content at the end of the experiment agreed well with the water-content profile derived from pressure head values. This supported the method of using tensiometers and a water retention curve to derive gravimetric water contents for the clay soil in the lysimeter.

The loss of water in the Bruchem heavy clay soil occurred mainly in the upper 15 cm of the soil, with 67% of the water loss originating from the upper 7.5 cm of the soil. The large gradients in the water-content profile reflect the formation of a dry surface soil with low hydraulic conductivities, on top of a relatively wet subsoil.

Due to the drying process as described above, the clay soil cracked and the surface subsided. The first four days, the measured surface subsidence in the clay-soil lysimeter was practically zero (Fig. 6). Thereafter, surface subsidence started. The subsidence rate was large in the beginning of the experiment and became almost zero around day 25. After increasing the potential evaporation

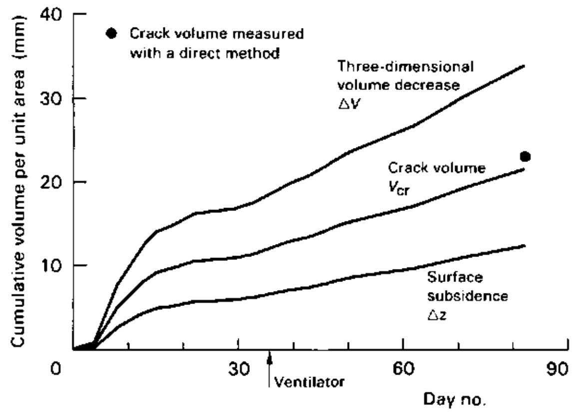

Fig. 6. Shrinkage of Bruchem heavy clay in a lysimeter upon drying. Surface subsidence was directly measured. Three-dimensional volume decrease and crack volume were derived according to Equations 1 and 2. A measured value of crack volume at the end of the experiment is indicated as well

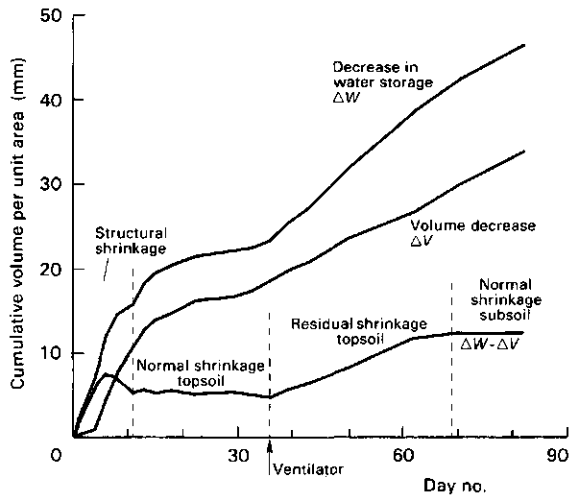

Fig. 7. Comparison between decrease in water storage, ΔW, and decrease in volume of the soil matrix, ΔV, of Bruchem heavy clay. For each period, the dominant shrinkage phase is indicated

demand (day 36), the surface subsidence rate increased again. Cumulative subsidence amounted to 12.4 mm. Crack volume (expressed per unit area) increased by 21.7 mm, and three-dimensional shrinkage of the soil matrix equalled 34.1 mm. The directly measured change in crack volume at the conclusion of the experiment agreed well with the values derived from surface subsidence measurements.

In Figure 7, the three-dimensional change in volume of the clay soil matrix, ΔV, is compared with the measured change in water storage, ΔW. The first four days, water storage in the soil decreased rapidly, while shrinkage of the soil was still very small. From day 4 to day 35 the decrease in water storage was about equal to the volume decrease or shrinkage rate of the soil. After the higher potential evaporation demand had been established at day 36, the decrease in water storage was again higher than shrinkage, until day 68.

Around that time, the decrease in water storage in the soil equalled the shrinkage rate once again. This apparently strange behaviour can be explained by looking at the drying front in the soil and at the shrinkage characteristic of the soil aggregates, as will be discussed in the next section.

Comparison between behaviour of soil aggregates and soil in lysimeter

According to the shrinkage characteristics of the soil aggregates, we would expect normal shrinkage to be the main shrinkage type in this soil. For normal shrinkage, the decrease in soil matrix volume has to be equal to the decrease in water storage, which is obviously not the case (Fig. 7). The loss of water without corresponding shrinkage during the first four days of the experiment, amounting to about 7 mm, has to be explained by the occurrence of structural shrinkage. In the present soil, water loss in the structural-shrinkage phase originates from interaggregate pores, because a structural-shrinkage phase is absent in the shrinkage characteristic of the soil aggregates (Fig. 2A). From day 4 to day 35, the shrinkage rate was more or less equal to the decrease in water storage, reflecting normal isotropic shrinkage of the soil matrix. The differences observed during this period between the two are likely the result of an experimental error caused by the third-power dependence of calculated three-dimensional shrinkage on measured subsidence (Equation 1).

After the enhanced evaporation regime had been established at day 36, the decrease in water storage again became higher than the three-dimensional shrinkage rate. From the shrinkage characteristic of the soil aggregates (Fig. 2A) it can be concluded that residual shrinkage in this clay soil occurs below a moisture ratio of 0.50, which corresponds with a gravimetric water content of 0.19. From the water-content profiles of Figure 5, it appears that before day 30, at every depth in the soil profile, water content was higher than this threshold value, so residual shrinkage did not take place. After day 36 however, the water content of the top layer was decreasing strongly because of the higher evaporative demand. At that time, the threshold gravimetric water content of 0.19 was reached in the top of the soil profile and residual shrinkage started. The zero-shrinkage range, starting below moisture ratios of 0.18 (which equals a gravimetric water content of 0.07) was not reached in the clay-soil lysimeter.

The successive occurrence of structural shrinkage, normal shrinkage and residual shrinkage during drying of the soil before day 68 is in agreement with other experiments on drying and shrinkage of clay soils (e.g. Yule and Ritchie, 1980). Around day 68, however, residual shrinkage is succeeded by normal shrinkage again. The reason for this second occurrence of a normal-shrinkage phase is probably that the water loss rate in the top layer, which is in the residual-shrinkage phase, decreases around day 68 while the water loss rate in the subsoil, still in the normal-shrinkage phase, became more prominent (Fig. 4B) at that time. As a result, the soil as a whole exhibits normal shrinkage again. It is possible that the enhanced water loss from the subsoil occurred by evaporation through the shrinkage cracks, but this could not be assessed in the present experiment.

CONCLUSIONS

The water storage in a heavy clay soil in a lysimeter decreased by 45 mm in 82 days due to evaporation. This drying process was accompanied by a shrinkage of the soil matrix of 34 mm, consisting of a crack volume of 22 mm and a surface subsidence of 12 mm.

The shrinkage behaviour of the clay soil revealed the occurrence of structural shrinkage, isotropic normal shrinkage, and isotropic residual shrinkage. Structural shrinkage can only be derived from experiments on large undisturbed samples. The other two shrinkage phases can be predicted accurately using measured shrinkage characteristics of natural soil aggregates. After successive occurrence of structural, normal and residual shrinkage during prolonged drying, a second normal-shrinkage phase occurred. This phenomenon was due to the fact that water loss from the subsoil, which was still in the normal-shrinkage phase, became greater than water loss from the top soil, which was in the residual-shrinkage phase.

The loss of water in the clay-soil lysimeter amounted to 58% of the loss in a rigid silty soil, at equal potential-evaporation rates.

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5. THE RELATION BETWEEN VERTICAL SOIL MOVEMENTS AND WATER CONTENT CHANGES IN CRACKING CLAY SOILS

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THE RELATION BETWEEN VERTICAL SOIL MOVEMENTS AND WATER CONTENT CHANGES IN CRACKING CLAY SOILS

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ABSTRACT

Field studies on swelling and shrinkage in clay soils are scarce, due to the lack of sound experimental methods and mathematical equations. This study was aimed at developing such methods and equations. Rotating disks were positioned at various depths in the soil in order to measure vertical movements in undisturbed soil. A newly developed equation was applied to convert these vertical soil movements into three-dimensional volume changes and crack volume and to relate them with water content changes. The present equation is unique in that it is valid for water loss in the structural, normal, residual and zero shrinkage phase and for both isotropic and anisotropic shrinkage. Methods and equations were successfully tested in a one-year field experiment in a heavy marine clay soil in the Netherlands. The use of seven rotating disks for measuring soil volume changes was about 10% more accurate than two other less laborious methods. An interesting application of the present methods and equations is the determination of soil water content changes by measuring vertical soil movements.

INTRODUCTION

Drying of clay soils results in the formation of shrinkage cracks and in subsidence of the soil surface. Water and solutes flow rapidly through the cracks into the subsoil, thus bypassing the relatively dry root zone. This process may lead to water and nutrient shortage of crops and to pollution of subsoil and groundwater. Besides the occurrence of horizontal shrinkage leading to cracks, vertical swelling and shrinkage can also be of importance. Buildings and pavements built on swelling and shrinking clay soils, for instance, have an increased risk of damage. Due to the significance of the consequences, an understanding of the swelling and shrinkage behaviour of clay soils is essential.

When a clay soil dries, four shrinkage phases can be distinguished (Haines, 1923; Keen, 1931; Stirk, 1954):

- structural shrinkage: when saturated soils dry, large water filled pores may be emptied without accompanying volume changes;
- normal shrinkage: volume decrease of soil aggregates is equal to water loss. The soil aggregates remain fully saturated;
- residual shrinkage: in the process of drying, although the volume of the soil aggregates decreases, water loss exceeds volume decrease. Air enters the pores of the soil aggregates;
- zero shrinkage: the soil particles have reached their densest configuration. The water loss is equal to the increase of the air volume in the soil aggregates. Aggregate volumes do not decrease any further.

The relation between water content and volume changes has been investigated in numerous laboratory experiments, using clay pastes, soil aggregates and soil cores of various sizes. Field experiments dealing with this subject, however, are scarce. This is largely due to the problem of determining volume changes in field soils.

One approach towards solving this problem has been to measure the vertical and horizontal components of three-dimensional soil shrinkage independently. However, determining the horizontal component of soil shrinkage, i.e. crack volume, is difficult. The method described by Zein el Abedine and Robinson (1971) which was also applied by Yaalon and Kalmar (1984), Dasog et al. (1988) and Hormann and Widmoser (1990), is likely to miss small cracks or those that are closed at the soil surface.

Crack volume in a field soil can also be monitored by comparing clod bulk density with bulk density of a large ring sample at various times of the year (Hallaire, 1984). The disadvantage of this last method, however, is that due to the presence of cracks, the variance of field bulk density is high and therefore large numbers of samples are required. The method is also destructive.

A second approach to determine volume changes in field soils has been to measure vertical soil movements only and to convert them into three-dimensional volume changes which can be compared with water loss. The advantage of this approach is that vertical soil movements are much more easily measured than crack volumes (Woodruff, 1937; Aitchison and Holmes, 1953; Jamison and Thompson, 1967; Yule and Ritchie, 1980). In order to relate measured vertical soil movements with water loss, these workers used various simplifications with regard to the nature and geometry of the shrinkage process. As a result, the developed methods and equations are only valid during structural shrinkage and normal isotropic shrinkage. Due to the lack of sound experimental methods and mathematical equations, the processes of swelling and shrinkage have not yet been described satisfactorily in field soils.

The objective of this paper is to investigate the relation between vertical soil movements, cracking and water loss in field soils. First, a simple method is presented to measure vertical soil movements at various depths in a clay soil in a non-destructive way. Second, a set of mathematical equations is derived which relates measured vertical soil movements to crack volume, three-dimensional volume change and water content changes of the soil. The present equations are unique in that they are valid for all four shrinkage phases and for both isotropic and anisotropic shrinkage. The developed methods and equations were tested in a one year field experiment in which water content changes and volume changes were measured independently. Possible simplification of the proposed method for measuring vertical soil movements was investigated. Finally, the prediction of water content changes using measured vertical soil movements is discussed.

THE RELATION BETWEEN VERTICAL SOIL MOVEMENTS AND WATER-LOSS

The geometry of shrinkage of a saturated clay soil cube with sides z (m), can be described by a dimensionless geometry factor r_s, according to Bronswijk (1990):

$$(1 - \frac{\Delta V}{V}) = (1 - \frac{\Delta z}{z})^{r_s} \tag{1}$$

where V is the volume of soil matrix at saturation (m^3), z is the layer thickness of a soil cube with volume V at saturation (m), ΔV, Δz are the decrease in volume of soil matrix (m^3) and layer thickness (m), respectively, as a result of shrinkage (both positive) and r_s is a dimensionless geometry factor (for three-dimensional isotropic shrinkage: r_s = 3, for one-dimensional subsidence: r_s = 1). When r_s is known, Eqn (1) can be applied to convert measured vertical changes in layer thickness into three-dimensional volume decrease, ΔV:

$$\Delta V = \{1 - (1 - \frac{\Delta z}{z})^{r_s}\} z^3 \tag{2}$$

To express ΔV per unit area, we divide by z^2 and arrive at:

$$\Delta V = \{1 - (1 - \frac{\Delta z}{z})^{r_s}\} z \tag{3}$$

with ΔV in m. In the remainder of the text, volume decreases of soil matrix, volumes of cracks and volumes of water will be expressed per unit area, i.e. in m. For isotropic shrinkage (r_s = 3), Eqn (3) leads to (e.g. Giraldez et al., 1983):

$$\Delta V = 3\Delta z - 3\frac{\Delta z^2}{z} + \frac{\Delta z^3}{z^2} \tag{4}$$

Aitchison and Holmes (1953) simplified this equation by considering that $\Delta z/z$ is small compared to Δz, and that therefore the last two terms of Eqn (4) may be disregarded. Furthermore, they assumed *normal* shrinkage and arrived at:

$$\Delta V = 3\Delta z \tag{5a}$$

and

$$\Delta W = \Delta V \tag{5b}$$

where ΔW = change in water content (m).

Yule and Ritchie (1980) simplified Eqn (4) by disregarding only the last term. They included *structural* shrinkage in their analysis and suggested the following equations:

$$\Delta V = 3\Delta z - 3\frac{\Delta z^2}{z} \tag{6a}$$

and

$$\Delta W = S + \Delta V \tag{6b}$$

where S = water loss in the structural shrinkage phase (m). Eqns (6a) and (6b) are valid during structural shrinkage and isotropic normal shrinkage. In many field soils, however, shrinkage may be residual (Jayawardane and Greachen, 1987; Bronswijk and Evers-Vermeer, 1990), and/or anisotropic (Hallaire, 1984).

Equations 6a and 6b will now be extended for *residual* shrinkage, *zero* shrinkage and *anisotropic* shrinkage, taking into account the shrinkage characteristic of the soil matrix and the geometry factor r_s of Eqn (3). This approach results in the following equation (see Appendix 1 for derivation) :

$$\Delta W = S + \Delta V + \frac{\{e(\vartheta) - \vartheta\}\, z}{1 + e_s} \tag{7}$$

with ϑ = moisture ratio (volume of water/volume of solids), $e(\vartheta)$ = void ratio at moisture ratio ϑ and e_s = saturated void ratio (volume of pores/volume of solids). ΔV in Eqn (7) should be calculated according to Eqn (3).

The first difference between Eqns (3) and (7) and previous equations is the extra term R:

$$R = \frac{(e(\vartheta) - \vartheta)\, z}{1 + e_s} \quad (8)$$

This term arises because in the residual and zero shrinkage phase, water loss ΔW is larger than volume change ΔV. R represents that part of the water loss in the residual and zero shrinkage phase which is not accompanied by volume changes. In the normal shrinkage phase, $e(\vartheta) = \vartheta$, and this term vanishes.

The second difference lies in the calculation of ΔV (Eqn 3), which is now dependent on the geometry factor r_s. This dependency enables the conversion of Δz into ΔV during anisotropic swelling and shrinkage. The sum of ΔV and R is equal to the sum of water loss in the normal, residual, and zero shrinkage phase.

One assumption lies at the basis of Eqns (3) and (7), namely that all vertical soil movements must lead to changes in soil layer thickness. This assumption requires horizontal cracks to be either stable or negligible.

A simplification of Eqn (7) is achieved when, as suggested by Yule and Ritchie (1980), there is a sharp distinction between water loss in the structural shrinkage phase and water loss in the normal, residual and zero shrinkage phase. In that case, outside the structural shrinkage phase, i.e. $\Delta W > S$, S is constant. Within the structural shrinkage phase, $\Delta V = 0$, $R = 0$ and $\Delta W = S$.

MATERIALS AND METHODS

Soils

The proposed methods and equations were tested at an experimental site in the northern part of the Netherlands close to the town of Sneek. The land use at the site was pasture. The soil at the experimental site is of marine origin and can be classified as a very fine clayey, mixed illitic-montmorillonitic, mesic, Typic Fluvaquent (Soil Survey Staff, 1975). A brief description of the profile is presented in Table 1. The soil was drained with tile drains at 1 m depth and 12 m intervals.

Shrinkage characteristics of the soil aggregates were determined on natural clods coated with SARAN F-310 resin (Brasher et al., 1966). From each soil horizon, three clods were taken in early spring when the soil was almost submerged. Complete saturation was ensured by placing the aggregates on a saturated sandbox for about four weeks after which the SARAN coating was applied and the drying process started. Weight losses of the clods became negligible after about ten to twenty days of drying. Final water content and volume of each soil aggregate were determined after oven drying.

Table 1. Properties of the soil at the experimental site in the northern part of the Netherlands

Depth (m)	Horizon	Composition					
		$CaCO_3$ content	organic matter content	particle size (µm)			
				<2	2-16	16-50	>50
		in mass % of the soil		in mass % of mineral fraction			
0-0.22	A11	0.0	10.3	39.9	20.9	33.4	5.8
0.22-0.42	ACg	0.0	6.9	40.7	25.9	28.3	5.1
0.42-0.78	C1g	2.5	4.5	58.1	24.7	16.2	1.1
0.78-1.20	C2g	6.9	2.2	24.1	14.3	53.5	8.1

The shrinkage characteristics of the four soil horizons are given in Fig. 1. The two upper horizons show normal shrinkage over a wide range of water contents as well as some residual shrinkage. The third horizon shows mostly residual shrinkage, but the deflection from normal shrinkage is small. The fourth horizon from 0.78 down to 1.20 m depth with a clay content of 24 % (Table 1), shows hardly any normal shrinkage and mostly residual shrinkage.

Field methods

The position of the soil surface relative to a benchmark moored in the sandy subsoil at six meters depth, was measured weekly with a telescope level indicator. The following procedure was applied to measure vertical changes in layer thickness at various depths in the soil. At seven positions, 30 cm apart, one rotating disk was installed in the soil at a certain depth (0.2 cm, 5.4 cm, 15.1 cm, 36.5 cm, 54.9 cm, 93.7 cm, and 133.8 cm, respectively). The disks were constructed in such a way to ensure positioning in the undisturbed soil (Fig. 2). The position of the disks in the soil, relative to each other, was measured weekly using a thin steel probe and a telescope level indicator.

Wetness of the soil at depths of 0-5, 5-10, 10-20, ... 90-100 cm, was determined weekly by gravimetric sampling at five positions around the site where the disks for measuring of swelling and shrinkage had been installed. Large samples of more than 0.001 m^3 were taken to ensure determination of the average water content of a certain soil layer.

Precipitation was recorded continuously using a pluviograph. Potential evapotranspiration was calculated according to Makkink as the multiplication of a reference crop evapotranspiration with a crop factor (Feddes, 1987).

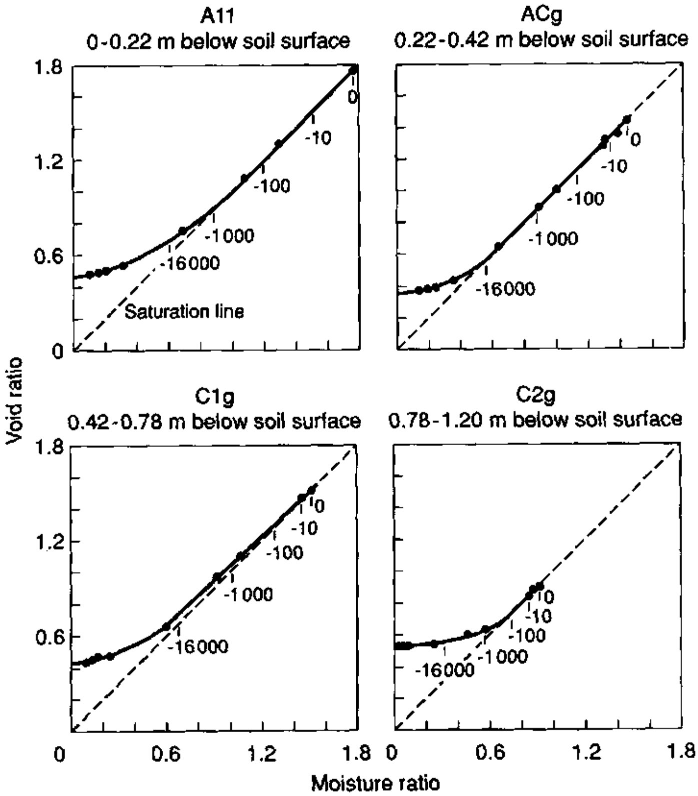

Fig. 1 Shrinkage characteristics of natural aggregates of four soil horizons from a heavy marine clay soil as determined in the laboratory. Void ratio = volume of pores/volume of solids, moisture ratio = volume of water/volume of solids. Some pressure head values are indicated

Calculation of three-dimensional volume changes and crack volumes

In well-developed alluvial soils, volume changes with changing water contents are isotropic (Bronswijk, 1990). Therefore, the values of the original layer thickness and the measured changes in the layer thickness were converted into three-dimensional volume changes applying Eqn (3) with $r_s = 3$. Crack volume, V_{cr}, was calculated as the difference between three-dimensional volume change and change in layer thickness. This was done for each individual soil layer. By adding the values of each layer, three-dimensional volume change and crack volumes of the entire soil profile were obtained. The value of ΔV in Eqn (7) was thus calculated. ΔW was calculated from gravimetric water content sampling. R in Eqn (7) was calculated for each soil layer at each time

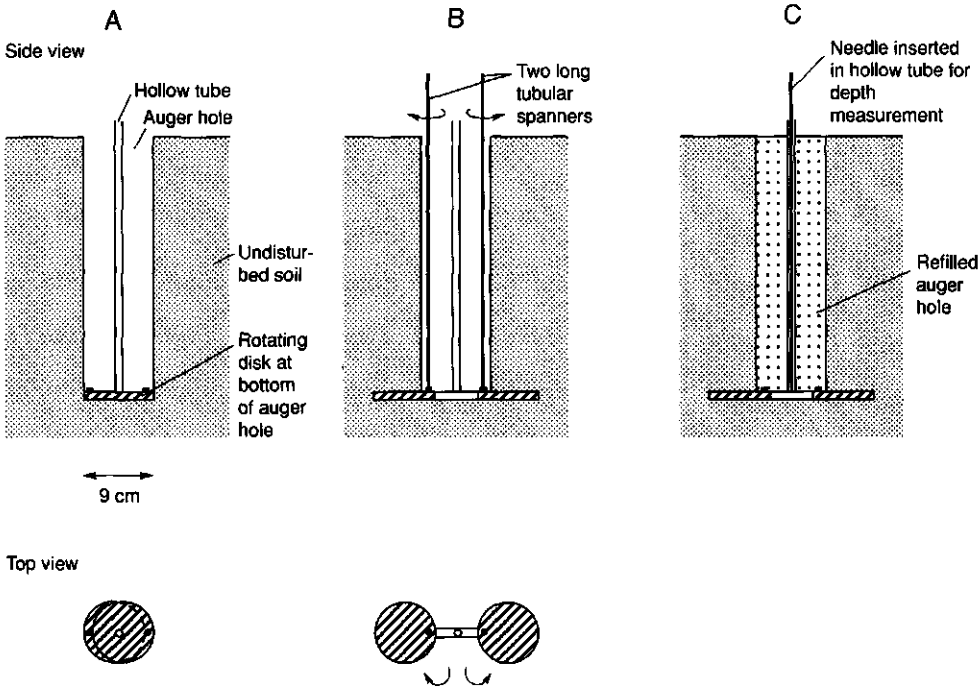

Fig. 2 The setup used to measure changes in layer thickness in the undisturbed soil. a: placing of disks at the bottom of an auger hole; b: turning of disks into the undisturbed soil; c: final set-up

interval, using the shrinkage characteristics of Figure 1. Again, the values were added to obtain the total for the whole soil.

When applying Eqn (3) to convert measured values of z and Δz into ΔV, one assumes uniform shrinkage of the soil layer under consideration. This means that estimating ΔV and V_{cr} is more accurate when Δz is measured over smaller depth increments. Therefore, in the present study we used as many as seven rotating disks. This method will be referred to as method 1. To investigate whether the use of seven disks is necessary, we also calculated ΔV with two other, less laborious, methods. In method 2, only the upper and lower disks are used to calculate ΔV with Eqn (3). Method 3 is the approximation of Aitchison and Holmes (Eqn 5a), where only the surface subsidence is used to calculate three-dimensional volume change.

RESULTS AND DISCUSSION

Swelling and shrinkage in field soils

Measured net precipitation (precipitation minus potential evapotranspiration), change in soil water content, surface subsidence, three-dimensional volume changes and crack volumes are depicted in Fig. 3. Throughout the whole year, swelling and shrinkage reflect the successive wet and dry periods.

At the beginning of the experiment the soil was almost submerged and fully swollen. A short dry period, starting around day 95 caused a decrease in water content and, somewhat later, a small subsidence of the soil surface. The second dry period started around day 158 and caused a rapid decrease in water content and a large subsidence of the soil surface. The driest soil profile and the largest subsidence occurred around day 215. Thereafter, precipitation caused the soil to wet, as a result of which the soil surface moved up again, but not yet regaining its original position. Around day 340, the soil profile was again almost saturated, and the soil surface recovered its initial height. Maximum surface subsidence in the field was 26 mm, maximum crack volume

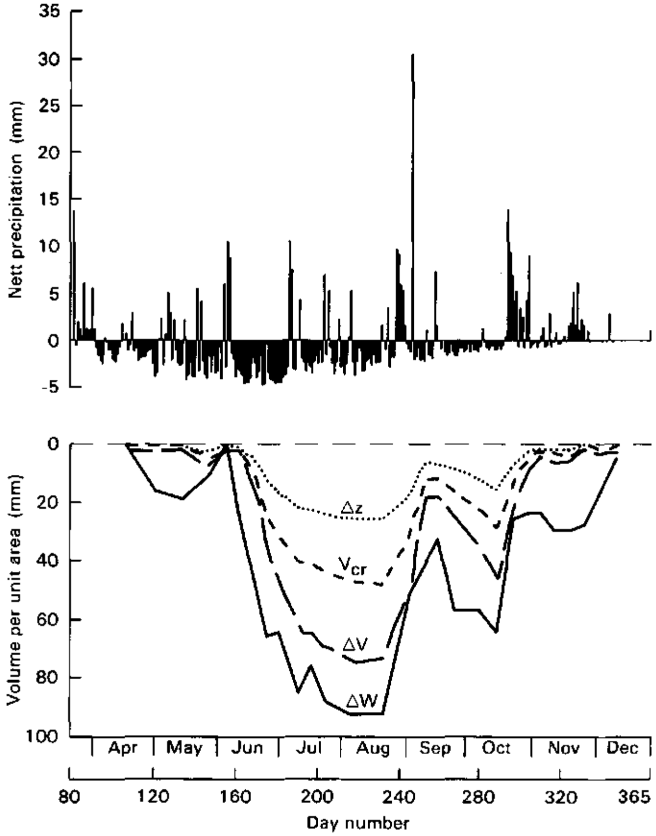

Fig. 3 Net precipitation and resulting changes in water content of the soil profile ΔW, subsidence of the soil surface Δz, three-dimensional volume changes ΔV, and crack volumes V_{cr} in a marine heavy clay soil in 1986

per unit area was about 48 mm, and maximum three-dimensional volume decrease per unit area was 74 mm.

On day 215, the driest day of the measurement period, the ratio of three-dimensional volume change over water loss = 74.2/92.4 = 0.80. Because this value is lower than one, we can conclude that shrinkage partly occurred outside the normal shrinkage phase. From Fig. 3, we can conclude that in May and June, when water loss in almost submerged conditions did not result in shrinkage, structural shrinkage occurred. Furthermore, as can be seen in Table 2, it appears that residual shrinkage occurred in the A11 horizon and the C1g horizon.

Because in the present soil there is no sharp boundary between the normal and the residual shrinkage phase (Fig. 1), quantification of water loss in the various shrinkage phases in the field is difficult. Comparing the measured field water contents and volume changes with the laboratory shrinkage characteristics (Fig. 1) at the driest time of the year (day 215), showed that water loss in the structural, normal and residual shrinkage phase amounted to approximately 14%, 56% and 30% of the total water loss respectively.

It should be noted that although water loss in the residual shrinkage phase is large in the All and Clg horizon, the accompanying volume decrease is also considerable, which is indicated by the small deviation of the respective shrinkage characteristics from the saturation line. This explains why, on the one hand, water loss in the residual shrinkage phase is rather prominent in this soil, but, on the other, the ratio of three-dimensional volume change over water loss is as high as 0.80.

In order to investigate whether Eqns (3) and (7) could describe the shrinkage process in the present clay soil, measured values of $\Delta V+R$ were plotted against ΔW measurements (Fig. 4). Linear regression analysis on the data outside the structural shrinkage range resulted in an r^2 value of 0.95. The obtained slope and the intercept of the linear relationship were 0.96 and 12.6, respectively. The slope-value of 0.96 was not statistically different than 1 at 5%

Table 2. Comparison of gravimetric water contents below which residual shrinkage starts (w_{res}) with the minimum water content ($w_{f,min}$) observed in the field

Horizon	w_{res} (kg.kg^{-1})	$w_{f,min}$ (kg.kg^{-1})
A11	0.43	0.26
ACg	0.22	0.30
C1g	0.52	0.30
C2g	0.27	0.32

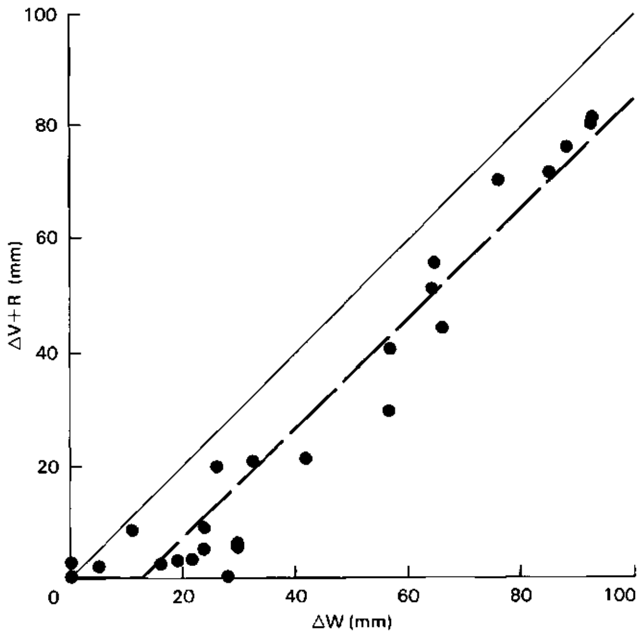

Fig. 4 Relationship of volume changes (ΔV) plus water loss without volume change (R) vs total water loss (ΔW) for a heavy marine clay soil. Structural shrinkage is 13 mm

level (Student t-test). We concluded that Eqn (7) described the measured values of water loss and volume change well. Fitting Eqn (7), to the data in Fig. 4 outside the structural shrinkage phase yielded $\Delta V+R = \Delta W - 13$. Therefore, water loss in the structural shrinkage phase amounted to 13 mm in the present soil.

Yule and Ritchie (1980) found that for clay soils in small cores and in a lysimeter there is a sharp transition between water loss in the structural shrinkage and water loss in the normal shrinkage phase. As can be seen in Figure 4, this sharp transition also occurs in field soils.

To illustrate the applicability of the present methods and equations to other cracking clay soils, data obtained in a fluvial heavy clay soil in the Netherlands are also presented (Fig. 5, data taken from Bronswijk, 1988). Again Eqns. (3) and (7) described the relation between water loss and volume changes well. Results were comparable with the marine clay soil used in this study, except for the magnitude of structural shrinkage, which was equal to 38 mm in the fluvial soil.

Comparison of three methods to determine three-dimensional volume changes

Table 3 shows the calculated values of three-dimensional volume changes,

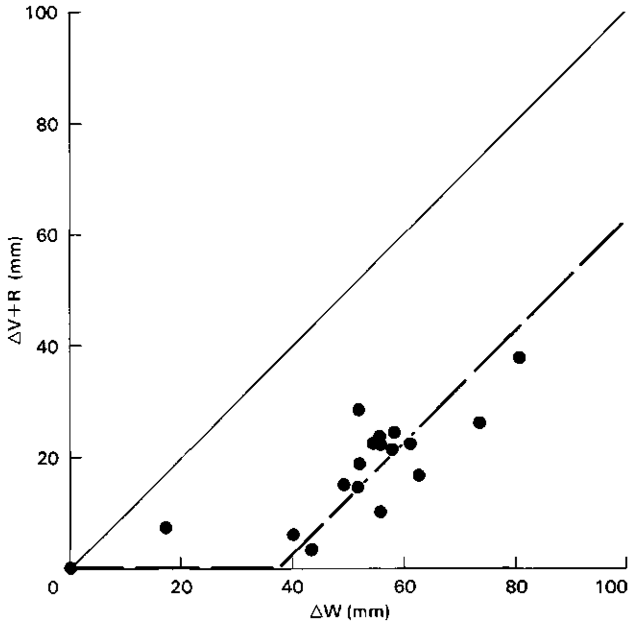

Fig. 5 Relationship of volume changes (ΔV) plus water loss without volume change (R) vs total water loss (ΔW) for a heavy fluvial clay soil. Structural shrinkage is 38 mm

using method 1 (seven disks, Eqn 3), method 2 (top and lower disk, Eqn 3) and method 3 (surface subsidence, Eqn 5). With respect to three-dimensional volume changes, the results of method 1 differ from methods 2 and 3 by about 8% at the maximum. Methods 2 and 3 are almost equally inaccurate. Regarding changes in crack volume, method 2 differs some 8%, and method 3 some 10% from method 1.

An example may elucidate the observed differences between the three methods. Imagine a soil in which rotating disks are positioned at the soil surface, at 5 cm depth and at 10 cm depth. Upon drying, the top layer of 5 cm thickness shrinks by 1 cm, while the lower 5 cm layer does not shrink. In such a situation the three methods would yield the following results: Method 1: applying Eq. 3 for the top 5 cm layer yields $\Delta V = (1-(1-1/5)^3)5 = 2.44$ cm. For the second 5 cm layer $\Delta V = 0$, so for the top 10 cm, $\Delta V = 2.44$ cm. V_{cr} is equal to 2.44 - 1 = 1.44 cm. These are the correct values. Method 2: applying Eq. 3 for the top 10 cm yields $\Delta V = (1-(1-1/10)^3)10 = 2.71$ cm, $V_{cr} = 1.71$. Method 3: applying Eq. 5a yields $\Delta V = 3 * 1 = 3$ cm and $V_{cr} = 2$ cm.

It is clear that neglecting the true value of z, as in method 2 and 3, causes an overestimation of volume changes and crack volumes. In our field experi-

Table 3. Calculation of three-dimensional volume decrease ΔV and crack volume V_{cr} using Methods 1, 2 and 3, at selected times of the year. Differences between Method 2 and 1 and between Method 3 and 1 are represented as Diff.

Day of year	Δz	Method 1		Method 2				Method 3			
	(mm)	ΔV (mm)	V_{cr} (mm)	ΔV (mm)	Diff. (%)	V_{cr} (mm)	Diff. (%)	ΔV (mm)	Diff. (%)	V_{cr} (mm)	Diff. (%)
121	0.7	2.0	1.3	2.1	7.8	1.4	7.7	2.1	7.8	1.4	7.8
181	17.2	49.2	32.0	51.0	3.7	33.8	5.6	51.6	5.0	34.4	7.5
216	26.2	74.0	47.8	77.1	4.2	50.9	6.5	78.6	6.2	52.4	9.6
279	12.5	35.7	23.2	37.2	4.0	24.7	6.5	37.5	5.0	25.0	7.8
308	1.4	4.0	2.6	4.2	5.6	2.8	7.7	4.2	5.7	2.8	7.7
337	1.2	3.5	2.3	3.6	2.8	2.4	4.3	3.6	2.9	2.4	4.3

ment, the differences were restricted to 8-10%. Whether or not this inaccuracy is acceptable will obviously depend on the precision required and the time and money available.

Using vertical soil movements to determine changes in water content in clay soils.

Because the determination of water content in swelling clay soils is laborious, an interesting application of Eqns (3) and (7) would be to convert easily and non-destructively measured vertical soil movements into water content changes. In the case of isotropic normal shrinkage, the procedure is obvious because ΔW = ΔV. In most cases, however, the more complicated equations presented in this paper should be applied. Knowledge of three parameters is required: the magnitude of water loss in the structural shrinkage phase, the value of r_s, and the shrinkage characteristic of the soil matrix. If these three parameters are known, the procedure is as follows (for derivation of the equations, see Appendix 1): Changes in layer thickness are measured using the method outlined in this paper. These changes are converted into a change of void ratio of the soil matrix according to:

$$e(\vartheta) = (1 + e_s)(1 - \frac{\Delta z}{z})^{r_s} - 1 \qquad (9)$$

Using the shrinkage characteristic of the soil matrix, $e(\vartheta)$ can be converted into ϑ. ΔW can then be calculated according to:

$$\Delta W = S \frac{(e_s - \vartheta)z}{1 + e_s} \tag{10}$$

Independent determination of the magnitude of S, however, is difficult, if not impossible. Determining S can be avoided if the determinations of changes in water storage are restricted to periods outside the structural shrinkage phase, which means avoiding very wet conditions. Then S vanishes from the equations. Another feasible method is to measure, for instance gravimetrically, a water content profile once or twice during the experimental period, and to use these measurements to estimate the value of S.

CONCLUSIONS

The methods applied in this study yielded a more accurate measurement of subsidence, cracking and three-dimensional volume changes in the field. In the present field experiment, water loss occurred in the structural shrinkage phase, the normal shrinkage phase and the residual shrinkage phase. The newly developed equation was able to describe the water loss in all of these phases. It was shown that residual shrinkage can be significant in the field. When using vertical soil movements to derive three-dimensional volume changes disks should be placed at several depths in the soil. When an inaccuracy of 8-10% is acceptable, measurement of surface subsidence is sufficient. The present methods and equations can also be applied as a non-destructive method to estimate water content changes in swelling clay soils in situ.

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6. MODELING OF WATER BALANCE, CRACKING AND SUBSIDENCE OF CLAY SOILS

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MODELING OF WATER BALANCE, CRACKING AND SUBSIDENCE OF CLAY SOILS

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ABSTRACT

Bronswijk, J.J.B., 1988. Modeling of water balance, cracking and subsidence of clay soils. J. Hydrol., 97: 199–212.

A general procedure has been developed to model water balance, cracking and subsidence of clay soils. The main feature of this procedure is the introduction of the shrinkage characteristic in addition to the water retention and hydraulic conductivity curves into simulation models.

The proposed procedure enables direct calculation of volume changes in dependance on moisture transport. With appropriate assumptions for geometry of swelling and shrinkage, these volume changes are converted into cracking and subsidence. Taking into account the calculated area of shrinkage cracks at the soil surface, together with the maximum infiltration rate of the soil matrix and the rainfall intensity, rainfall is dynamically partitioned in matrix and crack infiltration. In this way bypass flow and resulting rapid rises of groundwater levels in cracked soils can be simulated.

The procedure was validated by adapting a model for calculation of transient moisture flow in soils, FLOWEX, into a version applicable on clay soils, FLOCR. Computations with FLOCR of subsidence, cracking, groundwater level and top layer wetness of a Dutch basin clay soil during 1985 were in good agreement with field observations. Moreover, the proposed method of bypass calculation is supported by good correspondence between measured and simulated rapid rises of groundwater levels.

INTRODUCTION

The use of simulation models in water management studies has become widespread in recent times. Simulation models offer the opportunity to assess in a relatively quick and cheap way the effects of changes in water management on soil utilization conditions like workability and trafficability (Wind, 1976; Van Wijk and Buitendijk, 1987), crop production (Van Wijk and Feddes, 1986), and farmers income (Van Bakel, 1986). The vast majority of the simulation models that have been developed are based on the assumption that soil is homogeneous and isotropic. Moisture flow is described by a combination of the Darcy equation with the continuity equation and with appropriate top and bottom boundary conditions. The assumption that soil is homogeneous, however, has been questioned by many authors. For instance, Stirk (1954), Edwards et al. (1979), Bouma (1981), and Beven and Germann (1982) stress the importance of flow of water and solutes through macropores.

Although the heterogeneity of field soils is generally recognized, only few studies on simulation of the water balance in soils with macropores exist. In clay soils shape, magnitude and pattern of shrinkage cracks change constantly throughout the year and soil matrix has a low saturated hydraulic conductivity. In these soils the influence of macropores on water and solute transport is important but difficult to quantify. Bouma and De Laat (1981) have accounted for the effect of vertical cracks in water balance simulations by reducing the effective rainfall that infiltrates into the soil surface by 10–20% depending on the time of year. Van Aelst et al. (1986) adapted the SWATRE model (Belmans et al., 1983) for use in cracking clays by calculating a quantity of crack flow dependent on the moisture content of the topsoil. The disadvantage of these approaches is that they are not easily transferable to situations different from those defined in the papers because they have no generally valid physical basis. Furthermore, the cracking and subsidence of clay soils is not incorporated in the models, so they cannot be used in situations where the change in soil volume itself is important. This is for instance the case in assessing efficiency of basin irrigation in cracked clays (Boels, pers. commun., ICW, Wageningen, 1987) or in engineering practice like the destruction of buildings and pavements on clay soils (McCormack and Wilding, 1975; Gillot, 1986).

In this paper a general method is outlined to develop simulation models for the calculation of water balance, subsidence and crack volume of clay soils. In this method the shrinkage characteristic is introduced as a third soil-water function besides the water retention curve and the hydraulic conductivity curve. By introducing shrinkage characteristics in simulation models, a clay soil may be considered a continuously changing configuration of soil matrix and shrinkage cracks. This allows a dynamic partition of rainfall into matrix and crack flow, calculation of bypass flow, adaption of layer thickness over which Darcy fluxes can be calculated and calculation of cracks and subsidence of the soil.

PROCEDURE FOR INTRODUCING SWELLING AND SHRINKAGE IN SIMULATION MODELS

Calculation of subsidence and cracking

Simulation models that compute one-dimensional transient moisture flow in soils are generally based on the combination of the Darcy equation and the continuity equation. To solve these equations, the water retention curve and the hydraulic conductivity curve of a soil must be known. Examples of this type of models are FLOWEX (Wind and Van Doorne, 1975; Buitendijk, 1984) and SWATRE (Belmans et al., 1983).

When trying to use models of this type in clay soil problems arise. This is due to the fact that in clay soils the soil system swells and shrinks continuously in close relation with changes in moisture content. This swelling and shrinkage results in opening and closing of cracks and change in thickness of soil layers. Therefore, calculation of moisture transport in clay soils cannot adequately be done on basis of the hydraulic conductivity and the water retention curve only. In clay soils a third relationship is needed: the shrinkage characteristic. The shrinkage characteristic can be defined in many ways but is in essence the relation between soil volume and soil water content. One of the most-used forms of the shrinkage characteristic is the relation between moisture ratio and void ratio of soil aggregates. Moisture ratio ϑ and void ratio e are defined as:

$$\vartheta = \text{volume of water/volume of solids} \tag{1}$$

$$e = \text{volume of pores/volume of solids} \tag{2}$$

The use of moisture ratio and void ratio is preferred to water content θ and porosity ε, because of volume changes of aggregates. ϑ and e can simply be converted into θ and ε:

$$\theta = \frac{\vartheta}{1 + e} \tag{3}$$

$$\varepsilon = \frac{e}{1 + e} \tag{4}$$

The general form of the shrinkage characteristic is shown in Fig. 1.

Three shrinkage phases can be distinguished (Haines, 1923): (1) Normal shrinkage. Volume decrease of clay aggregates is equal to moisture loss. The

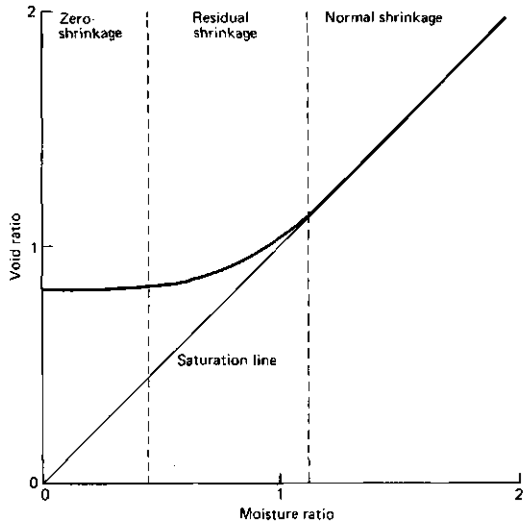

Fig. 1. General form of the shrinkage characteristic with three shrinkage phases.

aggregates remain fully saturated; (2) Residual shrinkage. Upon drying the volume of the aggregates still decreases, but moisture loss is greater than volume decrease. Air enters the pores of the aggregates; and (3) Zero shrinkage. The soil particles have reached their densest configuration. Upon further moisture extraction, the volume of aggregates stays constant. Moisture loss is equal to increase of air volume in the aggregates.

Shrinkage characteristics of field soils can deflect markedly from the idealized form given in Fig. 1. In general heavy clay soils show normal shrinkage over a wide range of moisture contents while light clay soils show mostly residual shrinkage (Fig. 2).

In the field, sometimes a fourth shrinkage phase can be distinguished: structural shrinkage (Stirk, 1954). Structural shrinkage occurs in saturated soils. When saturated soils dry, large water-filled pores may be emptied. As a result of this, aggregates can get a somewhat denser packing. On the whole, the volume changes in this shrinkage phase are negligible but water loss can be considerable. The magnitude of structural shrinkage depends strongly on soil structure (Reeve and Hall, 1978) and therefore on land use and tillage.

In the field, volume changes of the soil aggregates become visible as cracking and subsidence. In general, the dimensionless geometry factor rs determines the partition of total volume change over change in layer thickness and change in crack volume (Rijniersce, 1983; Bronswijk, 1986):

$$V_1 = (z_1)^3, \; V_2 = (z_1)^{(3-rs)}(z_2)^{rs}, \; V_2/V_1 = (z_2/z_1)^{rs} \quad (5)$$

with:

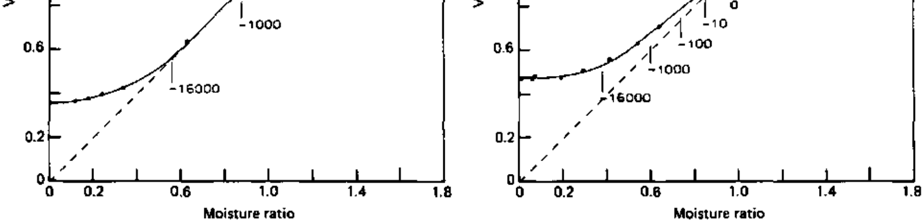

Fig. 2. Shrinkage characteristic of two clay soils from The Netherlands, measured on undisturbed clods and some values of pressure heads (cm). (a) Oosterend marine clay (depth: 22–42 cm below soil surface; 41% particles $< 2\,\mu$m) showing mostly normal shrinkage; (b) Kats marine clay (depth: 0–35 cm below soil surface; 31% particles $< 2\,\mu$m) showing mostly residual shrinkage.

V_1, V_2 = volume of soil matrix before and after shrinkage/swelling respectively (m^3)
z_1, z_2 = layer thickness before and after shrinkage/swelling, respectively (m)
rs = geometry factor

For three-dimensional isotropic shrinkage: $rs = 3$, for one-dimensional subsidence: $rs = 1$. From eqn. (5) it follows that:

$$\Delta z = z_1 - (V_2/V_1)^{1/rs} z_1 \quad (6a)$$

$$\Delta CR = (V_1 - V_2) - z_1^2 (z_1 - z_2) \quad (6b)$$

in which:
ΔCR = change in crack volume (m^3)
Δz = change in layer thickness (m)

When total volume change of a soil layer is calculated with the shrinkage characteristic and rs is known, the changes in layer thickness and crack volumes are easily calculated with eqns. (6a) and (6b). Factor rs depends on ripening stage and moisture content. Aitchinson and Holmes (1953), Berndt and Coughlan (1977), and Bronswijk (1986) stated that volume change in unloaded ripened clay samples was isotropic. Fox (1964) reported unidimensional subsidence in wet soils while, in contradiction with this, Hallaire (1984) found in wet soils volume changes that were caused solely by cracking. Talsma (1977) reported that under loads that occur in field soils shrinkage is isotropic so rs is not depending on load. In the approach followed here, rs is either a constant or varying with water content. For the majority of soils, $rs = 3$, i.e. shrinkage and swelling are isotropic from saturation to oven dryness.

Moisture transport in soil matrix and cracks

When rainfall reaches the surface of a cracked clay soil, part of the water infiltrates into the soil matrix and part of the water flows into the cracks. This asks for adaption of the top boundary condition of simulation models. Generally, in simulation models, moisture content of the top layer corresponds with a certain maximum infiltration rate into the soil. When rainfall exceeds this maximum, surface runoff occurs. In cracked soils, a similar procedure can be used to calculate bypass flow: when rainfall exceeds maximum infiltration rate of soil matrix, water flows into the cracks. In addition a certain part of rainfall falls directly in the cracks. Surface runoff only occurs when cracks are closed. Matrix infiltration and crack infiltration at a given rainfall intensity can be calculated as follows (Fig. 3):

$$\left.\begin{array}{ll} P < I_{max}: & I = A_m P \\ & I_c = A_c P \\ P > I_{max}: & I = A_m I_{max} \\ & I_{c,1} = A_m (P - I_{max}) \\ & I_{c,2} = A_c P \\ & I_c = I_{c,1} + I_{c,2} \end{array}\right| \quad (7)$$

in which:

P = rainfall intensity ($m\,s^{-1}$)

I_{max} = maximum infiltration rate of soil matrix ($m\,s^{-1}$)

I = infiltration rate in soil matrix ($m\,s^{-1}$)

I_c = infiltration rate in cracks (bypass flow) ($m\,s^{-1}$)

A_m, A_c = relative areas of soil matrix and cracks respectively (–)

$I_{c,1}$ = part of total crack infiltration caused by rainfall intensity exceeding maximum infiltration rate of soil matrix ($m\,s^{-1}$)

$I_{c,2}$ = part of total crack infiltration caused by rainfall directly into the cracks ($m\,s^{-1}$)

Defined in this way, all infiltration rates are based on total surface area. Calculated according to eqn. (7), the amount of water infiltrating in the cracks depends on rainfall intensity, maximum infiltration capacity of the soil matrix of the top layer and relative area of the cracks. Partition of rainfall into infiltration in matrix and cracks varies continuously. Most of the water flowing through cracks accumulates at the bottom of the cracks. In the present approach, horizontal infiltration into crackwalls of water running rapidly downwards along cracks is neglected. At this moment, no theory is available

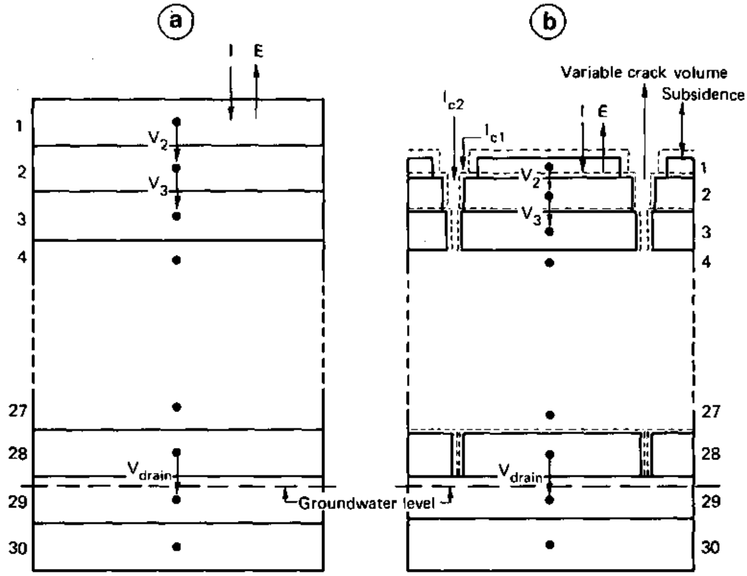

Fig. 3. Schematic representation of a simulation model and its adapted version. (a) FLOWEX, a one-dimensional simulation model for calculation of water balance of soils; (b) FLOCR, an adaption of FLOWEX for calculation of water balance, cracking and subsidence in clay soils. I = infiltration rate in soil matrix ($m\,s^{-1}$); $I_{c,1}$ = part of total crack infiltration caused by rainfall intensity exceeding maximum infiltration rate of soil matrix ($m\,s^{-1}$); $I_{c,2}$ = part of total crack infiltration caused by rainfall directly into the cracks ($m\,s^{-1}$); E = actual evapotranspiration ($m\,s^{-1}$); V = Darcy flux between two nodal points ($m\,s^{-1}$); V_{drain} = drain discharge ($m\,s^{-1}$). Matrix-crack system at time T is indicated by a broken line, matrix-crack system at time $T + \Delta T$ is indicated by a solid line.

to predict this process. However, Hoogmoed and Bouma (1980) showed that this infiltration is small. Moreover, calculations of the water balance of the soil as a whole are not influenced by horizontal infiltration. For this reason all water infiltrating into cracks is assumed to accumulate at the bottom of the cracks and is added to the moisture content of the corresponding soil layers.

Enhancement of soil evaporation because of evaporation out of cracks was not taken into account. Ritchie and Adams (1974) reported that of 0.74 mm d^{-1} evaporation from a bare cracked clay soil surface, 0.60 mm d^{-1} originated from the cracks. For cropped soils at high moisture contents, however, transpiration will be large in comparison with evaporation. Moreover, a certain part of evaporation out of vertical cracks is already included in the determination of the hydraulic conductivity as a function of pressure head, especially when the hot air method (Arya et al., 1975) or the evaporation method (Boels et al., 1978) is used.

Besides vertical cracks, horizontal cracks may also occur upon drying (Bouma and De Laat, 1981). Horizontal cracks hamper vertical moisture flow through the soil matrix. This effect can be accounted for by measuring unsaturated hydraulic conductivities on large samples, for instance with the evaporation method (Boels et al., 1978). If a field soil cracks horizontally, large undisturbed cores of this soil will behave in the same way so that the effect of horizontal cracks is incorporated in the unsaturated hydraulic conductivity.

Adaption of existing models

The procedure outlined in this paper can be applied to many existing simulation models designed for calculation of water balance in rigid soils. This has the advantage that one can choose the model one wishes. This choice is determined for instance by the aim of the simulation and by the experience that is available in working with a certain model.

The proposed procedure for adapting existing "rigid soil" models for calculation of the water balance, cracking and subsidence of clay soils can be summarized as follows (Fig. 3): (1) Rainfall is divided into matrix infiltration and crack infiltration according to eqn. (7). (2) Crack infiltration is added to the bottom of the cracks, and to the moisture content of the soil matrix at that depth. (3) Matrix infiltration is added to the top layer of the soil matrix. (4) Calculation of $h(z)$, $\theta(z)$ and $k(z)$ of the soil matrix is carried out in the same manner as in the original model. The distances between nodal points are held constant within one timestep but must be adapted when the next timestep starts. (5) Using shrinkage characteristics, the new $\theta(z)$ profile gives a new volume of soil matrix at each depth. (6) With the aid of eqns. (6a) en (6b) and the *rs* factor, layer thickness and crack volume can be calculated at each depth. (7) This procedure is repeated in the next time increment.

EXPERIMENTAL VALIDATION OF THE PROPOSED PROCEDURE AND DISCUSSION

Experimental site, soils and methods

In order to validate the proposed method, the simulation model FLOWEX (Wind and Van Doorne, 1975; Buitendijk, 1984) was adapted in the way outlined here. The adapted version will be referred to as FLOCR (FLOwex-CRacking). In the FLOWEX model rainfall and potential evapotranspiration are top boundary conditions. The bottom boundary condition is represented by a flux–groundwater-table depth relationship based on conventional drainage theory. For the numerical calculations, in this case the soil profile is divided in 30 layers of 5 cm thickness. Moisture flow between the nodal points of each layer is calculated with an integrated form of the Darcy equation.

To compare simulation results with field behaviour, a field experiment was carried out in a basin clay area in The Netherlands. The experimental site was situated in the riverine area in the central part of The Netherlands and was in use as pasture. The soil at the site can be classified as a typic Fluvaquent, very fine clayey, mixed illitic–montmorillonitic, mesic (Soil Survey Staff, 1975). Its percentage of particles smaller than 2 μm ranges from 52 to 69%. The soil was tile-drained with drains at 77 cm below soil surface and spacings of 20 m.

The water retention curve of the soil matrix was determined on a sand box and with pressure membrane apparatus. Hydraulic conductivity as a function of pressure head was determined on undisturbed samples using the evaporation method (Boels et al., 1978) for low pressure heads and the hot air method (Arya et al., 1975) for high values. Shrinkage characteristics of the soil matrix were determined on natural clods coated with SARAN F-310 resin (Brasher et al., 1966). Structural shrinkage was estimated by measuring subsidence and water loss of a large undisturbed soil core (Bronswijk, 1986). Figure 4a,b shows the water retention and the hydraulic conductivity curve of the soil at the experimental site. The shrinkage characteristic (Fig. 4c) shows normal shrinkage from ϑ = 1.5 to ϑ = 0.44 and no shrinkage from ϑ = 0.33 down to ϑ = 0. The distinction between normal shrinkage and zero shrinkage is rather pronounced, implying that residual shrinkage hardly occurs in this soil. Measured structural shrinkage was equal to 13 mm.

At the experimental site rainfall was recorded continuously. Groundwater levels were measured weekly, using 1.2 cm diameter tubes and tensiometers. Wetness of the top layer was determined weekly by gravimetric sampling. The position of the soil surface, relative to a benchmark moored in the sand subsoil at 7 m depth, was measured weekly with a telescope level indicator. Direct measurement of crack volume is not possible. Therefore an alternative. procedure was applied: rotating disks were installed at six depths in the soil (0.3, 3.6, 11.2, 23.0, 43.2, 66.6 cm). On turning, both halves of the disk are positioned in the undisturbed soil (Fig. 5). With a thin steel probe and a telescope level indicator, the position of the disks in the soil relative to each other can be measured. Because soil volume change in the soil under

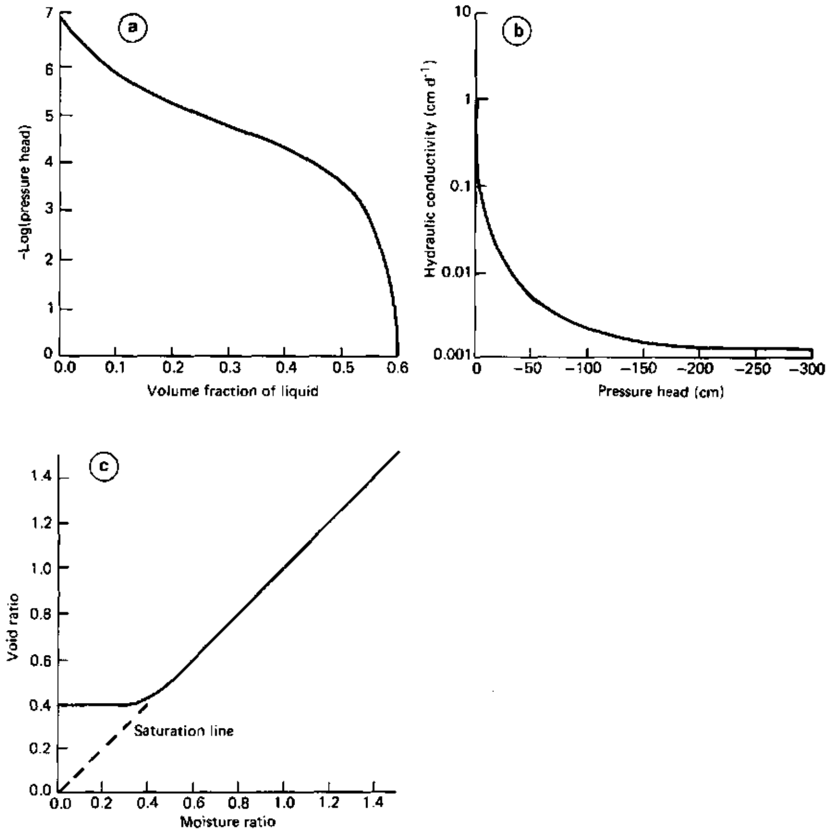

Fig. 4. Soil physical properties of Bommelerwaard basin clay soil. (a) water retention curve; (b) hydraulic conductivity as function of pressure head; (c) shrinkage characteristic.

consideration is isotropic (Bronswijk, 1986) the measured changes in layer thickness can be converted into crack volumes per layer and added to give total crack volume of the soil. In this way even very small cracks that cannot be detected with other methods are incorporated in the total volume of shrinkage cracks.

The model FLOCR was run with the measured water retention curve, hydraulic conductivity curve and shrinkage characteristics, the necessary information on drainage situation and actual rainfall and potential evapotranspiration as input and a timestep of 0.02 d.

Results of validation and discussion

We can divide the results into two categories: (1) simulation of volume changes; and (2) simulation of water balance. With respect to simulation of

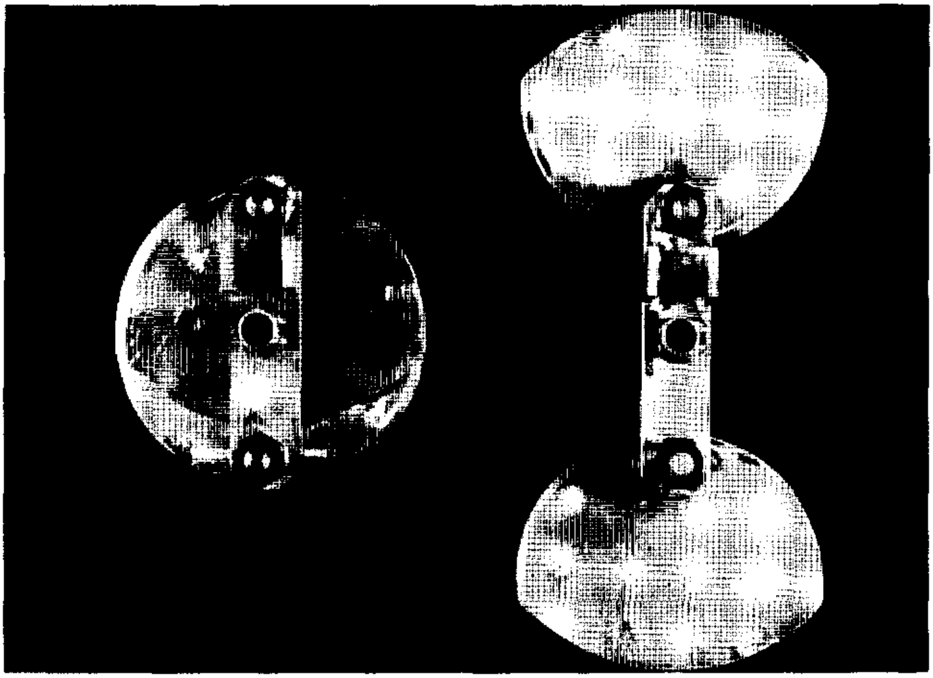

Fig. 5. Disk for measuring changes in layer thickness, seen from above. The disk is lowered in an auger hole to the required depth. On turning, both halves are driven into the undisturbed soil. Thereafter the auger hole is refilled. From time to time the position of the disk in the soil is measured with a thin steel probe. By placing several disks in a row, changes in layer thickness of undisturbed soil can be measured.

volume changes, Figure 6a,b shows that the model calculates subsidence and cracking satisfactorily. Both the calculated shrinkage of the clay soil upon drying and the swelling upon wetting are in good agreement with the observations. In 1985 maximum subsidence was only 17 mm due to a wet summer. However, the total crack volume is approximately 300 m^3 ha^{-1} showing that even in wet summers cracking can be considerable and that effects of cracks on water and solute transport must always be kept in mind.

The most notable feature of the simulation of water balance is the rapid response of the cracked clay soil system to rainfall. For instance bypass flow induced by high-intensity showers around May 13th results in an immediate rise of the groundwater table and a swelling of the soil. The effect of bypass flow can be traced during the whole measurement period by the erratic movements of the groundwater table. The wetness of the top layer varies between 0.33 and 0.60 (Fig. 6d).

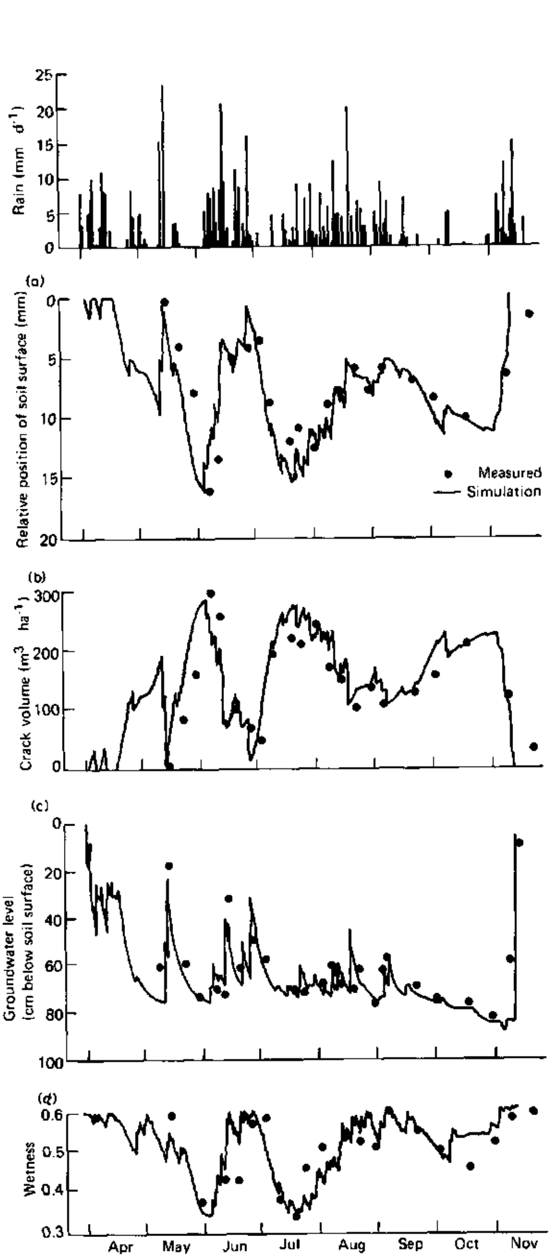

Fig. 6. Results of simulation with FLOCR of: (a) subsidence; (b) crack volume; (c) groundwater level; (d) top layer wetness (mass fraction of liquid) (0–10 cm below soil surface). The location is an experimental site in the Bommelerwaard basin clay area in The Netherlands during the period from March to December 1985. Measured rainfall at the experimental site is also pictured.

The agreement between field measurements and model calculations of top layer wetness is not as good as for subsidence, crack volume and groundwater level (Figs. 6a, b, c). This is caused by both the limitations of the original FLOWEX model and the difficulty of determining water content or wetness in structured soils. With respect to the limitations of FLOWEX, it is important to note that in FLOWEX water extraction is restricted to the top layer. Although grassland on heavy clay soils at and around the experimental site is very shallow rooted, there will be some water extraction from deeper soil layers, especially in dry periods. It is emphasized that this is merely a limitation of the FLOWEX model and not of the modeling principles outlined here.

Comparing the results of simulations of groundwater table depth and wetness of top layer with corresponding field observations, the method of dynamic partition of rainfall into matrix infiltration and bypass flow works satisfactorily. Figure 7 shows the simulated bypass in 1985. Computed cumulative bypass amounted to 143 mm which is 27% of total rainfall. For separate showers simulated bypass varied from 0 to a maximum of 78% in the case of a thunderstorm of 22 mm in 2 h (May 14th). In this study, the FLOCR model used rainfall per one-fifth of a day as input. Calculations with rainfall averaged over the day as input yielded poor agreement between observed and calculated groundwater levels because bypass flow depends on rainfall intensity. For instance a thunderstorm with 25 mm in 2 h at the end of a dry

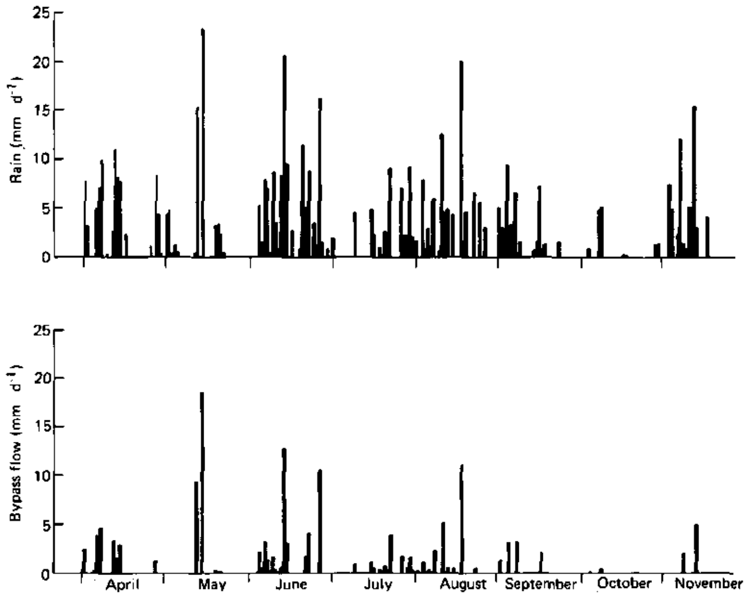

Fig. 7. Rainfall and simulated bypass flow in Bommelerwaard basin clay soil during the period from March to December 1985.

summer day has an intensity of either 25 or 125 mm d^{-1} depending on whether the intensity is calculated over an entire day or for one-fifth of a day. When in such a case maximum soil-matrix infiltration rate is equal to 75 mm d^{-1} then bypass is equal to respectively 50 mm d^{-1} or 0 mm. The fact that observed rises of groundwater levels after high-intensity showers (for instance around May 13th and June 12th) were sometimes higher than the computed ones indicates that even one-fifth of a day may be too long. However, availability of accurate rainfall measurements is often limited. Bearing this in mind, rainfall intensities based on measuring periods of one-fifth of a day are a good compromise between accuracy and practical applicability of the present simulation model.

CONCLUSIONS

The introduction of shrinkage characteristics in addition to water retention and hydraulic conductivity curves into simulation models makes it possible to calculate accurately water balance, subsidence and cracking of clay soils. The present method of dynamic partitioning of rainfall into matrix and crack infiltration simulates bypass flow and resulting rapid rises in groundwater table satisfactorily. Bypass flow is of great importance in a clay soil. Especially in the case of high-intensity rain on dry clay soil, a large part of the infiltrating water is transported quickly to the groundwater table.

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7. EFFECT OF SWELLING AND SHRINKAGE ON THE CALCULATION OF WATER BALANCE AND WATER TRANSPORT IN CLAY SOILS

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EFFECT OF SWELLING AND SHRINKAGE ON THE CALCULATION OF WATER BALANCE AND WATER TRANSPORT IN CLAY SOILS

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ABSTRACT

Volume changes and resulting shrinkage cracks are of great importance for water transport in clay soils. Therefore these processes should be taken into account when applying soil water simulation models on these soils.

The effects of swelling and shrinkage on water transport are shown by comparing calculations of a soil water balance model for rigid soils (FLOWEX), a model for cracking soils (FLOCR) and field measurements. Bypass flow as calculated with FLOCR amounted to 28 % of precipitation, which resulted in a drier top soil, a higher groundwater table with very rapid response on precipitation events, and a higher drain outflow in the cracking-soil model. The good correspondence between results of FLOCR and field measurements of groundwater levels supports the use of this model in clay soils. The effects of cracks are unfavourable with respect to crop water availibility and transport of pollutants to subsoil, drains and to surface water.

Cracks, however, can also have favourable effects. For instance, the computed number of days at which the soil had a bearing capacity inadequate for grazing cattle decreased from 63 to 28 when swelling and shrinkage was taken into account.

INTRODUCTION

Simulation models for calculation of one-dimensional water transport through soil can be useful in predicting the effects of changes in water management on soil utilization conditions like workability and trafficability and on crop production. Examples of such models are SWATRE (Belmans et al., 1983) and FLOWEX (Wind and Van Doorne, 1975; Buitendijk, 1984). In general, these simulation models are based upon the assumption that soil is a homogeneous medium in which one-dimensional moisture flow is described by combining the Darcy equation and the continuity equation. In clay soils changes in moisture content are accompanied by changes in soil volume. Because of this, the soil surface sinks and shrinkage cracks develop, turning a clay soil into a constantly varying heterogeneous two-phase medium: soil matrix and cracks. Most of the existing simulation models do not account for these phenomena.

In the study reported here, FLOWEX, a numerical model to calculate vertical water transport through soils (Buitendijk, 1984) was adapted into a version including swelling and shrinkage processes. The adapted version is referred to as FLOCR (FLOwex-CRacking). A complete description of FLOCR and its underlying assumptions, together with a field validation of the model has been given by Bronswijk (1988). FLOCR calculates the water balance of clay soils giving for each soil layer at the end of each time step: pressure head, water content, crack volume and layer thickness. For the whole soil profile groundwater level, drain discharge, soil matrix infiltration, bypass flow, surface runoff, actual evapotranspiration and surface subsidence are computed.

The objective of this paper is to illustrate the necessity of introducing swelling and shrinkage processes into water balace simulations for clay soils. This is done by comparing calculations of a rigid soil model (FLOWEX) with calculations of an adapted non-rigid version of the same model (FLOCR) and with field observations.

CALCULATION OF WATER BALANCE, GROUNDWATER LEVEL AND BEARING CAPACITY

To illustrate the consequences of swelling and shrinkage on water transport and water balance, calculations were caried out on a clay soil during the period March-November 1985 both with FLOWEX and FLOCR. Besides water balance, the groundwater level was calculated because this parameter is easy to compare with field measurements. To illustrate the effect of reckoning with swelling and shrinkage on calculation of utilization conditions of the topsoil, the number of days is calculated at which the bearing capacity of the soil surface is insufficient for grazing cattle.

The experimental site where field data were collected is situated in the riverine area in the central part of the Netherlands and was in use as pasture. The soil at the site can be classified as a typic Fluvaquent, very fine clayey, mixed illitic-montmorillonitic, mesic (Sois Survey Staff, 1975). Its percentage of particles smaller than 2 μm ranges from 52 to 69 %. The soil was tile drained with drains at 77 cm below soil surface and spacings of 20 m. The water retention curve of the soil matrix was determined on a sand box and with pressure membrane apparatus. Hydraulic conductivity as a function of pressure head was determined on undisturbed samples using the evaporation method (Boels et al., 1978). Shrinkage characteristics of the soil matrix were determined on natural clods coated with SARAN F-310 resin (Brasher et al, 1966). Geometry of volume change was determined by measuring subsidence and diameter decrease of drying 100 cc undisturbed soil cores. Structural shrinkage (Stirk, 1954) was estimated by measuring subsidence and water loss of a large undisturbed soil core (Bronswijk, 1986). Figure 1 shows the water retention curve, the hydraulic conductivity curve and the shrinkage characteristic of the soil at the experimental site. Measured structural shrinkage was equal to 13 mm. Volume change in the considered soil was found to be isotropic.

At the experimental site rainfall was recorded continuously and groundwater levels were measured weekly, using 1.2 cm diameter tubes and tensiometers.

FLOWEX was run with the measured hydraulic conductivity curve and wa-

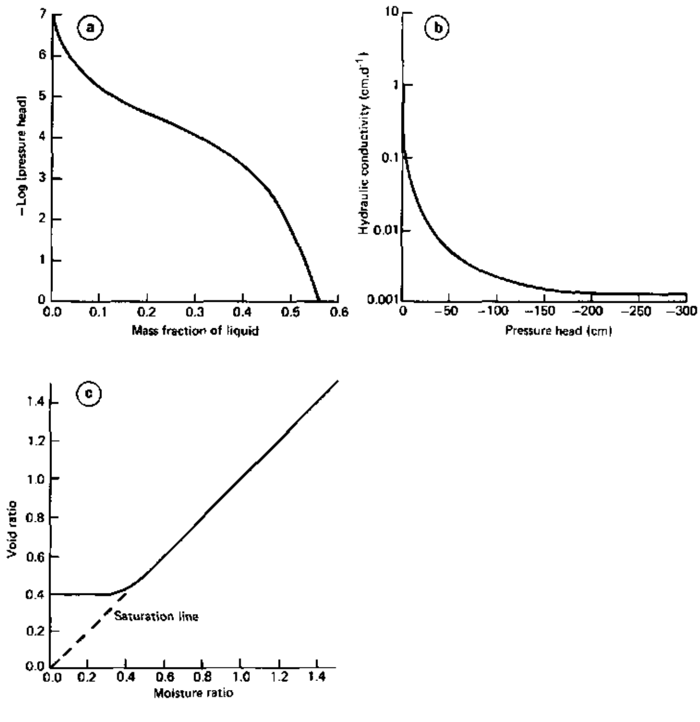

Fig. 1. Soil physical properties of Bommelerwaard basin clay soil
a) water retention curve
b) hydraulic conductivity as function of pressure head
c) shrinkage characteristic

ter retention curve as input. FLOCR was run with the same curves, but also the shrinkage characteristic of Figure 1c was given as additional input. Actual rainfall and potential evapotranspiration together with information on drainage situation were used as boundary conditions. Timestep of the calculations was 0.02 day.

RESULTS AND DISCUSSION

Figure 2 gives the water balance as calculated with FLOWEX and FLOCR. Cumulative precipitation amounted to 538 mm. No runoff occurred in this period so actual infiltration into the soil was equal to precipitation. Comparing the results of FLOWEX and FLOCR, the main difference lies in the relative part of evapotranspiration and drain outflow in the total water extraction. Both in the rigid soil and in the cracking soil, total extraction of water from the soil profile amounts to 546 mm. The mechanism of this extraction, however, is different. In the rigid soil, 82 % is evapotranspiration while the remaining 18 % is drain outflow. In the cracking soil, 75 % is evapotranspiration, while 25 % is drain outflow. Bypass flow amounted to 150 mm, 28% of total infiltration.

In Figure 3 actual precipitation, and the course of the groundwater levels calculated by FLOWEX and FLOCR are pictured together with field measurements. Groundwater levels as calculated with FLOCR rise rapidly following a rainfall event. This is due to the occurrence of bypass flow. Agreement between model calculations and field observations is good, supporting the method of calculating of matrix infiltration and crack infiltration. FLOWEX calculations result in lower groundwater levels, because all water transport takes place through the soil matrix. The course of the groundwater level is much smoother. Agreement between FLOWEX calculations and field observations is poor. It is interesting to note that not only in FLOCR computations but in FLOWEX computations as well, rapid rises in groundwater level occur. These rapid rises, however, are of a different nature. In FLOCR, they are caused by bypass flow. In FLOWEX, the rapid rises must be ascribed to the steepness of the water retention curve of the considered soil. Because of this steepness, only little water is needed to saturate the soil layers close above the groundwater level. So when a slowly infiltrating wetting front finally reaches the groundwater table, rises of several tenths of cm's are possible, for instance at the end of June. This process, however, is much slower than bypass flow. From comparision of FLOCR, FLOWEX and field observations, it is evident that in reality bypass flow causes the rapid groundwater table rises in clay soils.

Both the results pictured in Figure 2 and Figure 3 emphasize the importan-

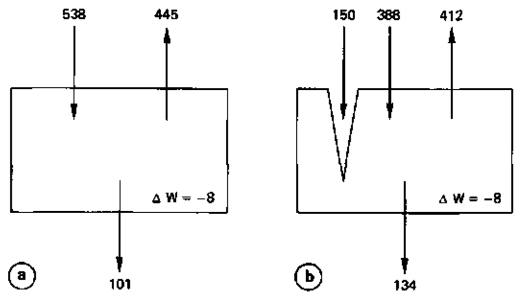

Fig. 2. Water balance of a clay soil over the period 1 April 1985 - 30 November 1985 as calculated with (all quantities in mm):
a) FLOWEX, a model for rigid soils
b) FLOCR, a model for cracking soils

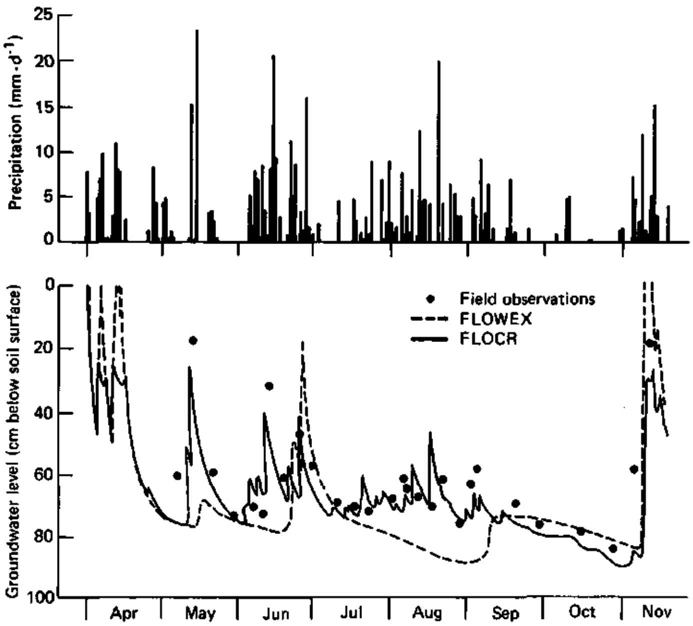

Fig. 3. Recorded precipitation, and comparison of the groundwater level calculated with FLOWEX and FLOCR with data measured in the Bommelerwaard basin clay area in the Netherlands during the period from 1 April to 30 November 1985

ce of shrinkage cracks for water transport. Water transport through cracks causes a rapid rise of groundwater table, resulting in larger and more rapid drain outflow. At the same time, the topsoil receives less water and remains relatively dry, resulting in lower evapotranspiration. As a result of these processes, shrinkage cracks have a negative effect on water availability for crops and therefore on crop production.

Another unwanted effect is the transport of solutes to the subsoil. Out of a total of 538 mm infiltration, 150 mm (28 %) flows through cracks (Figure 2). Together with these 150 mm of water, pollutants can be transported quickly to subsoil, groundwater, drains and, eventually, surface water. In case of solutes that are strongly absorbed in the soil like some herbicides and pesticides, bypass will be the main transport mechanism to the subsoil and therefore of great importance. Accounting for swelling and shrinkage is also neccessary when predicting utilization conditions of the soil.

One of the most important utilization conditions of clay soils in use as pasture is the bearing capacity of the soil surface for grazing cattle. This bearing capacity depends on soil water pressure head at the soil surface. For cattle, a bearing capacity of the soil surface of at least 0.6 MPa is necessary. In clay soils, this corresponds with a soil water pressure head at 2.5 cm depth of at least -35 cm (Van Wijk, 1984). The course of pressure head at 2.5 cm depth as calculated both with FLOWEX and FLOCR is given in Figure 4. The calculations confirm the results mentioned before. The top layer is drier and pressure heads are more negative when cracks are present, resulting in higher

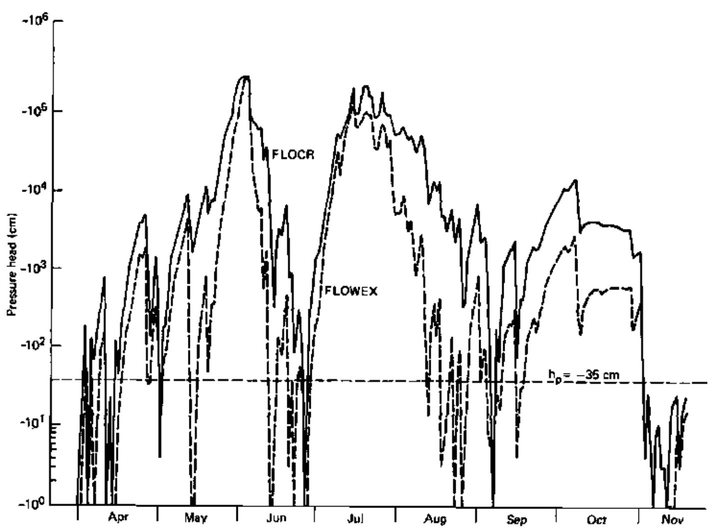

Fig. 4. Comparison between pressure head at 2.5 cm below soil surface as calculated with FLOWEX and FLOCR. The critical value of the soil water pressure head with respect to bearing capacity for cattle (h_p = -35 cm) is indicated

(more negative) pressure heads, and higher bearing capacities. As a result, FLOWEX computes 63 days with unsufficient bearing capacity, while FLOCR calculates only 28 days.

CONCLUSIONS

The introduction of shrinkage characteristics into soil-water simulation models, in addition to the hydraulic conductivity and the water retention curve offers the possibility to calculate water balance and water transport in cracking soils in a dynamic way. The occurrence of shrinkage cracks results in considerable bypass flow, in the presented case 28 % of total precipitation. As a result of this, the topsoil is drier, and both groundwater levels and drain outflow are higher and respond more quickly to precipitation events in cracking soils. Cracks decrease crop water availability and increase transport of solutes to subsoil, groundwater and surface water. On the other hand, the drier topsoil conditions in cracked soils increase the number of days on which the soil surface has sufficient bearing capacity for grazing cattle. The presented examples show that swelling and shrinkage must be taken into account when applying soil water simulation models to clay soils.

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8. PREDICTION OF ACTUAL CRACKING AND SUBSIDENCE IN CLAY SOILS

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PREDICTION OF ACTUAL CRACKING AND SUBSIDENCE IN CLAY SOILS

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Numerous methods have been developed to estimate potential swelling and shrinkage of soils. In practice, however, one is usually interested in the actual magnitude of these processes. This paper describes a procedure developed to predict actual swelling and shrinkage in clay soils. The procedure consists of calculating cracking and subsidence with the computer model FLOCR, using 30-yr weather data. The procedure was applied to quantify the influence of installing tile drains in a poorly drained heavy clay soil on swelling and shrinkage. It appeared that both magnitude and frequency of swelling and shrinkage of the soil matrix would strongly increase, especially in the subsoil.

Consequently, buildings, pavements, and other constructions on this clay soil have an increased risk of damage. Agricultural users of the soil will profit from a water regime that is more adapted to their needs and, in the long run, also from an improvement in the soil structure.

Upon drying, the volume of aggregates in a clay soil decreases. In field soils this process results in the occurrence of shrinkage cracks and in subsidence of the soil surface. Upon wetting, aggregates swell, cracks close, and the soil surface regains its original position. This process of alternate swelling and shrinkage has important consequences for utilization of clay soils. In agricultural soils, the main consequence is the rapid transport of water through cracks: bypass flow. Part of rain or irrigation water and dissolved fertilizers flows through cracks to the deeper subsoil. This may result in drought damage and nutrient deficiency (Bouma and Dekker 1978; Germann et al. 1984). An important and unwanted consequence of this process for the environment is the leaching of solutes via cracks to the subsoil and tile drains, contributing to pollution of groundwater and surface water (Thomas and Phillips 1979; Coles and Trudgill 1985). However, swelling and shrinkage have some favorable effects too. Due to shrinkage cracks, deep penetration of relatively large amounts of irrigation water in clay soils is possible, whereas in the absence of cracks, only little water would infiltrate into the topsoil (Farbrother 1972). More difficult to observe, but equally important, is the favorable effect of swelling and shrinkage on genesis of soil structure (Baver et al. 1972; Wilding and Hallmark 1984). In civil engineering practice, the vertical movements of the soil are of main interest. The damage to buildings, pavements, and other constructions on heavy clay soils is a well known phenomenon (McCormack and Wilding 1979; Gillot 1986).

Because of the importance of swelling and shrinkage in clay soils, many methods have been developed to quantify and predict the volume changes that are to be expected in a field soil. In this respect two parameters are widely applied: the coefficient of linear extensibility (COLE) and the potential volume change (PVC). Direct measurement of COLE is possible with several methods (Brasher et al. 1966; Grossman et al. 1968; Schafer and Singer 1976; Simon et al. 1987). PVC can be obtained from swell index measurements (Lambe, 1960). Several attempts have been made to predict COLE and PVC from other soil properties, such as clay mineralogy, (fine) clay content, Atterberg limits, and moisture content at 15 bar (McCormack and Wilding 1975; Parker et al. 1977). The essence of all these methods is that they yield a *potential* volume change of a certain clay soil. In the field, however, one is usually interested in the *actual* volume change of a soil. This actual volume change depends strongly on the external factors—weather, drainage, and crops. It is easy to imagine that a soil with a small COLE under well-drained conditions, covered with a deep-rooted crop exhibits more cracking and subsidence than a large COLE soil in the opposite circumstances. For these reasons it is essential that the actual water loss be taken into account when trying to predict cracking and subsidence in a field soil. Crops and drainage are controllable, but weather is not. Therefore, to be useful

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in decision making, predicting actual cracking and subsidence of a field soil with given drainage system and crops should be based on representative climatic data for the area under consideration. Because of the complexity of the calculations involved, computer simulation models are indispensable.

This paper presents a procedure to predict actual cracking and subsidence in soils. A simulation model has been developed that calculates water regimes and the cracking and subsidence of clay soils. With this model, calculations are carried out, using 30-yr weather data that are representative for the area under consideration.

MODELING OF ACTUAL CRACKING AND SUBSIDENCE

Simulation models that compute one-dimensional transient moisture flow in soils are generally based on the combination of the Darcy equation and the continuity equation. Examples of such models are FLOWEX (Wind and Van Doorne 1975; Buitendijk 1984) and SWATRE (Belmans et al. 1984). Because these models calculate moisture profiles and change in total moisture content of the soil profile, they are in principle suitable to calculate actual volume change in soil. The shrinkage characteristic of a soil plays the central role in relating changes in moisture content with changes in soil matrix volume. Therefore, to calculate volume change processes in clay soil, this characteristic has to be incorporated in simulation models, in addition to the water retention curve and the hydraulic conductivity curve.

Along these principles, the simulation model FLOCR has been developed (Bronswijk 1988). FLOCR calculates the water regime of clay soils, giving for each soil layer at the end of each time step: pressure head, moisture content, crack volume, and layer thickness. For the soil as a whole, surface subsidence, total crack volume, cracking pattern and average crack width, groundwater level, drain discharge, matrix infiltration, bypass flow, surface runoff, and actual evapotranspiration are computed. The calculation of water transport and water balance is described in Bronswijk (1988), together with an experimental validation in which model calculations of water balance and soil volume change were compared with extensive field measurements. In the present paper, attention is focused on the coupling between changes in moisture content and cracking and subsidence. For each individual soil layer, the quantitative conversion of changes in moisture content into cracking and change in layer thickness is illustrated in Fig. 1. The different steps pictured in this figure are described below.

1. The conversion of moisture content

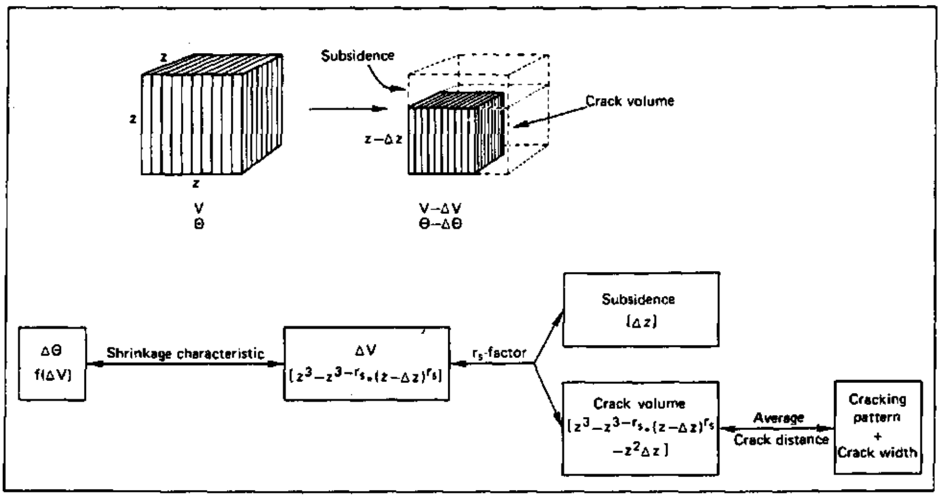

FIG. 1. Procedure to calculate cracking and subsidence of a soil layer with thickness z (m) resulting from changes in water content. V and θ are volume (m^3) and volumetric water content, respectively, of a soil cube with sides z (m). Factor r_s is a dimensionless geometry factor that determines the partition of total volume decrease into a grate of cracks and decrease of layer thickness.

changes $\Delta\theta$ into volume changes of soil matrix ΔV. The relation between $\Delta\theta$ and ΔV follows directly from the shrinkage characteristics (Haines 1923; Bronswijk 1988).

2. Conversion of volume change of soil matrix ΔV into crack volume and subsidence. This conversion is carried out with Eqs. (1) and (2).

$$\Delta z = z - z((V - \Delta V)/V)^{1/r_s} \qquad (1)$$

$$\Delta V_{cr} = \Delta V - z^2 \cdot \Delta z \qquad (2)$$

with

Δz = change in layer thickness due to shrinkage/swelling (m)
ΔV_{cr} = change in crack volume (m^3)
V = volume of cube of soil matrix before shrinkage/swelling (m^3)
ΔV = change in volume of soil matrix due to shrinkage/swelling (m^3)
z = layer thickness before shrinkage/swelling (m)
r_s = geometry factor

The dimensionless geometry factor r_s determines the partition of total volume change over change in layer thickness and change in crack volume (Rijniersce 1983; Bronswijk 1986). For three-dimensional isotropic shrinkage: $r_s = 3$, for one-dimensional subsidence: $r_s = 1$. Factor r_s depends on sedimentation, ripening stage, moisture content, and load (Aitchinson and Holmes 1953; Berndt and Coughlan 1977; Talsma 1977; Hallaire 1984). This dependence should be determined for each individual soil, prior to any model calculation. Surface subsidence and total crack volume of the soil as a whole are calculated by adding up the changes in layer thicknesses and crack volumes of the individual soil layers.

3. Calculation of cracking pattern and crack width. With the aid of the shrinkage characteristic and the r_s factor, calculation of crack volume at each depth is possible. In some situations, however, the distance and width of the cracks are more important than the total volume. This is true in evaluating air availability for roots in cracking clay soils, where the spacing of air-containing cracks within a saturated soil matrix is more important than the actual volume of the cracks. Simulation of cracking patterns, however, is difficult. Lachenbruch (1961) and Raats (1984) described the forces that determine crack distances and depths in shrinking substrates. These theories apply only to homogeneous media. In many field soils cracking is governed by soil structure. Moreover, the duration and spatial distribution of water extraction (for instance by roots) is important. In the present model, the crack pattern is calculated in a simplified way. The pattern is assumed to be hexagonal. An average crack distance, typical for the considered soil, should be given as an input. The model calculates average crack width for each depth. Because of the one-dimensional nature of the model, the effect of crop distribution on the crack pattern cannot be taken into account.

To calculate the actual cracking and subsidence that are to be expected in a given soil, FLOCR is run with 30-yr data of daily actual precipitation and daily potential evapotranspiration. When calculations are repeated, for instance with another drainage system or crop, the influence of this factor on actual soil volume changes can be evaluated.

The main feature that distinguishes FLOCR from other soil-water simulation models is that this model computes a continuously changing system of soil matrix and shrinkage cracks. An example of a soil with shrinkage cracks, as calculated with FLOCR is illustrated in Fig. 2.

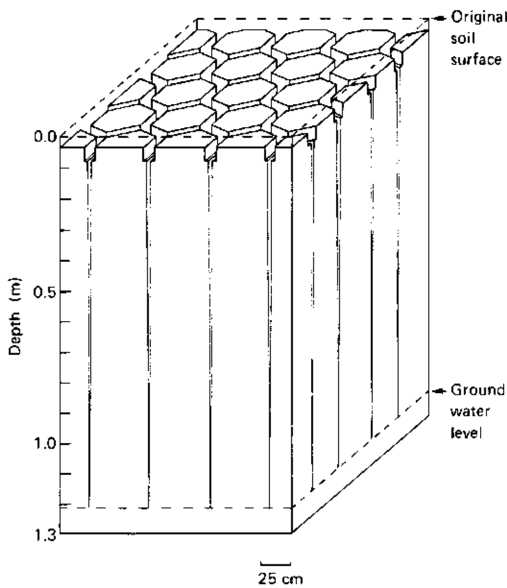

FIG. 2. Configuration of matrix and cracks in a clay soil after an extremely dry period, as calculated with the model FLOCR. Widths and volumes of cracks are calculated for each soil layer. Total crack volume is 71.7 mm; surface subsidence is 39.6 mm.

EXAMPLE OF APPLICATION: PREDICTING THE EFFECT OF DRAINAGE ON ACTUAL VOLUME CHANGES IN A CLAY SOIL

In many parts of the world, clay soils are drained to improve bearing capacity and crop yield. To assess the expected strong influence of drainage on cracking and subsidence, the procedure outlined in this paper was applied on a heavy clay soil in the central part of the Netherlands. The present undrained situation with high natural groundwater levels was compared with the future situation with tile drains at the 120-cm depth and 20-m spacing. The simulation focused on the influence of this improved drainage on frequency, magnitude, and depth of swelling and shrinkage processes, as well as on the influence on surface subsidence.

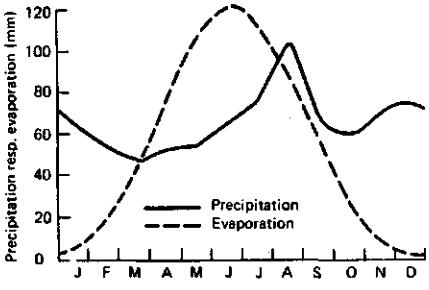

FIG. 3. Average monthly precipitation and open water evaporation at De Bilt, the Netherlands (after Anonymous 1971).

SOILS, LAND USE, CLIMATE, AND MEASUREMENTS

The test area, situated in the central part of the Netherlands, is used as pasture. The soil at the site can be classified as a typic Fluvaquent, very fine clayey, mixed illitic-montmorillonitic, mesic (Soil Survey Staff 1975). Its percentage of particles smaller than 2 μm ranges from 50 to 70%. The water retention curve of the soil matrix was determined on a sand box and with pressure membrane apparatus. Hydraulic conductivity as a function of pressure head was determined on undisturbed samples using the evaporation method (Boels et al. 1978). Shrinkage characteristics of the soil matrix were determined on natural clods coated with Saran F-310 resin (Brasher et al. 1966). Geometry of shrinkage was determined by measuring subsidence

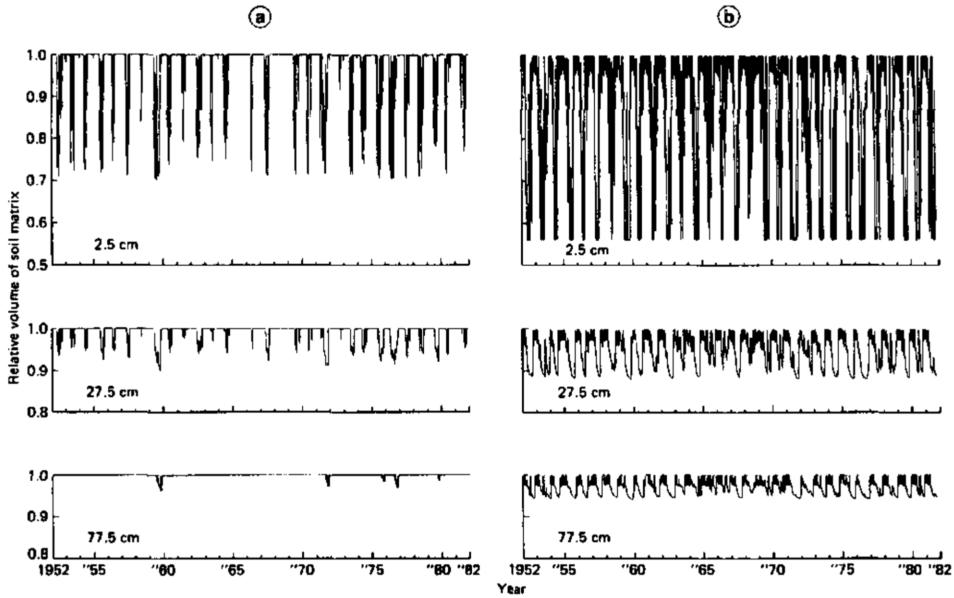

FIG. 4. Course of soil volume change at 2.5, 27.5, and 77.5 cm below the soil surface, simulated over a 30-yr period. Two drainage situations are given: (a) present situation with poor drainage; (b) future situation with tile drains installed at the 1.20-m depth with 20-m spacing. Calculations have been carried out with the model FLOCR with actual climatic data from 1952 till 1982.

and total volume decrease of undisturbed 100-cm^3 samples upon drying (Bronswijk 1986). Factor r_s was equal to 3 for all soil layers. Climatic input data consisted of daily actual precipitation and daily potential evapotranspiration from 1952 till 1982. Figure 3 shows average values of precipitation and evaporation in the central part of the Netherlands. The model FLOCR was run with the measured soil water retention curve, hydraulic conductivity curve and shrinkage characteristics, and the necessary information on drainage situation and climatic data as input. The soil profile was schematized into 30 layers of 5-cm thickness. The time step of the model calculations was 0.02 d.

RESULTS AND DISCUSSION

In the present, poorly drained situation, volume changes of the soil matrix at the 2.5-cm depth are maximally 30% (Fig. 4a). In the subsoil, the current volume change is much lower, namely maximally 10% at the 27.5-cm depth and only 3% at 77.5 cm. Not only the magnitude, but also the frequency of swelling and shrinkage strongly decreases with increasing depth.

In the future, tile-drained, situation, the maximum volume change in the topsoil will increase to 45%. This maximum is determined by the onset of the zero-shrinkage phase, when the soil matrix has reached its minimum volume. The frequency of shrinkage is also greater, and almost every year the maximum shrinkage will be reached. In the subsoil, volume changes will be both larger (maximally 13 and 7% for the 27.5- and 77.5-cm depths, respectively) and much more frequent than at present.

In the topsoil, swelling and shrinkage are mainly determined by soil evaporation and water uptake by plant roots. Because rooting depth of grass on these heavy clay soils is very shallow, volume changes in the subsoil are determined by drainage. This explains why the difference between the poorly drained and the

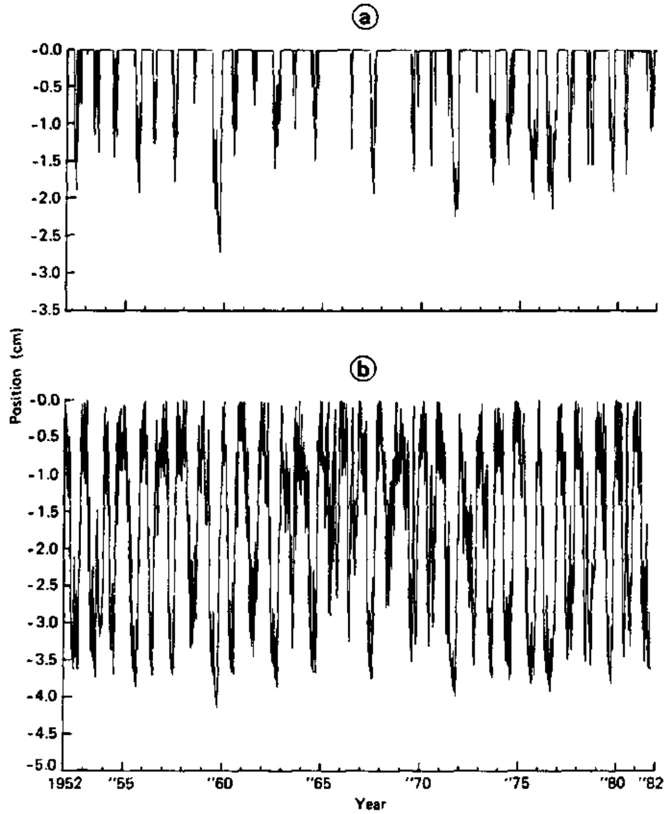

FIG. 5. Course of position of the soil surface of a clay soil, simulated over a 30-yr period, for two drainage situations: (a) present situation with poor drainage; and (b) future situation with tile drains installed at the 1.20-m depth with 20-m spacing. Calculations have been carried out with the model FLOCR with actual climatic data from 1952 till 1982.

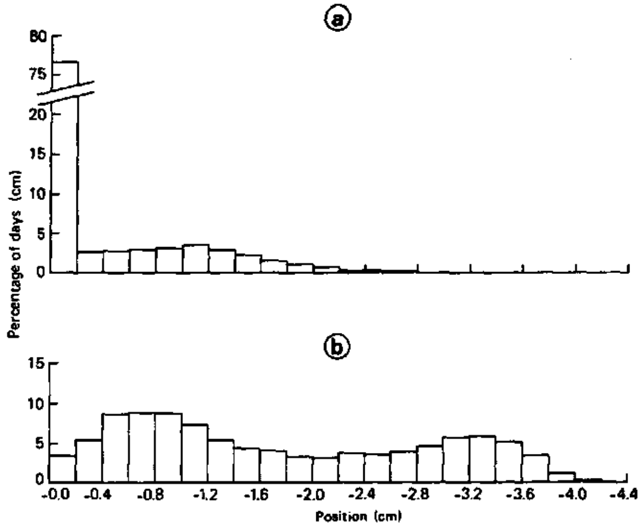

FIG. 6. Frequency of occurrence of positions of soil surface relative to the position in completely swollen conditions. Results are based on a simulation over 30 yr for two drainage situations: (a) the present situation with poor drainage; and (b) a future situation with tile drains installed at the 1.20-m depth with 20-m spacing. The percentages of days have been calculated with the model FLOCR with actual climatic data from 1952 till 1982.

tile-drained situations is more extreme at greater depth.

The difference in swelling and shrinkage frequency at greater depth as a result of improved drainage has some important consequences. Alternate swelling and shrinkage reduces the volume of soil aggregates and improves soil structure (Baver et al. 1972; Wilding and Hallmark 1984). Therefore, in this clay soil, improved drainage leads to improved structure of the subsoil.

Under the prevailing climatic circumstances, the subsidence of the soil surface in the poorly drained situation is maximally 28 mm (Fig. 5). Maximum subsidence in the future well-drained situation will increase to 42 mm. Figure 6 illustrates the increase in frequency of soil surface movements after tile drainage. Both the increase of maximum subsidence and of frequency of subsidence will enhance damage to buildings, pavements, and other constructions on this soil.

CONCLUSIONS

Actual cracking and subsidence in field soils can be predicted by running the computer model FLOCR with representative 30-yr data of actual precipitation and potential evapotranspiration as input. The consequences of installing tile drains in a heavy clay soil can be predicted in this way. After drainage tiles are installed in a poorly drained soil, both magnitude and frequency of swelling and shrinkage will increase, especially in the subsoil. Consequently, maximum subsidence of the soil surface will almost double, and frequency of surface movements will also increase strongly. As a result of this, buildings, pavements, and other constructions on this soil have an increased risk of being damaged. Agricultural users of the soil, however, will profit from a water regime that is better adapted to their needs and, in the long run, from an improved subsoil structure.

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9. EXTENSION OF THE DEVELOPED MODEL APPROACH TO EVAPORATION AND OXYGEN DIFFUSION IN CRACKING CLAY SOILS

9.1 Introduction

In this thesis, an approach has been developed to model and predict the volume change processes in cracking clay soils. This approach has subsequently been applied to simulate infiltration and water transport in clay soils. Owing to its general applicability and simplicity, however, the same model approach can be extended to other fields of soil physical research. Two examples of such an extension, namely evaporation from shrinkage cracks and oxygen diffusion in cracking clay soils, will be presented in this chapter.

9.2 Evaporation from shrinkage cracks

In addition to the surface of the soil, the walls of the shrinkage cracks in clay soils form an extra surface area that is exposed to the atmosphere. Obviously, evaporation of water will occur from these crack walls. The actual evaporation from shrinkage cracks is determined by:
- the evaporative demand of the atmosphere inside the cracks;
- the exposed surface area of crack walls;
- the conditions inside the soil matrix.

The effects of wind speed, crack width and crack depth on *the evaporative demand of the atmosphere inside the cracks*, have been investigated by Adams et al. (1969). Windspeed appeared to have the greatest effect on evaporation from cracks. These laboratory experiments, however, were conducted with large (artificial) cracks in an almost saturated medium, which is physically impossible and will not occur in field soils. The quantitative results of these experiments are therefore difficult to extrapolate to field conditions. In a field experiment, Adams and Hanks (1964) found that potential bare soil evaporation at a depth of 61 cm inside a shrinkage crack was as much as 55% of the potential evaporation at the soil surface. They concluded that turbulent movement of air inside the cracks determined to a large extent the evaporative demand of the atmosphere inside the crack. Methods to predict this evaporative demand quantitatively, however, from factors such as wind speed, radiation, air temperature or crack dimensions for example, are not yet available.

The *exposed surface area of crack walls* is relatively easy to quantify. Adams and Hanks (1964) estimated that on 1 m^2 soil surface of a cracked vertisol, 4.6 m^2 crack wall was exposed to the atmosphere. Detailed measurements of crack

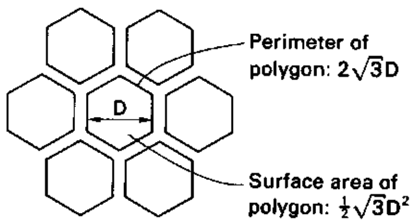

Fig. 1. Geometry of a crack pattern in a clay soil

wall surface area were obtained by Novak (1976), who determined a value of 8.3 m^2 crack wall per m^2 soil surface for the top 30 cm of soil.

In the model approach developed in this thesis, the surface area of crack walls is included in the output of the model as follows. In Figure 1, the surface of a cracked clay soil is pictured schematically.

For the area of one soil matrix polygon at the soil surface, A_{mat} (m^2), it holds that:

$$A_{mat} = \frac{1}{2} \sqrt{3}\ D^2 \tag{1}$$

with:
D = diameter of the polygon (m)

For the perimeter of this polygon, P (m), we can write:

$$P = 2 \sqrt{3}\ D \tag{2}$$

If, for simplicity, we ignore the widths of the cracks, then the surface area of the crack walls of one polygon, A_{crack} (m^2), is equal to the perimeter of the polygon, multiplied by the height of the polygon (or the depth of the crack), z (m):

$$A_{crack} = 2 \sqrt{3}\ D\ z \tag{3}$$

The relative surface area of the crack walls, $A_{crack,rel}$, is equal to A_{crack} (Eq. 3) divided by A_{mat} (Eq. 1) which yields:

$$A_{crack,rel} = \frac{4\,z}{D} \tag{4}$$

In the example presented in Figure 2 of Chapter 8, $A_{crack,rel}$ is equal to 4*1.2/0.5 = 9.6. This means that 9.6 m^2 of crack walls per m^2 of soil surface are exposed to the atmosphere. A quantitative comparison of this computed value with the measured values of Novak (1976) and Adams and Hanks (1964) is not possible, because of the difference in both soil type and soil wetness. However, considering the fact that the soil of Figure 2 in Chapter 8 is probably drier than the soils from Novak, and Adams and Hanks, a computed value of 9.6 is in agreement with the available literature data.

The influence of *the conditions inside the soil matrix* on evaporation from cracks is difficult to quantify. Qualitatively, it can be argued that the crack walls are rather wet, whereas the surface soil may often be very dry. Consequently, evaporation from the wet shrinkage crack walls may be greater than evaporation from the dry surface soil. Quantitative information is lacking on the relationship between the wetness of the soil matrix (or other soil matrix properties), and the magnitude of actual evaporation from shrinkage crack walls.

The results of the various aforementioned investigations on evaporation from shrinkage cracks can be summarized as follows:

- the evaporative demand of the atmosphere inside the shrinkage cracks may be very high;
- the exposed surface area of crack walls may be considerable;
- the shrinkage crack walls are often much wetter than the soil surface.

In view of these conclusions, it is understandable that from a field experiment on evaporation in cracking clay soils (Ritchie and Adams, 1974), it was concluded that the greater part of actual evaporation from a bare cracked clay soil occurred from the shrinkage cracks. This actual evaporation from the cracks, however, amounted to only 10-16 % of the potential soil evaporation at the soil surface. In the case of cropped soils with soil cover of more than 60 to 80 %, *potential* soil evaporation will be small in comparison with potential evapotranspiration (Feddes and Bastiaanssen, 1990), and *actual* soil evaporation even smaller. In such conditions, actual evaporation from cracks is negligible in water balance simulations.

In bare clay soils, however, or when there is only little soil cover by crops, actual evaporation from cracks may be the main process of water loss from the soil. If such is the case, a procedure to include evaporation from shrinkage cracks in water balance simulation models could be:

1) take the soil profile being divided into compartments for modeling vertical water transport (e.g. Chapter 6, Fig. 3b);
2) calculate potential soil evaporation at the soil surface;

3) calculate potential evaporation inside the cracks (per unit area of crack wall) as a fraction of potential soil evaporation at the soil surface, e.g. a lineair decrease from 100 % at the soil surface to 50 % at the bottom of the crack (Adams and Hanks, 1964);
4) reduce the potential evaporation rate inside the cracks to obtain the actual evaporation rate per unit area of crack wall. This reduction should depend on the water content of the soil matrix in each soil compartment, and could be computed with an (empirical) evaporation equation (e.g. Feddes and Bastiaanssen, 1990);
5) calculate the surface area of crack walls per m^2 soil surface for each compartment as outlined above;
6) for each compartment, calculate the actual evaporation originating from the cracks, by multiplying the actual evaporation rate per unit area of crack wall with the surface area of crack walls per m^2 soil surface.

In this way, the water extraction from the soil matrix by evaporation from the cracks, E_{crack}, can be calculated for each compartment in the soil profile. The sum of the evaporation from the various compartments yields the total actual evaporation from shrinkage cracks.

When modeling vertical water transport through unsaturated soil, water extraction at some depth in the soil by plant roots can be incorporated in the vertical water transport equation by adding a sink term S to this equation (e.g. Feddes et al., 1988).

Water extraction at some depth in the soil as caused by evaporation from shrinkage cracks can be treated similar to water extraction by roots. Before being added as a second sink S_2 to the water transport equation, E_{crack} should be expressed for each compartment in cm water.cm^{-1} soil profile.s^{-1}. This procedure results in:

$$\frac{\partial \theta}{\partial t} = - \frac{\partial v}{\partial z} - S - S_2 \qquad (5)$$

with:
v = Darcy flux (m.s^{-1})
θ = volumetric water content
S = sink term representing water extraction by roots (s^{-1})
S_2 = sink term representing evaporation from cracks (s^{-1})
t = time (s)
z = depth (m)

Computation of the actual evaporation per unit area crack wall (steps 2 to 4 in the procedure mentioned before) can be conducted, for instance, with equations presented by Menenti (1984) and Feddes and Bastiaansen (1990). In this approach, the depth of the evaporation front, being the boundary between

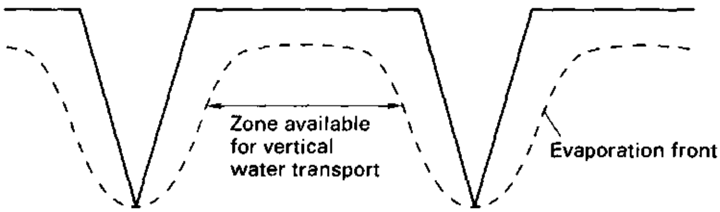

Fig. 2. Hypothetical position of the evaporation front in a cracked soil in arid conditions

vapour flow and water flow in the soil, is calculated together with the vapour flow from this evaporation front to the soil surface.

In the case of cracked clay soils, a sharp evaporation front is also likely to occur inside the soil matrix, parallel to the crack walls (Fig. 2). Essentially, the distance between this front and the crack wall, together with the vapour flow per unit area crack wall, could be estimated by similar equations as applied at the soil surface. The actual evaporation from shrinkage cracks can be computed by multiplying the magnitude of vapour flow per unit area crack wall by the surface area of cracks per m2 soil surface. Water extraction by crack evaporation at some depth in the soil profile can then again be included as a sink term in the vertical water transport equation for the soil matrix (Eq. 5), as outlined above.

Vertical movement of water is negligible in the dry zone between crack wall and evaporation front. Therefore, in dry conditions the volume of soil matrix through which vertical water transport takes place, should be decreased. Because the crack distance and the depth of the evaporation front inside the soil matrix are known, the vertical water flow through the soil can be adapted proportionate to the relative horizontal area of the soil matrix participating in vertical water flow (Fig. 2).

It should be realized, however, that in dry conditions with large and deep shrinkage cracks, *horizontal* transport of water and vapour inside the soil matrix towards the crack walls could constitute the dominant water transport process in the soil, resulting in horizontal water content gradients inside the bigger part of the soil matrix. In that case, modeling of unsaturated water transport in the soil matrix by applying a *vertical* water transport equation would be useless, and a two- or three-dimensional model approach ought to be applied.

9.3 Oxygen diffusion in cracking clay soils

Transport of oxygen in the air-filled pores of the soil can be described by (e.g. Christensen et al., 1986):

$$\varphi_a \frac{\partial C_a}{\partial t} = D_s \frac{\partial^2 C_a}{\partial x^2} - \alpha \qquad (6)$$

in which:
φ_a = air content of the soil ($m^3.m^{-3}$)
C_a = concentration of oxygen in air-filled pores ($m^3.m^{-3}$)
t = time (s)
D_s = diffusion coefficient of oxygen in soil ($m^2.s^{-1}$)
x = distance (m)
α = oxygen consumption rate ($m^3.m^{-3}.s^{-1}$)

To solve Eq. (6) analytically or numerically, we need to know the relationship between D_s and φ_a. Generally these relationships are of the type:

$$\frac{D_s}{D_o} = f\,(\varphi_a) \qquad (7)$$

in which:
D_o = diffusion coefficient of oxygen in the atmosphere ($m^2.s^{-1}$)
$f(\varphi_a)$ = some function of the air content
Various analytical and empirical expressions for $f(\varphi_a)$ have been reviewed by Bakker et al. (1987).

In this section, the approach to model the volume change processes in cracking clay soils, as developed in this thesis, will be used to compute oxygen diffusion in cracking clay soils.
Because of the low air content of the soil matrix, oxygen diffusion in a cracking clay soil is largely determined by the presence of continuous air-filled macropores. In poorly structured heavy clay soils vertical shrinkage cracks are the predominant type of macropores. When cracks in a soil column are continuous, the diffusion of oxygen through that column is determined by the horizontal cross-section of vertical shrinkage cracks. Therefore:

$$\frac{D_s}{D_o} = A_{rel} \qquad (8)$$

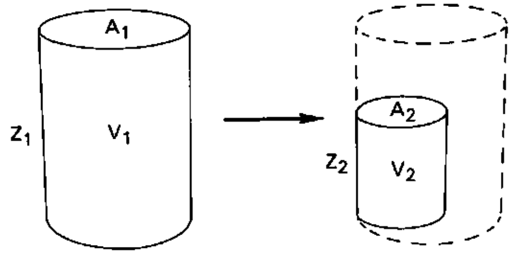

Fig. 3. Shrinkage of a cylindrical soil sample with original volume V_1 (m^3), surface area A_1 (m^2) and height z_1 (m), into a sample with volume V_2, height z_2 and surface area A_2

with:

A_{rel} = relative horizontal surface area of cracks

Eq. (8) can be used to derive an analytical expression for the diffusion coefficient of oxygen in heavy clay soils.

Consider a volume of soil at saturation and after drying and shrinkage (Fig. 3). The shrinkage geometry of this soil sample is described as (Chapter 8):

$$\frac{z_2}{z_1} = \left(\frac{V_2}{V_1}\right)^{\frac{1}{r_s}} \tag{9}$$

where:

V_1 = the original soil volume with height z_1 (m^3)

V_2 = the soil volume after shrinkage with height z_2 (m^3)

r_s = the dimensionless geometry factor.

Because $V_2 = A_2 * z_2$ and $V_1 = A_1 * z_1$, Eq. (9) can be converted into:

$$\frac{A_2}{A_1} = \left(\frac{V_2}{V_1}\right)^{1 - \frac{1}{r_s}} \tag{10}$$

During shrinkage, the air content, φ_a, of the sample from Figure 3 consists of air inside the soil matrix and air inside the cracks (including the "volume" of subsidence). Therefore:

$$\varphi_a = \varphi_{a,mat} + \varphi_{a,cracks} \tag{11}$$

and:

$$\varphi_{a,cracks} = \frac{V_1 - V_2}{V_1} \tag{12}$$

Combining Eqs. (11) and (12) leads to:

$$\frac{V_2}{V_1} = 1 - \varphi_a + \varphi_{a,mat} \tag{13}$$

Introducing this expression for V_2/V_1 in Eq. (10) yields:

$$\frac{A_2}{A_1} = (1 - \varphi_a + \varphi_{a,mat})^{1 - \frac{1}{r_s}} \tag{14}$$

The relative area of cracks, A_{rel}, is equal to $(A_1\text{-}A_2)/A_1$ (Fig. 2), or A_2/A_1 = 1-A_{rel}. If we combine this expression for A_2/A_1 with Eq. (14), and insert the resulting expression for A_{rel} in Eq. (8), we arrive at:

$$D_s = \{1 - (1 - \varphi_a + \varphi_{a,mat})^{1 - \frac{1}{r_s}}\} D_o \tag{15}$$

In many clay soils, normal isotropic shrinkage is the dominant shrinkage process. In that case, $\varphi_{a,mat} = 0$ and $r_s = 3$ and Eq. (15) simplifies to:

$$D_s = \{1 - (1 - \varphi_a)^{\frac{2}{3}}\} D_o \tag{16}$$

For zero or residual shrinkage, the air content of the soil matrix, $\varphi_{a,mat}$, at a specific water content can be derived from the shrinkage characteristic, and Eq. (15) should be applied.

In Figure 4 measurements of oxygen diffusion coefficients in heavy clay soils from Indonesia (Barambai) and the Netherlands (Nieuwkoop) (Nugroho, 1990) are compared with the theoretical expression of Eq. (16). For the poorly structured subsoil from Nieuwkoop, which showed large cracks upon drying, the agreement was good. For the well structured topsoil from Barambai, however, the agreement was rather poor due to the topsoil cracks being smaller and sometimes more tortuous than that of the subsoil. A tortuosity

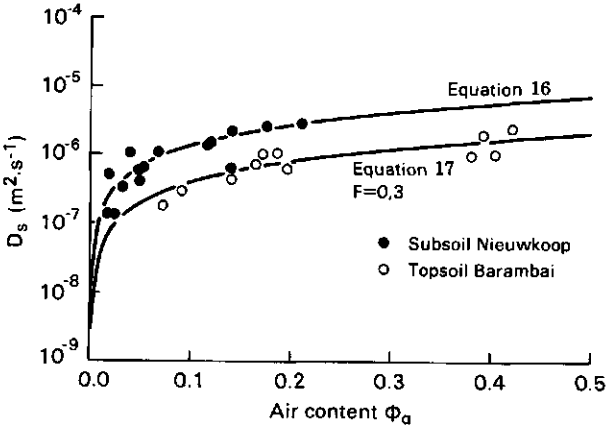

Fig. 4. Relation between air content φ_a and oxygen diffusion coefficient D_s for a well structured topsoil of a heavy clay soil from Indonesia (Barambai, 20-30 cm below soil surface), and a poorly structured subsoil of a heavy clay soil from the Netherlands (Nieuwkoop, 75-85 cm below soil surface). Measured values are compared with the theoretical relations of Eqs. (16) and (17)

factor, F, had to be introduced to account for the longer diffusion pathway and the irregularity of the crack walls, which yields Eq. (17):

$$D_s = F\{1 - (1 - \varphi_a)^{\frac{2}{3}}\} D_o \tag{17}$$

Eq. (17), with an empirical tortuosity factor of 0.3, is also pictured in Figure 4 and fits the measured topsoil data satisfactorily.

An example of the application of Eqs. (16) and (17) in a computer simulation model to compute the oxygen regime in cracking clay soils is presented by Bronswijk and Nugroho (1990).

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10. GENERAL DISCUSSION ON THE DEVELOPED MODEL APPROACH

10.1 Incorporation of swelling and shrinkage into existing soil water balance simulation models

In Chapters 2 to 5 of this thesis, procedures were presented to measure and predict the actual magnitude of cracking and surface subsidence in field soils, using easily measurable soil properties like the shrinkage characteristic of soil aggregates.

In applied agro-hydrological research, however, the prediction of swelling and shrinkage is often not an objective in itself. In most cases, it are chiefly the *consequences* of swelling and shrinkage, such as the preferential transport of water and solutes through shrinkage cracks, that are important. Therefore, the methodology to predict the volume change processes in clay soils, as described in Chapters 2 to 5, was subsequently applied to develop a water balance simulation model for cracking clay soils. The principles of this model, together with some examples of application, have been presented in Chapters 6 to 9.

From the start of the investigations, general applicability has been a major requirement for the simulation model to be developed. As there were already several water balance simulation models for rigid soils available, it was deliberately decided not to develop a new model. Each existing model has its own purpose, merits and disadvantages, and each its own group of users. Instead of developing a new model, only applicable to cracking clay soils, it was considered to be more useful to develop a procedure that would extend already existing one-dimensional models, making them applicable to cracking clay soils. Therefore, the present model approach was developed as a series of sub-models that could be incorporated into any existing one-dimensional water balance simulation model for rigid soils. The requirements for such an existing model are, that the soil profile be divided into discrete layers, that the soil water content profile be part of the model output, and that the maximum infiltration capacity of the soil surface be computed in the model. The complete model approach is pictured in Figure 1.

This chapter aims to discuss and criticize the possibilities and limitations of the developed model approach presented in Figure 1. The principles of modeling cracking and surface subsidence are discussed in Section 10.2 and the principles of modeling the soil water balance in Section 10.3. Following this discussion, conclusions will be reached as to the applicability of the developed model approach. Finally, some future research themes are indicated.

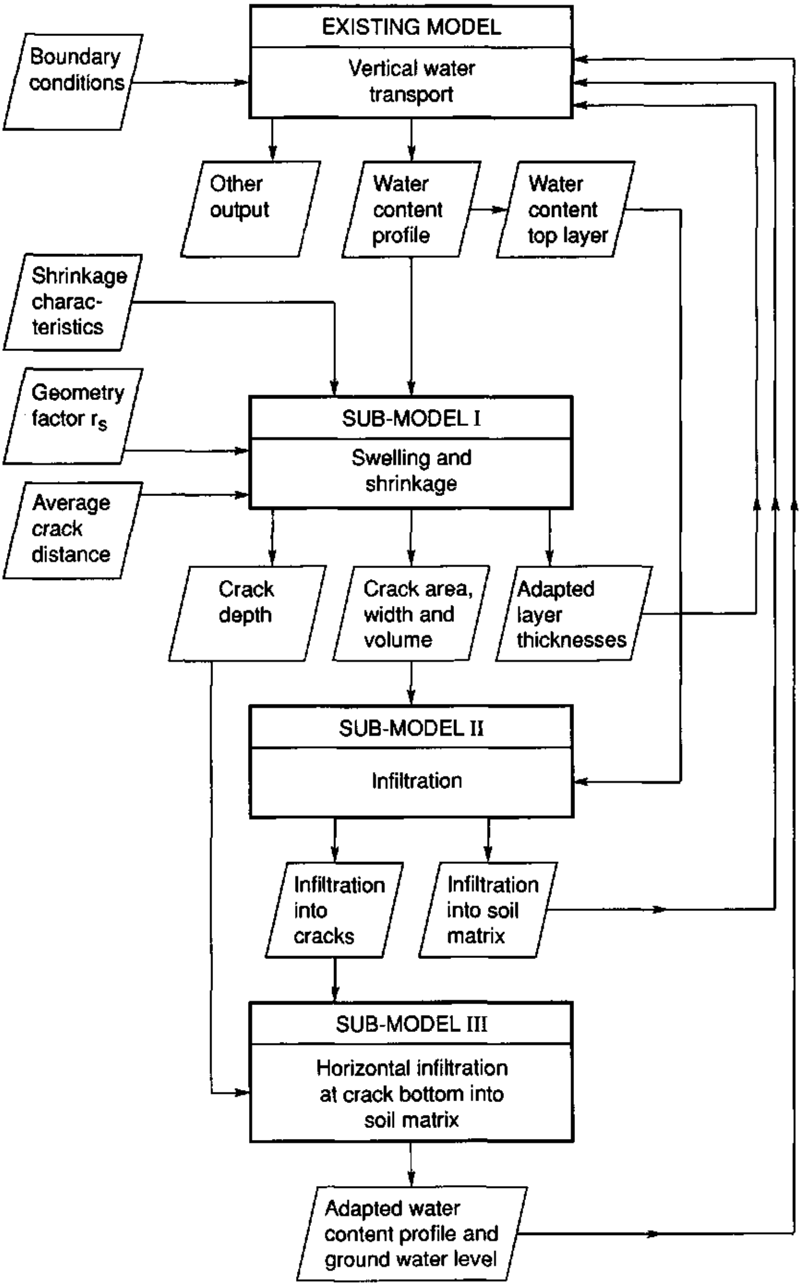

Fig. 1. The developed approach to model cracking, surface subsidence and water balance of cracking clay soils, by incorporating various sub-models into existing one-dimensional soil water balance simulation models

10.2 Principles of modeling cracking and surface subsidence

The volume changes of the soil matrix upon drying and wetting can be computed using measured shrinkage characteristics of soil aggregates.

Swelling and shrinkage of clay soils are complex processes. Many forces acting on a micro-scale determine the mechanism and magnitude of volume changes of clay upon wetting and drying. By determining the shrinkage characteristic of soil aggregates, description of all these micro-scale forces can be avoided. This is the only way to make modeling of swelling and shrinkage processes in field soils feasible.

Jarvis (1989) assumed a linear relationship between water content and matrix volume of the soil. Kihupi (1990) applied the equation of Giraldez et al. (1983) to model this relationship. In both approximations, however, some errors are introduced in the calculation of volume changes. By direct measurement of the shrinkage characteristic, all simplifying assumptions become superfluous.

There is a unique relationship between water content, pressure head and volume of the soil matrix.

As is the case in rigid soils, the water retention curve of a clay soil is the relationship between the water content and the pressure head of the soil matrix.

Hysteresis in the water retention curve of a clay soil is considered to be of minor importance as compared to sandy soils, because the pore size distribution of a clay soil matrix is rather uniform and because during normal shrinkage the soil matrix is saturated.

The sum of the volumes of the soil matrix and the cracks (including the "volume" of the subsidence) at any water content is equal to the volume of the soil matrix in fully saturated conditions.

The assumption that the sum of the volumes of soil matrix, cracks and surface subsidence is always equal to the volume of the saturated soil matrix implies that the developed model approach is solely applicable to reversible swelling and shrinkage processes. Irreversible volume changes due to structural changes inside the soil matrix ("soil ripening") fall outside the scope of this thesis.

The volume changes of the soil matrix can be converted into crack volume and changes in layer thickness by applying a dimensionless geometry factor.

The geometry factor, r_s, determines the conversion of the volume changes of the soil matrix into vertical and horizontal movements of the bulk soil, i.e. subsidence and cracking. It has been shown in Chapter 3 that $r_s = 3$ for cylindrical soil samples of a fluvial heavy clay soil, i.e. that shrinkage is isotropic. Whether the bulk soil's shrinkage geometry corresponds with the shrinkage geometry of a cylindrical soil sample would depend on the actual soil structure.

In the case of block-like structural elements (e.g. prismatic or blocky soil structure), isotropic shrinkage of the individual soil aggregates results in isotropic shrinkage of the bulk soil.

In the case of sphere-like stuctural elements (e.g. crumb structure), however, isotropic shrinkage of individual aggregates could well result in anisotropic shrinkage of the bulk soil. Nevertheless, this does not restrict the general validity of the concept of applying a geometry factor r_s to convert volume changes of the soil matrix into subsidence and cracking. For a crumb-like soil structure, r_s will only be more difficult to measure, all the more because in such a situation rs may vary with the soil water content as well.

The majority of the heavy clay soils, however, among which the fluvial and marine clay soils used in this thesis, contain block-like or prismatic structural elements (De Bakker, 1979). Therefore, the geometry factor r_s should be easy to determine on small cylindrical or cubical soil samples for the majority of soils.

The sum of the changes in thickness of each individual soil layer is equal to the surface subsidence.

In the developed model approach, it is only possible to accurately compute surface subsidence, if horizontal cracks are either absent or stable. When the width of a horizontal crack present at some depth inside the soil matrix increases upon drying, the actual subsidence of the soil surface will be less than the computed subsidence. The total vertical component of shrinkage as well as the volume of shrinkage cracks, however, remain unaltered. Therefore, if horizontal cracking occurs, it has no effect on the calculation of crack volumes and on the calculation of preferential flow through vertical cracks.

The influence of horizontal cracks on vertical water transport inside the soil matrix will be discussed in Section 10.3.

Crack volumes are converted into crack widths, using an average crack distance and a specific type of crack pattern.

The volume of shrinkage cracks can be predicted by applying the shrinkage characteristic and the geometry factor of the soil matrix. To compute the pattern, distance and widths of cracks, however, additional information is required. In the developed model approach, the average crack distance together with a specific type of crack pattern, e.g. cubical or polygonal, is required as input for model simulations. The average crack width is then model output.

In given climatic conditions, the crack pattern in clay soils is mainly dependent on the soil properties, on the type and intensity of tillage operations, and on the spatial distribution of water extraction from the soil. When water extraction is homogeneously distributed over the soil surface, as is the

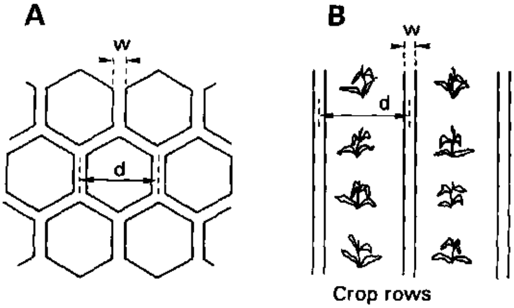

Fig. 2. Computation of the crack width, w, and the average crack distance, d, for a polygonal (A) and a longitudinal (B) crack pattern (view from above)

case in bare soils or under pasture, and tillage is absent, the occurring crack pattern is a soil property only. Virgo (1981) concluded that although the cracks in a Somali vertisol did not occur at exactly the same locations every year, the polygonal pattern of the cracks repeated itself yearly. Accordingly, in such conditions, a polygonal crack pattern and an average crack distance are used as model input parameters to predict crack widths.

In row crops like maize, the crack pattern is determined by the distribution of water extraction over the field. The shrinkage cracks occur in between the plant rows, where the soil is wetter and the cohesive forces are lowest (Swartz, 1966; Sharma and Verma, 1977). Obviously, in this instance a longitudinal crack pattern should be taken as model input, the average crack distance being equal to the distance between two rows of crops. Crack widths can then again be calculated. An example of the computation of crack width for a polygonal and a longitudinal crack pattern is provided in Figure 2.

Tillage operations may also influence the occurring crack pattern. The use of a seed drill has been observed to initiate cracks at the positions of the seeds (A.L.M. van Wijk, The Winand Staring Centre, Wageningen, the Netherlands, personal communication). Again, in this case, a longitudinal crack pattern should be taken as model input.

When a fixed crack distance is taken as model input, the evolution of crack distances upon drying, as mentioned by Luthin (1982) and Hallaire (1984), cannot be computed. In principle, it is possible to introduce a water-content-dependent crack distance and/or pattern into the model. At present, however, such a procedure is not feasible because of the lack of quantitative information on this phenomenon.

The relatively simple procedure to compute crack distance and width, as outlined above, is mostly acceptable. This is because in modeling the soil water balance, the distance between the cracks and their individual widths are of relatively minor importance compared to the volume, the depth and the area exposed at the soil surface.

The volume of the cracks, for instance, determines largely the immediate water storage capacity of a clay soil. The depth of the cracks determines the depth where preferential flow is collected and where horizontal infiltration into the soil matrix occurs. The area of the cracks at the soil surface determines the fraction of the precipitation falling directly into the cracks.

The width of the cracks, however, seldom limits the transport through the cracks, because the flow of water through cracks is chiefly film flow along crack walls (Hoogmoed and Bouma, 1980). The actual widths of individual cracks will be of significance only in nearly saturated soils when cracks are small, or during extreme precipitation/irrigation rates.

10.3 Principles of modeling the soil water balance

The water balance of clay soils can be simulated with a one-dimensional vertical water transport model. Horizontal flow processes can either be ignored or incorporated into the equation for vertical water flow inside the soil matrix.

The advantage of a one-dimensional approach is clearly its simplicity and applicability. There is no arguing that in reality, water infiltration in a cracked soil is a three-dimensional process. Both evaporation from shrinkage cracks and horizontal infiltration of water from the cracks into the soil matrix result in three-dimensional heterogeneous water distributions.

The incorporation of evaporation from shrinkage cracks in a one-dimensional model approach has already been discussed in Section 9.2. So far, because field applications of the FLOCR model were conducted on cropped soils, evaporation from shrinkage cracks was considered negligible.

Horizontal infiltration under ponded conditions at the bottom of the cracks occurs close to the groundwater level. At that depth, the soil is nearly saturated and only very little water and time is needed to saturate the soil and to close the cracks. Therefore, a computed average soil water content immediately after horizontal infiltration at the bottom of the cracks is a justifiable approximation.

Horizontal infiltration into the soil matrix during downward unsaturated film flow along the crack walls also gives rise to a three-dimensionally heterogeneous water distribution in the soil; the centre of the soil matrix being drier than the edges near the crack walls. In heavy clay soils, the quantities of water involved are only small (Hoogmoed and Bouma, 1980). In the developed model approach, horizontal infiltration into the soil matrix during unsaturated film flow along crack walls is ignored. The validity of this assumption in clay soils with lower clay contents, however, is not clear. At present, there is no quantitative experimental evidence proving otherwise.

Irrespective of whether horizontal infiltration of water from the cracks into the crack walls occurs during film flow along the crack walls, or under ponded conditions at the bottom of the cracks, the result is always an increase in water content of the soil matrix. This process can be modeled by extending the equation for vertical water flow in the soil matrix with an additional source term representing the horizontal infiltration from the shrinkage cracks into the soil matrix. The following equation is the result (Feddes et al., 1988):

$$\frac{\partial \theta}{\partial t} = - \frac{\partial v}{\partial z} - S + B \qquad (1)$$

with:
v = Darcy flux ($m.s^{-1}$)
θ = volumetric water content
S = sink term representing water extraction by roots (s^{-1})
B = source term representing horizontal infiltration of water from shrinkage cracks into the soil matrix (s^{-1})
t = time (s)
z = depth (m)

However, the difficulty of measuring the amount of horizontal infiltration make it questionable whether it will ever be possible to estimate the value of B independently. Moreover, after a precipitation event resulting in water flow through the cracks, it will take some time for horizontally infiltrating water to redistribute laterally within the soil matrix. During this time, a vertical one-dimensional flow equation for the soil matrix is in any case a gross simplification of reality.

A more pragmatic approach would be to add horizontally infiltrating water at certain time intervals to the soil matrix, as has been done in the FLOCR model (Chapter 6). A similar approach has also been proposed more recently by Kipuhi (1990), when modeling the interaction between matrix flow and macropore flow.

When discussing the validity of a one-dimensional approach, it should be borne in mind, that development of a two- or three-dimensional model can only be justified if the required extensive input data is sufficientely accurate. A completely three-dimensional description of the soil structure would then be needed for cracked clay soils, which is virtually impossible. It can therefore be concluded that at present, a one-dimensional approach is the most feasible.

A cracking clay soil should be considered as a two-domain system: soil matrix and shrinkage cracks.

Water flow in the shrinkage cracks is often film flow along the crack walls, for which Darcy's law cannot be applied. Darcy's law, however, is applicable within the soil matrix. Therefore, when modeling water flow in cracking clay soils, and considering both matrix flow and crack flow, it is feasible to divide the soil into matrix and cracks.

Precipitation/irrigation can be divided dynamically into soil matrix infiltration and crack infiltration, dependent on the area of the shrinkage cracks at the soil surface and the infiltration capacity of the soil matrix.

The area of the shrinkage cracks exposed at the soil surface is part of the model output (Sub-model I, Fig. 1). The maximum infiltration capacity of the soil matrix depends on the soil water content of the topsoil. Generally, water balance models compute in one way or another the infiltration capacity of the soil surface in dependance of the top layer water content, in order to predict surface runoff. Essentially, any method to compute surface runoff can be applied to compute infiltration into cracks as well.

Sensitivity analysis of the FLOCR model (Oostindie et al., 1990) showed that the infiltration capacity of the soil matrix is a critical factor determining the amount of preferential flow. Therefore, the infiltration capacity should be computed with great accuracy. Depending on the quality of the method used to compute soil infiltration, it is often advisable to substitute for the existing computation method a computation based on sorptivity equations. This was also done with the FLOCR model.

Water transport inside the soil matrix can be computed with the Darcy equation, taking into account the change of distances between the nodal points of the numerical compartments.

Vertical water transport inside the clay soil matrix can, in theory, be described using Darcy's equation. Two problems should be considered:

- because of changing layer thicknesses upon swelling and shrinkage, either Darcy's equation should be converted into material coordinates (Philip and Smiles, 1969) or the layer thicknesses of the numerical compartments should be adapted continuously. The latter approach is applied in the FLOCR model;
- in the description of water flow inside the clay soil matrix, the overburden potential should possibly be included in Darcy's equation (Groenevelt and Bolt, 1972; Feddes et al., 1988). A preliminary study on the effects of including the overburden potential in water balance modeling yielded no significant differences between relevant model output with and without overburden potential (A.D. van Vessem. 1989. MSc thesis, Agricultural University Wageningen). Furthermore, Talsma (1977) found that in field clay soils, the value of the overburden potential was low. Therefore, in the

FLOCR model, the overburden potential is presently not included in the computation of vertical water transport inside the soil matrix.

Although both problems make modeling of water flow inside the soil matrix more tedious, they do not affect the principal applicability of Darcy's equation inside the soil matrix.

Infiltration into the shrinkage cracks is added instantaneously to the bottom of the cracks.

In the developed model approach, water flow through cracks reaches the bottom of the shrinkage cracks instantaneously. This is a valid assumption in dry conditions, with deep and wide cracks. In wet soils, the actual size of the cracks may sometimes limit the water flow velocity inside the cracks. Then, water flow velocity in cracks should be calculated depending on crack dimensions (Childs, 1969; Jarvis and Leeds-Harrison, 1987).

Whether a more complicated calculation of crack flow velocity is necessary is largely determined by the time scale on which a specific simulation model operates. The time interval between successive calculations of the soil water balance is normally in the order of hours or days. The time taken for water to travel from the soil surface down to the bottom of the cracks is often in the order of seconds or minutes. Therefore, instantaneous addition of crack flow to the bottom of the cracks is an acceptable approximation.

The influence of horizontal cracks on vertical water flow inside the soil matrix is incorporated in the hydraulic conductivity curve of the soil matrix.

If the hydraulic conductivity curve of the soil matrix is determined on representative undisturbed soil samples, under conditions comparable to the field, then such a sample will exhibit horizontal cracking during the determination, comparable to that in a field situation.

Consequently, the effects of horizontal cracks on vertical water flow inside the soil matrix will be included in the hydraulic conductivity curve. No special adaption of models is required to account for this phenomenon.

10.4 Conclusion

With the developed model approach of Figure 1, it is possible to simulate the water balance of cracking clay soils satisfactorily. The computed soil water balance includes preferential flow of water via shrinkage cracks. Daily values of surface subsidence and crack volumes are computed. The approach of adding various sub-routines to existing one-dimensional water balance models ensures a general applicability. The model principles as discussed in Sections 10.2 and 10.3 are the best possible compromise between simplicity and reality.

The model FLOCR is an example of how the developed general model approach can be applied in practice to adapt an existing one-dimensional water balance simulation model for use in cracking clay soils. Using FLOCR, the effects of swelling and shrinkage in general, and preferential flow via shrinkage cracks in particular, can be incorporated in agricultural and environmental (model) studies. Examples of this have been presented in Chapters 7 and 8.

Application of the developed model approach in its present state is valid in heavy clay soils, under conditions where the bare soil evaporation is of relatively minor importance compared to transpiration.

The extension to soils with lower clay contents possibly requires the incorporation of horizontal infiltration of water, flowing downward along crack walls, into the soil matrix. The importance of the latter process, however, is not clear as yet, and requires additional research.

The extension to conditions where the bare soil evaporation constitutes a major term of the soil water balance requires incorporation of the evaporation from shrinkage cracks in the model approach. The principles of this were discussed in Section 9.2. Future research is needed to quantify the various mentioned process parameters.

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11. SAMENVATTING

Omvang, modellering en belang van zwel- en krimpprocessen in kleigronden

Kleigronden hebben een bijzondere eigenschap: als ze uitdrogen neemt het volume van de grond af. Dit proces resulteert in krimpscheuren en maaivelds-dalingen. Bij bevochtiging van een uitgedroogde kleigrond zwellen de scheuren weer gedeeltelijk of geheel dicht en komt het maaiveld omhoog. Het zwel- en krimpproces heeft belangrijke praktische consequenties, zoals het snelle transport van water en opgeloste stoffen door krimpscheuren naar de ondergrond, de toename van het waterbergend vermogen van een bodem, en het ontstaan van schade aan gebouwen en wegen.

Het doel van dit proefschrift is het analyseren van zwel- en krimpprocessen in kleigronden om tot meetmethoden en computer-simulatiemodellen te komen waarmee het zwel- en krimpproces kan worden opgenomen in (model-)studies op het gebied van landbouw en milieu. Om dit doel te bereiken zijn experimenten uitgevoerd met bodemaggregaten, kleine bodemkolommen, een lysimeter en in het veld.

De relatie tussen vochtgehalteveranderingen en volumeveranderingen van een kleigrond kan worden weergegeven in de krimpkarakteristiek. In zo'n krimpkarakteristiek zijn een aantal krimpfasen te onderscheiden: normale krimp, rest-krimp en nul-krimp. In Hoofdstuk 2 wordt aan de hand van de krimpkarakteristiek van bodemaggregaten van zeven Nederlandse kleigronden aangetoond dat enkele van deze kleigronden tot de sterkst krimpende gronden ter wereld behoren. Tussen verzadiging en volledige uitdroging komen volume-afnames van bodemaggregaten voor tot maximaal 49 %. Onder Nederlandse klimaatsomstandigheden zullen de drukhoogtes van het bodemvocht in een kleigrond nagenoeg altijd tussen 0 en -16000 cm liggen. Daarom is voor alle bodemaggregaten de krimp ook in dit drukhoogtetraject gemeten. De volume-afnames in dit traject zijn maximaal 42%, waarbij in de meeste kleigronden zowel normale krimp als rest-krimp optreedt. In enkele zware kleigronden treedt alleen normale krimp op, wat betekent dat in het veld de bodemaggregaten het gehele jaar door verzadigd zijn. Enkel inter-aggregaat poriën zoals krimpscheuren bevatten lucht.

Of volume-afnames van de bodemmatrix zichtbaar worden als maaiveldsdaling of als scheurvorming wordt bepaald door de geometrie van het krimpproces. In Hoofdstuk 3 is de geometrie van het krimpproces bestudeerd door zakking en scheurvorming te meten in uitdrogende kleine grondkolommen. Het krimpproces in een zware kleigrond is isotroop, indien de last die bodemmonsters van een bepaalde diepte in het veld ondergaan ten gevolge van bovenliggende bodemlagen, wordt gehandhaafd tijdens uitdrogen en krimpen in het laboratorium. Ook bij een grotere belasting dan veldbelasting blijft het krimpproces isotroop. Bij verwijdering van de last na bemonstering in het veld, wordt scheurvorming echter dominant in vergelijking met zakking. Dit kan worden verklaard door het omhoog veren van het monsteroppervlak indien de natuurlijke belasting wordt verwijderd. De resulterende totale zakking na uitdroging wordt daardoor kleiner.

Metingen aan bodemaggregaten en kleine grondkolommen hebben als voordeel dat ze eenvoudig uitvoerbaar zijn. De resultaten van dit type experimenten zijn echter niet zonder meer extrapoleerbaar naar hele bodemprofielen. Daarom is in Hoofdstuk 4 het zwel- en krimpgedrag van een komkleigrond in een lysimeter onderzocht. In deze grond trad eerst structuur-krimp op, waarbij water uit grote inter-aggregaat poriën verdampte zonder dat volumeveranderingen optraden. Vervolgens waren de overheersende krimpfasen achtereenvolgens isotrope normale krimp van de bovengrond, isotrope rest-krimp van de toplaag, en isotrope normale krimp van de ondergrond. De overgang van normale krimp naar rest-krimp kwam overeen met de gemeten krimpkarakteristiek van de bodemaggregaten van de betreffende grond.

Tijdens een veldonderzoek in een zware knipkleigrond in Friesland (Hoofdstuk 5), zijn in 1986 regelmatig vochtgehalteveranderingen, scheurvolumes en maaiveldsdalingen gemeten. In deze knipkleigrond traden structuur-krimp, isotrope normale krimp en isotrope rest-krimp op. De maximale maaiveldsdaling bedroeg 26 mm, het maximale scheurvolume was 480 m^3/ha. Ook nu konden de waargenomen zwel- en krimpprocessen in het veld worden verklaard met behulp van de gemeten krimpkarakteristieken van bodemaggregaten.

Een nieuwe vergelijking is ontwikkeld waarmee verticale bodembewegingen in kleigronden gerelateerd kunnen worden aan vochtgehalteveranderingen tijdens alle krimpfasen en voor zowel isotrope als anisotrope krimpgeometrie. Deze vergelijking levert goede resultaten voor knipklei. Ook veldwaarnemingen in een komkleigrond in de Bommelerwaard blijken goed overeen te komen met de ontwikkelde vergelijking.

De resultaten van de hoofdstukken 2 tot en met 5 zijn vervolgens gebruikt voor het ontwikkelen van een computermodel, FLOCR (FLOw in CRacking soils). Dit model simuleert de waterbalans van zwellende en krimpende kleigronden. Het model berekent naast de waterbalans ook maaiveldsdaling, scheurvorming en preferent watertransport door krimpscheuren. De opzet en principes van FLOCR zijn beschreven in Hoofdstuk 6 en Figuur 1 van Hoofdstuk 10. Het model is gevalideerd aan de hand van veldmetingen in een komkleigrond in de periode maart-december 1985. Berekende waarden van maaiveldsdaling, scheurvolume, grondwaterstand en vochtgehalte van de toplaag kwamen goed overeen met metingen. De berekende preferente stroming door krimpscheuren in de betreffende periode was 143 mm, overeenkomend met 27% van de totale neerslag. Voor een onweersbui van 22 mm in 2 uur op een uitgedroogde en gescheurde kleigrond, bedroeg de preferente stroming zelfs 78% van de neerslag.

Om de gevolgen van zwel- en krimpprocessen op modelberekeningen te kwantificeren zijn in Hoofdstuk 7 modelberekeningen van FLOCR vergeleken met berekeningen van een bestaand model voor rigide gronden. Deze berekeningen zijn uitgevoerd voor een komklei met de weersgegevens van 1985. De belangrijkste verschillen tussen de twee modelbenaderingen ontstonden doordat in het geval van een gescheurde kleigrond een deel van de neerslag via krimpscheuren dieper in het bodemprofiel infiltreert. De praktische gevolgen hiervan waren:

- de berekende (bodem- en gewas-)verdamping nam af van 445 mm naar 412 mm, indien met zwel en krimp rekening werd gehouden;
- de berekende drainafvoer steeg van 101 naar 134 mm;
- de berekende grondwaterstanden waren hoger en vertoonden meer plotselinge pieken;
- het voor een graslandperceel berekende aantal dagen met onvoldoende draagkracht voor inscharen daalde van 63 naar 28.

In veel gevallen zijn niet alleen de gevolgen van zwel en krimp op bijvoorbeeld de waterbalans van een grond van belang, maar ook de grootte van de zwel- en krimpprocessen zelf. Daarom is in Hoofdstuk 8 een voorbeeld gegeven van het berekenen van de effecten van ingrepen in de waterhuishouding van een grond op de grootte van zwel en krimp. Door toepassing van het model FLOCR kon voor een slecht gedraineerde kleigrond worden voorspeld dat na verbetering van de drainage, de relatieve volumeveranderingen op 2.5, 27.5 en 77.5 cm diepte in de grond aanzienlijk zullen toenemen, respectievelijk van 30 tot 45%, van 10 tot 13% en van 3 tot 7%. Als gevolg hiervan zullen wegen en gebouwen een grotere kans op beschadiging hebben. Aan de andere kant zullen boeren op lange termijn kunnen profiteren van een verbeterde bodemstructuur, als gevolg van de intensievere zwel- en krimpprocessen op grotere diepte in het bodemprofiel.

In Hoofdstuk 9 worden twee mogelijke uitbreidingen voorgesteld van de ontwikkelde methode om de waterbalans, de maaiveldsdaling en de scheurvorming in kleigronden te modelleren. De eerste uitbreiding is het modelleren van verdamping uit krimpscheuren. Hierbij wordt de potentiële verdamping in de scheuren berekend als functie van de potentiële verdamping aan het bodemoppervlak. Vervolgens wordt aan de hand van de eigenschappen van de bodemmatrix de werkelijke verdamping per oppervlakte-eenheid scheurwand berekend. Vermenigvuldiging met het scheurwandoppervlak, dat is afgeleid uit de berekende scheurafmetingen en scheurdiepte, resulteert in de werkelijke verdamping uit de krimpscheuren.

De tweede uitbreiding betreft de diffusie van zuurstof in zwellende en krimpende kleigronden. Onder de aanname dat in zware kleigronden zuurstofdiffusie voornamelijk plaatsvindt via de krimpscheuren, is een relatie afgeleid tussen de zuurstofdiffusiecoëfficiënt en het luchtgehalte van kleigronden. Voor slecht gestructureerde ondergronden blijkt deze relatie goed overeen te komen met metingen. Voor beter gestructureerde bovengronden is de gemeten diffusiecoëfficiënt kleiner dan de berekende.

In Hoofdstuk 10, tenslotte, worden de veronderstellingen die aan de basis van het ontwikkelde simulatiemodel liggen, kritisch besproken. Er wordt geconcludeerd dat de ontwikkelde modelbenadering een goed compromis is tussen werkelijkheid en praktische toepasbaarheid.

Toekomstig (model-)onderzoek op het gebied van zwellende en krimpende gronden moet zich richten op de horizontale infiltratie tijdens preferente stroming door de krimpscheuren, en op de verdamping uit de krimpscheuren.

DERIVATION OF A GENERAL EQUATION FOR THE RELATION BETWEEN WATER CONTENT CHANGES AND STRUCTURAL, NORMAL, RESIDUAL AND ZERO SHRINKAGE IN CRACKING CLAY SOILS

Consider a soil cube with volume V (m^3) and sides z (m), containing volumes of solids, V_{solids} (m^3), and pores, V_{pores} (m^3). V_{water} (m^3) is the volume of water in the pores. The shrinkage characteristic gives the relation between moisture ratio ϑ and void ratio e for this cube of soil:

$e = V_{pores} / V_{solids}$
$\vartheta = V_{water} / V_{solids}$

The following relationships will be used in the analysis:

$V = (1 + e)V_{solids}$

Expressed per unit area i.e. dividing by z^2:

$$V = \frac{(1 + e)\ V_{solids}}{z^2} \tag{A1}$$

Furthermore

$V_{water} = \vartheta V_{solids}$

To obtain the water content per unit area W (m), we again divide by z^2:

$$W = \frac{\vartheta V_{solids}}{z^2} \tag{A2}$$

Consider a shrinkage characteristic of the type as given in Fig. 1 of Chapter 5 (page 67). When the soil dries from moisture ratio ϑ_0 to moisture ratio ϑ_1, then for the decrease in water content, ΔW, and the corresponding decrease in soil matrix volume, ΔV, it follows that:

$$\Delta W = W_0 - W_1 = \frac{\vartheta_0 V_{solids}}{z^2} - \frac{\vartheta_1 V_{solids}}{z^2} = \frac{(\vartheta_0 - \vartheta_1)V_{solids}}{z^2} \qquad \text{(A3)}$$

and also:

$$\Delta V = \frac{(e_0 - e_1)\ V_{solids}}{z^2} \qquad \text{(A4)}$$

Combination of Eqns (A3) and (A4) results in:

$$\Delta W = \Delta V + \frac{\{ (e_1 - \vartheta_1) + (\vartheta_0 - e_0) \}\ V_{solids}}{z^2} \qquad \text{(A5)}$$

If W and V at a certain moisture ratio ϑ_1 are compared with the saturated values, then $e_0 = e_s = \vartheta_s$. Furthermore, at saturation $V = (1 + e_s)V_{solids} = z^3$ so $V_{solids} = z^3/(1 + e_s)$. Introducing these expressions in Eqn (A5) yields the following general equation describing water loss in the *normal*, *residual* and *zero* shrinkage phases:

$$\Delta W = \Delta V + \frac{\{ e(\vartheta) - \vartheta \}z}{1 + e_s} \qquad \text{(A6)}$$

Including *structural* shrinkage yields:

$$\Delta W = S + \Delta V + \frac{\{ e\ (\vartheta) - \vartheta \}z}{1 + e_s} \qquad \text{(A7)}$$

where ΔW = change in water content in comparison with saturation (m), S = water loss in the structural shrinkage phase (m), ΔV = three-dimensional decrease of volume of the soil matrix in comparison with saturation (m), z = thickness of soil layer at saturation (m), e_s = saturated void ratio and $e(\vartheta)$ = void ratio at moisture ratio ϑ.

To derive water content changes in clay soils from measured vertical soil movements, we combine Eqn (3) of Chapter 5 (page 63), Eqn (A4) and $V_{solids} = z^3/(1 + e_s)$ yielding:

$$\{1 - (1 - \frac{\Delta z}{z})^{r_s} \}z = \frac{(e_s - e(\vartheta))z}{1 + e_s} \qquad \text{(A8)}$$

which can be converted into:

$$e(\vartheta) = (1 + e_s)(1 - \frac{\Delta z}{z})^{r_s} - 1 \qquad \text{(A9)}$$

By applying the shrinkage characteristic of the soil matrix, $e(\vartheta)$ can be converted into ϑ. Introducing Eqn (A4) and $V_{solids} = z^3/(1 + e_s)$ into Eqn (A7) yields:

$$\Delta W = S + \frac{(e_s - \vartheta)z}{1 + e_s} \qquad \text{(A10)}$$

which enables the conversion of ϑ-values into values of ΔW.

WATER CONTENT, POROSITY AND BULK DENSITY IN CRACKING CLAY SOILS

In clay soils the definitions of the parameters soil water content and porosity differ from those in rigid soils. This may cause some confusion. Therefore, in this appendix, various parameters commonly used in clay soils are briefly explained and related to corresponding parameters in rigid soils.

In Figure 1, a soil matrix cube with volume V is pictured. The soil matrix consists of solids and pores. The pores are filled with water and air. In general:

$$V = V_{solids} + V_{water} + V_{air} \qquad \text{(B1)}$$

with:

V = volume of the soil matrix (m^3)

V_{solids} = volume of the solid phase (m^3)

V_{water} = volume of the liquid phase (m^3)

V_{air} = volume of the gaseous phase (m^3)

As $V_{water} + V_{air}$ is equal to the volume of the pores, V_{pores}, Eq. (B1) can also be written as:

$$V = V_{solids} + V_{pores} \qquad \text{(B2)}$$

Rigid soils

In rigid soils the soil matrix volume, V, is constant. The volumetric water content θ, being the volume ratio of water to soil, is expressed as:

$$\theta = \frac{V_{water}}{V} \qquad \text{(B3)}$$

The volume fraction of soil pores, ε, commonly called porosity, is expressed as:

$$\varepsilon = \frac{V_{pores}}{V} \qquad \text{(B4)}$$

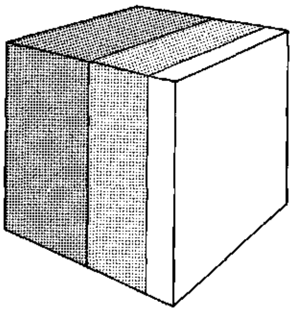

Fig. 1. A soil matrix with volume V, containing a volume of solids (V_{solids}), a volume of water (V_{water}), and a volume of air (V_{air})

The mass of solids divided by the bulk volume of the soil matrix is called the dry bulk density, ${}^{b}\rho_d$ ($kg.m^{-3}$):

$$ {}^{b}\rho_d = \frac{G_{solids}}{V} \tag{B5} $$

Eqs. (B4) and (B5) are often combined into:

$$ \varepsilon = 1 - \frac{{}^{b}\rho_d}{\rho_s} \tag{B6} $$

in which ρ_s is the density of the solid phase: G_{solids}/V_{solids} ($kg.m^{-3}$).

Clay soils

In clay soils, the volume of the soil matrix decreases upon drying, implying that both V and V_{water} in Eq. (B3) are changing. This causes two problems:

i an observed change in volumetric water content θ cannot be ascribed uniquely to either a change in the volume of water, V_{water}, or a change in the soil matrix volume, V;

ii the definition of V in Eqs. (B3) to (B4) may cause confusion during the shrinkage phase. V can be defined as the soil matrix volume before shrinkage but also as the soil matrix volume after shrinkage.

As a result, in clay soils it is suitable to express water content and porosity in a different way. The moisture ratio ϑ is defined as:

$$\vartheta = \frac{V_{water}}{V_{solids}} \tag{B7}$$

The void ratio e is defined as:

$$e = \frac{V_{pores}}{V_{solids}} \tag{B8}$$

Relations between θ, ε, ϑ and e are derived by rewriting Eq. (B7) as $V_{water} = \vartheta V_{solids}$ and Eq. (B8) as $V_{pores} = e\ V_{solids}$. Eq. (B3) gives $\theta = (\vartheta\ V_{solids})/V = (\vartheta\ V_{solids})/(V_{solids} + V_{pores}) = (\vartheta\ V_{solids})/(V_{solids} + e\ V_{solids})$, which results in:

$$\theta = \frac{\vartheta}{1 + e} \tag{B9}$$

Furthermore Eq. (B4) gives $\varepsilon = (e\ V_{solids})/V = (e\ V_{solids})/(V_{solids} + V_{pores}) = (e\ V_{solids})/(V_{solids} + e\ V_{solids})$, which results in:

$$\varepsilon = \frac{e}{1 + e} \tag{B10}$$

Combining Eqs. (B6) and (B10) results in $e/(1 + e) = 1 - ({}^b\rho_d/\rho_s)$ which can be converted into:

$$e = \frac{\rho_s}{{}^b\rho_d} - 1 \tag{B11}$$

For example, when in Figure 1 $V_{solids} = 0.5\ m^3$, $V_{pores} = 0.5\ m^3$, $V_{water} = 0.3\ m^3$ and $\rho_s = 2680\ kg.m^{-3}$, then:

$\theta = 0.3$
$\varepsilon = 0.5$
$\vartheta = 0.6$
$e = 1.0$
${}^b\rho_d = 1340\ kg.m^{-3}$

CURRICULUM VITAE

Jozefus Johannes Bernardus Bronswijk werd op 17 juli 1959 geboren te Delden. Na het behalen van zijn Atheneum diploma aan het Twickel College te Hengelo (O), begon hij in 1977 met zijn studie aan de Landbouwhogeschool te Wageningen. In 1980 behaalde hij het kandidaatsdiploma van de studierichting Bodemkunde en Bemestingsleer. Zijn praktijktijd van 6 maanden bracht hij in Canberra, Australië, door. Bij de "CSIRO Division of Forest Research" en de "CSIRO Division of Environmental Mechanics", verrichtte hij onderzoek naar de hydrologie van bossen en naar infiltratie van water in gronden met macroporiën.

In mei 1984 rondde hij zijn studie af met als doctoraalvakken Bodemfysica, Agrohydrologie, Tropische bodemkunde en Wiskunde.

Dezelfde maand trad hij in dienst bij het Instituut voor Cultuurtechniek en Waterhuishouding (ICW), waar hij onderzoek startte naar fysische processen in zwellende en krimpende kleigronden. In die periode zijn de experimenten uitgevoerd waarvan in dit proefschrift verslag wordt gedaan.

Bij het opgaan van het ICW in het Staring Centrum werd hij hoofd van de afdeling Bodemfysische Transportverschijnselen. In die functie verricht hij tegenwoordig onderzoek naar preferente stroming van water en stoffen in de bodem en naar fysische en chemische processen in tropische kattekleigronden, waarbij de ontwikkeling en toepassing van computersimulatiemodellen een grote rol speelt.