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A soil technological study on effectuating and maintaining adequate playing conditions of grass sports fields

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Abstract

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Playing conditions of grass sports fields have been studied focusing on top layer soil strength meeting the requirements of usage. In a field investigation a reproducible soil strength criterion was found from firmness appraisals and simultaneous measurements of soil strength. From relationships between soil strength and soil water pressure head for differently composed and compacted sandy top layers, pressure head and bulk density values were derived that limit playing conditions. The incompatibility between top layer compaction required for adequate playing conditions and grass viability has been examined. The oxygen status of grass sports field soils was compared with oxygen diffusion rates and concentrations mentioned in literature to limit grass growth. To interpret the field measurements, oxygen distributions at different oxygen consumption rates for various combinations of top layer and subsoil as well as for different rooting depths were calculated. From laboratory investigations detailed information was obtained about compaction susceptibility of differently composed and wetted sands and about the contribution of texture, organic matter, pressure head, bulk density and grass roots to soil strength. To find out best top layer–subsoil–drainage combinations, model research was done. Taking steady-state conditions for soil water flow, the top layer thicknesses required to prevent ponding on differently permeable subsoils were derived. To illustrate the effects of type of top layer, subsoil and drainage on soil water conditions in the top layer, pressure head profiles have been calculated. The same effects have been studied by using an electronic analog that simulates the non-steady-state flow of water in soil. From the simulated course of the pressure head in the top layer, duration and frequency of inadequate playing conditions have been established with the aid of pressure head and density limits obtained from the field and laboratory measurements. Finally, a number of conclusions and recommendations to effectuate and maintain adequate playing conditions of grass sports fields are given.

Free descriptors: construction, maintenance, soil physical properties, drainage, electronic analog, grass viability

Preface

The research described in this book could not have been completed without the assistance of many persons.

In the first place I would like to express my gratitude to prof. dr. R. H. A. van Duin for the fruitful discussions and his valuable remarks on the subject.

I am also indebted to ir. G. A. Oosterbaan, Director of the Institute for Land and Water Management Research (ICW) and to dr. C. van den Berg, former Director of the Institute, for the opportunity to work freely on the here presented research.

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Great personal appreciation goes to my wife Annet. Her encouragements, affectionate tolerance for my absent-mindedness and her capable family management optimized my condition to play this match. Cees, Joris and Matthijs, you missed our daily game of rough-and-tumble during the final stage of the study. I promise you that from now on I will cease to measure soil strength only.

Contents

List of used symbols

Some incidental symbols are defined in the text only. Some symbols are also used for any given constant.

Symbol	Interpretation	Dimension
A	Drain intensity	t^{-1}
C	Concentration of soil gas (volume per volume)	—
c'	Soil cohesion	$M \cdot L^{-1} \cdot t^{-2}$
D, D_a	Diffusion coefficient in soil respectively air	$L^2 \cdot t^{-1}$
D_h	Thickness of aquifer between drain level and impervious base	L
d	Thickness of so-called equivalent layer	L
F	Gas flux in the soil	$L \cdot t^{-1}$
g	Acceleration due to gravity ($g = 9.813\ m \cdot s^{-2}$)	$L \cdot t^{-2}$
H	Hydraulic head	L
h_m	Hydraulic head at phreatic level midway between the drains	L
h_0	Hydraulic head at the open water level in the drains	L
h_{hor}, h_{rad}, h_{vert}	Hydraulic head for horizontal, radial respectively vertical flow	L
I	Amount of infiltration	L
i	Rate of infiltration	$L \cdot t^{-1}$
k	Hydraulic conductivity	$L \cdot t^{-1}$
k_0	Hydraulic conductivity at $\psi = 0$	$L \cdot t^{-1}$
L	Distance between parallel drains	L
m_0	Height of water table midway between the drains	L
P	Amount of precipitation	L
R_{hor}, R_{rad}, R_{vert}	Resistance to horizontal, radial respectively vertical flow	t
r	Radius of the cylinder sheared by blades of vane shear apparatus	L
S	Amount of precipitation to be stored in top layer	L
S_R	Degree of saturation (volume per volume)	—
S_v	Vane shear strength	$M \cdot L^{-1} \cdot t^{-2}$
T	Torque applied to vane apparatus	$M \cdot L^2 \cdot t^{-2}$
t	Time	t

Symbol	Interpretation	Dimension
u	Height of the cylinder sheared by blades of vane shear apparatus	L
v	Flux of soil water; drain discharge rate	$L \cdot t^{-1}$
z	Vertical distance from reference level as indicated in text	L
α	Soil constant: exponent of $k(\psi)$ relationship	L^{-1}
β	Volume of oxygen consumption per unit volume of soil per unit time	t^{-1}
ε	Total volume of pores per unit volume of soil in bulk	—
ε_g	Volume of air-filled pores per unit volume of soil in bulk	—
θ	Volume of water per unit volume of soil in bulk	—
ρ, ρ_w	Bulk density of soil resp. water	$M \cdot L^{-3}$
ρ'	Relative density of soil	—
σ, σ'	Total respectively effective stress	$M \cdot L^{-1} \cdot t^{-2}$
τ	Soil shear strength	$M \cdot L^{-1} \cdot t^{-2}$
ϕ'	Angle of shear resistance	—
χ	Area fraction over which ψ contributes to σ'	—
Ψ_{mass}	Total water potential expressed as energy per unit mass	$L^2 \cdot t^{-2}$
Ψ_{weight}	Total water potential expressed as energy per unit weight	L
ψ	Soil water pressure head	L

1 Introduction

1.1 General

The playing condition of a grass sports field depends on many characteristics. The most significant prerequisite is a smooth, stiff, resilient but sufficiently firm turf, free from ponding. Here turf is defined according to Beard (1973) as: a covering of grass vegetation plus the matted, upper stratum of soil filled with roots and/or rhizomes. The term sward is used for the above-ground parts of the grass cover, while grass is used to indicate the entire grass plant.

The main factors determining the playing condition requirements are:

- intensity and type of use (degree of treading intensity, type of sports shoes, nature of actions as scuffing, turning or stopping, size of the ball, etc.);
- frequency of use (number of matches per weekend or per day);
- weather conditions (summer or winter use).

In the case of ball sports such as soccer and field hockey the smoothness and resilience of the turf must be such that trueness and distance of ball roll and ball bounce is not influenced negatively. The use of a small ball (e.g. hockey) sets other requirements at smoothness of the surface and cutting height of the grass than that of larger balls. At the same time the turf must have sufficient bearing capacity. It then can take up the forces exerted, without deformation to the extent that playing is adversily affected and a repair of the playing surface therefore becomes necessary.

To fulfill the required playing conditions, the combined influence of both grass and soil component must be considered. The role of grass with regard to the playing conditions mainly is a functional one. It reinforces the soil, it contributes to the surface resilience and prevents direct contact between sport practiser and soil surface.

In this study playing conditions are considered to be adequate when the top layer maintains the mentioned prerequisites at the weather conditions, playing frequency and intensity pertaining to the usage intended.

During the last decades in the Netherlands the number of practisers of outdoor sports as well as sports fields is strongly increasing (see Table 1). There are a number of reasons for this development such as growth of the population, increase in income, in leasure time, in mobility, compensation for the little physical exercise during work and revaluation of sports in general.

To quantify the demand in number of sports fields within a certain region one first has to know the population figure and the participation rate in different kinds

Table 1. Number of organized practisers and available grass fields for some main outdoor sports in the Netherlands (derived from NSF, 1975; CBS, 1971, 1976)

	Number of practisers			Number of fields		
	1963	1969	1975	1963	1970	1975
Soccer	487 515	618 850	900 000	4 543	6 293	8 076
Korfball	40 853	56 170	74 477	563	715	844
Hockey	35 142	46 090	66 884	468	673	879
Handball	37 566	51 515	72 327	211	397	681

of sports for various groups of the population, subdivided by age and sex. Other important factors are the number of players per team, the permissible number of matches per field, per weekend or per day and the number of home-matches played (Van Duin, 1971; Rosenboom, 1977). The spatial demand for sports fields is inversely proportional to the number of matches, possible with respect to the available time, which can be permitted while maintaining adequate playing conditions. When the playing conditions are poor, matches frequently have to be cancelled. Then more fields are required to realize a competition programme.

Because of the growing demand, an increasing spatial claim in a densely populated country as the Netherlands and the generally high construction and maintenance costs of grass sports fields, it is worthwhile to try to improve the playing conditions by means of a well-thought-out construction and maintenance. The objective of this study is to contribute to the knowledge of soil physical properties and processes responsible for the playing conditions of grass sports fields and to improve their construction and maintenance.

1.2 Earlier investigations

1.2.1 Design criteria and construction methods

Design criteria for sports fields should be directives or standards set by the intended form of usage. Design criteria found in literature about top layers of fields for outdoor sports all refer to sandy soils or soils amended with sand, other coarse textured materials and peat. The hydraulic conductivity is the characteristic of these materials mainly considered (Table 2). Most of these standards are derived from prospective rainfall amounts or application rates of surface irrigation. They are often used as a standard to test the suitability of sands, or soils amended with all kinds of anorganic or organic materials for top layer or root zone construction.

Apart from setting a quantitative standard for the hydraulic conductivity, the acquiring of a sufficient permeability is often indirectly pursued by prescription of a particle size distribution or distribution area (Fig. 1) and a maximal organic matter content (see Table 3). When a particle size distribution area is prescribed,

Table 2. Minimal requirements of hydraulic conductivity of top layers or root zone materials of sports fields, as proposed in various countries

Country	Hydraulic conductivity ($cm \cdot d^{-1}$)	Author
Denmark	24–48	Petersen (1974)
German Federal Republic	130	Deutscher Normenausschuss (1974)
The Netherlands	60	Stuurman (1970)
Great Britain	240	Adams et al. (1971)
United States of America	60	Schwartz & Kardos (1963)
		Beard (1973)
		Waddington et al. (1974)
	120	Bingaham & Kohnke (1970)
	120–240	Daniel et al. (1974)
	408	Brown & Duble (1975)

it is stated that the particle size distribution curve of the material applied must have a shape corresponding with and lying between the boundary curves. The figure shows little similarity in the coarseness of the root zone material as given by the US Golf Association Green Section (Radko, 1974), Deutscher Normenausschuss (1974) and Working group (1970). This difference in root zone materials indicates a different elaboration by various authors of hydraulic conductivity requirements.

In literature the requirements of hydraulic conductivity and particle size dis-

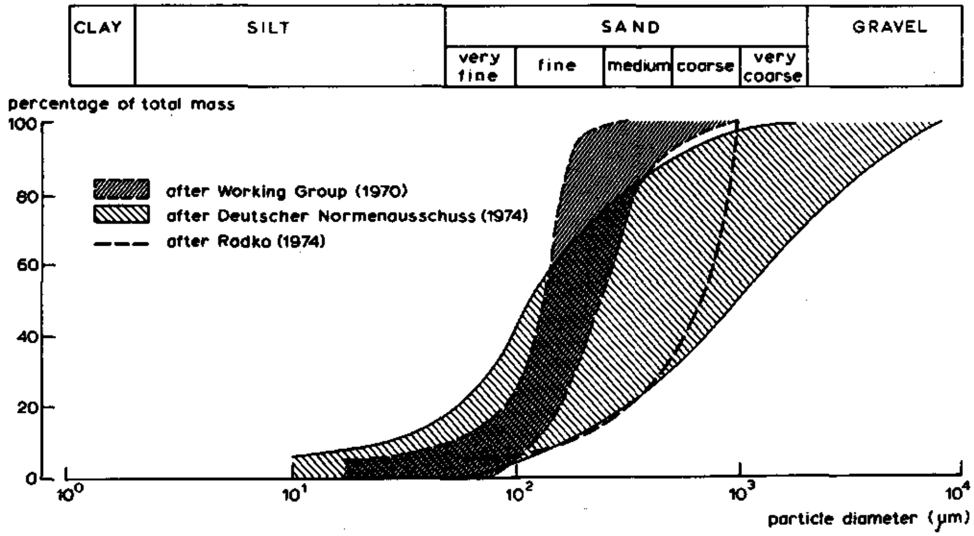


Fig. 1. Particle size distribution areas for root zone materials (texture nomenclature according to Soil survey staff, 1975).

Table 3. Requirements of particle size distribution, median particle diameter (M50) and organic matter content of top layer or root zone materials.

Author	Particle size distribution
Working Group (1970)	$130 < M50 < 230\ \mu m$
	$<10\%$ of the particles $<20\ \mu m$
	organic matter content 2–5%
Bingaham & Kohnke (1970)	$200 < M50 < 400\ \mu m$
Adams et al. (1971)	$100 < 90\%$ of the particles $<600\ \mu m$
Radko (1974)	100% of the particles $<1000\ \mu m$
	35% of the particles $<500\ \mu m$
	15% of the particles $<250\ \mu m$
	5% of the particles $<60\ \mu m$
Deutscher Normenausschuss (1974)	$200 <$ high particle content $<600\ \mu m$
	$60 <$ high particle content $<200\ \mu m$
	8% of the particles $<20\ \mu m$
	organic matter content $<4\%$
Petersen (1974)	80–85% of the particles $>50\ \mu m$
	12–15% of the particles $<20\ \mu m$
	organic matter content $<5\%$

tribution are sometimes supplemented by qualifications of factors as total porosity, air porosity and water holding capacity (Table 4).

The design criteria mentioned in the Tables 2, 3 and 4 all refer to the top layer or root zone. Qualifications of the subsoil are very scanty. Deutscher Normenausschuss (1974) judges the drainage of a subsoil inadequate when the hydraulic conductivity is less than $0.001\ cm \cdot s^{-1}$, i.e. $86.4\ cm \cdot d^{-1}$. In this case a coarse textured drainage layer must be constructed between top layer and subsoil. When a drainage layer is constructed, an additional subsurface drainage system is considered to be necessary when groundwater tables higher than 70 cm below the surface occur. When a drainage layer is not necessary, a drainage system must be installed if the phreatic surface regularly rises above 85 cm below the surface. Beard (1973) judges a drainage system to be needed if the groundwater table

Table 4. Requirements of total pore volume (ε), air-filled pore volume (ε_g) and water availability (θ_a) of top layer or root zone materials.

Author	ε ($cm^3 \cdot cm^{-3}$)	ε_g ($cm^3 \cdot cm^{-3}$)	θ_a ($cm^3 \cdot cm^{-3}$)
Bingaham & Kohnke (1970)	>0.30	>0.10	>0.15
Beard (1973)	0.35–0.40		
Gandert (1973)	>0.50	>0.20	0.30–0.40
Daniel et al. (1974)		>0.10	0.15–0.30
Petersen (1974)	>0.50	>0.15	
Radko (1974)	0.40–0.55	>0.15	>0.20
Skirde (1974)			0.35–0.40

reaches above 120 cm below the surface. In the Netherlands, natural drainage of a grass sports field soil is considered to be insufficient if the groundwater level regularly rises above 50 cm below the surface. The drainage system installed in that case must satisfy a discharge of 1.5 cm · d^{-1} with a groundwater table at 50 cm below the surface.

The design criteria summarized in this section show partly similarities, partly large differences. Differences in design criteria will reflect differences in construction. A number of constructions as proposed in literature are schematically given in Fig. 2. They roughly vary between a subsoil simply covered by a thin sandy top layer and sophisticated constructions where soil water conditions are highly controlled (Beard, 1973; Daniel, 1969; Daniel et al., 1974; Deutscher Normenausschuss, 1974; Langvad, 1968; Moesch, 1975).

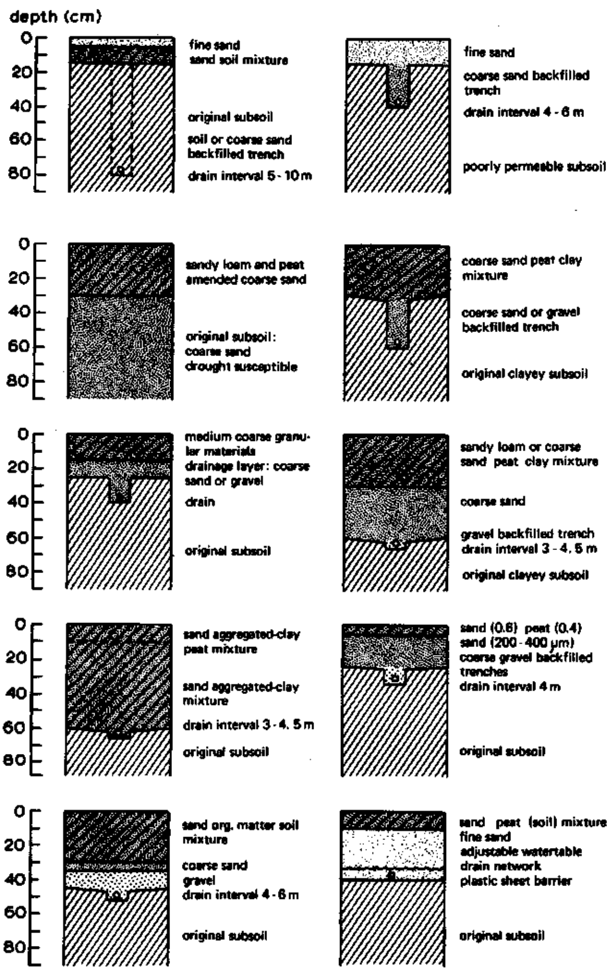


Fig. 2. Schematic representation of grass sports field constructions as given in literature.

1.2.2 *Comments*

When formulating standards it must be brought to mind that a strong generalization of standards increase the probability of deviations from the result desired. Against an overall application of standards it can be argued that usage of sports fields can widely differ with regard to place (climate, soil conditions), frequency, intensity and type of use.

Most of the standards mentioned in literature are empirically derived and show little theoretical or experimental background. Experiments on transferability of standards to actual field conditions scarcely are found. A number of standards create the impression of high security. Over-dimensioning of standards, however, has the disadvantage that many soils in natural state do not satisfy the standards prescribed. This may lead to expensive soil modifications or to every kind of artificial soil mixtures.

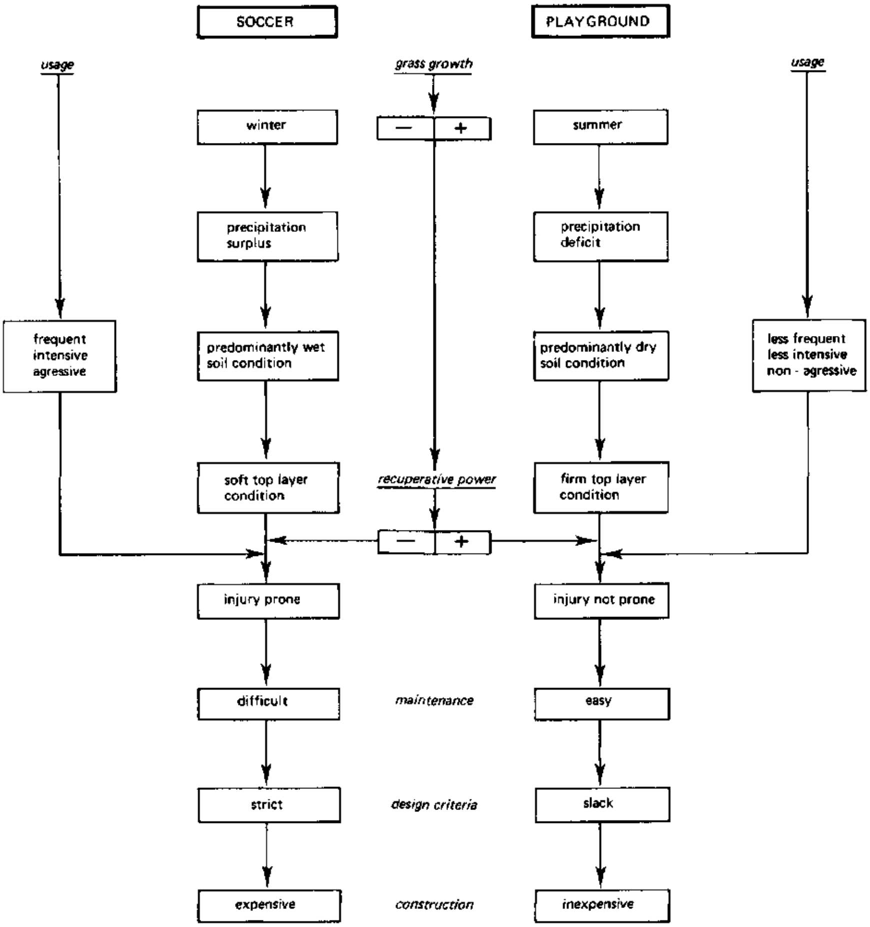


Fig. 3. Factors influencing the possibilities for use, grass growth, maintenance and construction of a soccer field respectively playground turf.

Once it is agreed that the use of grass sports fields requires a resilient but sufficiently firm surface which in spite of compacting actions maintains an adequate permeability and viability of the turf, then the main characteristics of the top layer to which attention must be paid are: soil strength, soil water characteristic, hydraulic conductivity, and gas diffusion coefficient. Most of the existing standards as a particular grain size distribution, permissible portion of some granular fractions or organic matter content are indirect measures only.

When studying design criteria it is better to start from the functional purpose of grass sports fields. Differences in type, intensity and frequency of use and in prevailing weather conditions must lead to differences in design criteria, construction methods and maintenance. An example is given in Fig. 3, where the conditions and consequences of the use of a turf for playing soccer is compared with its use as a playground. Both types of use differ widely with respect to the attack on the turf (soccer use with and playground use without studded boots) and the weather conditions during the main period of use. In the Netherlands the playing season of soccer mainly coincides with a period of precipitation surplus (winter) and of playgrounds with a period of a precipitation deficit (summer). When aiming at favourable playing conditions also when weather conditions are poor, a sufficient bearing capacity of the top layer is essential (see also Boekel, 1972; 1979). Improvement of the bearing capacity is, however, limited by the growth conditions of the grass and the hydraulic conductivity of the top layer. Bearing capacity results from a combination of soil physical factors and processes and the reinforcing action of roots. If the bearing capacity meets the usage requirements, the top layer will hardly deform and the turf will remain smooth, stiff and firm. Therefore this study is primarily dealing with the bearing capacity of grass sports fields.

1.3 Scope of present investigations

In this study grass sports fields to be used for soccer are considered. Soccer has been chosen not only because it is the most popular sport in the Netherlands (Table 1), but also because it is the most aggressive type of usage of a sports field. Moreover the playing season coincides mainly with wet soil conditions in autumn and winter. This provides the opportunity to study the significance of bearing capacity under extreme circumstances.

In the Netherlands most sports fields used for outdoor sports are grass covered. From the number of competition fields for the sports mentioned in Table 1, 96% consists of natural turf. For fields used for training this amounts to 76% (CBS, 1976). Apart from hard topped fields, mostly used for training, in recent years also some fields are constructed with an artificial turf. Such fields have a number of advantages, such as higher speed and precision of play, and the possibility to play frequently because of its high resistance to tear and wear and its independency of the weather. Disadvantages of artificial turf are the very high construction costs, a friction and resiliency differing too much from natural turf and the likelihood of injury to players (Kocher, 1976). Therefore for soccer competition purposes artificial turf cannot yet be considered as an equivalent alternative to natural turf.

Investigations on the bearing capacity of agricultural grassland in the Netherlands in connection with the sensibility for trampling of the sod by cattle have been carried out by means of penetrometers (Wind & Schothorst, 1964). Because of the totally different way of usage and weather conditions during the playing season of most field sports, the standards for the penetration resistance and groundwater table depth valid for natural grasslands do not apply to grass sports fields, however.

To some of the aspects of the investigations reported in this study attention has been paid by Van Wijk (1973, 1980); Van Wijk & Beuving (1975a, 1975b, 1978); Van Wijk et al. (1977). The present study offers an integrated soil physical – soil mechanical – hydrological approach to evaluate playing conditions of grass sports fields, and it is intended to contribute to theory and practice of construction and maintenance of these fields. The research described here is divided into three parts:

- an inventorizing part based on field data;
- an analysing part based on laboratory measurements;
- an analysing and generalizing part based on model research.

The procedure of investigation and presentation is schematically given in Fig. 4.

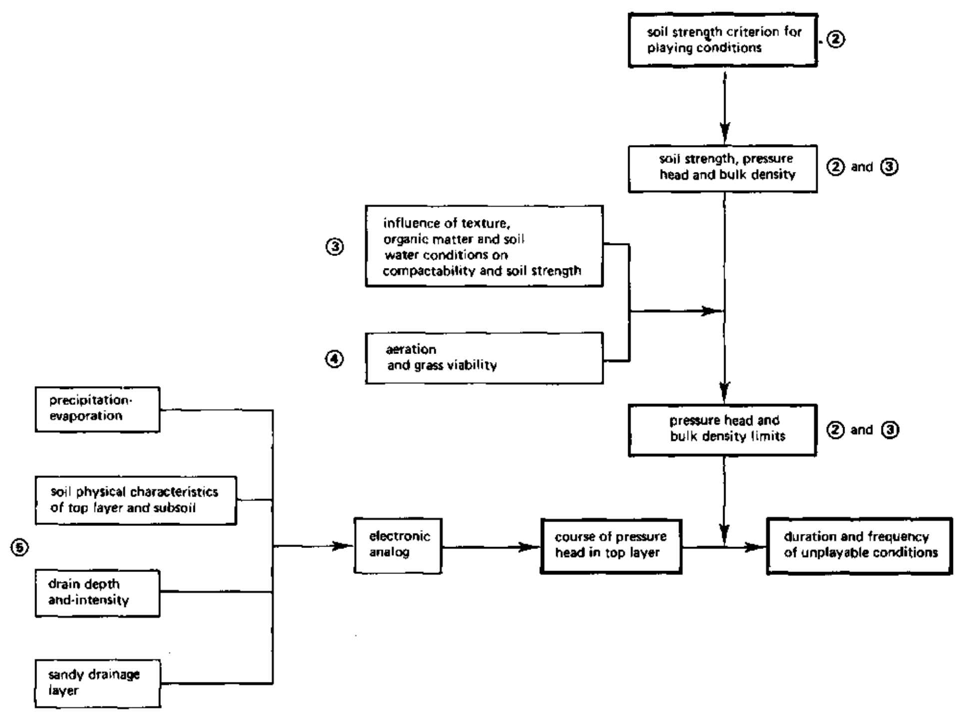


Fig. 4. Scheme of the procedure followed to evaluate, with the aid of basic soil properties, the playing conditions of grass sports fields with different top layer, subsoil and drainage conditions. Encircled numbers refer to the chapters in this study.

Field investigations In first instance an inventory type of investigation was performed on a number of sports fields that differed in top layer, soil profile and water regime. Many sensory firmness appraisals and simultaneous measurements of soil strength, water content, water pressure head and bulk density were conducted to derive a measurable soil strength criterion for adequate playing conditions and to establish the soil physical properties responsible for soil strength, their interrelations and limiting values (Chapter 2).

Additionally it was investigated to what extent the requirements set to the top layer in view of playing conditions and of grass viability are controversial. Information on this point was obtained by comparing the oxygen demands of grass as given in literature with oxygen levels and diffusion rates measured on several established grass sports fields (Chapter 4).

Laboratory research For a better understanding of the field measurements a more thorough examination of compaction behaviour, and the soil strength – soil water pressure head – bulk density relationship of sandy top layer materials was performed. Detailed information was obtained on compaction susceptibility of differently composed sands and on the contribution of texture, organic matter, pressure head, bulk density and grass roots to soil strength. Moreover, pressure head limits for playing conditions as derived from field data could be supplemented and confirmed (Chapter 3).

Model research Its purpose is to supplement and generalize the field and laboratory experiments. An evaluation is given of the effect of organic matter content, compaction and thickness of sandy top layers, type of subsoil and subsurface drainage by means of tubes or a tube drained sandy layer between top layer and subsoil, on the soil water conditions of the top layer. Taking steady-state conditions for the soil water flow the thickness of the top layer required to prevent ponding was estimated. To illustrate the effects of top layer, subsoil and drainage on soil water conditions in both top layer and subsoil, pressure head profiles were calculated. The same effects were studied by using an electronic analog that simulates the non-steady-state flow of water in soil as a combined effect of precipitation, hydrological characteristics of top layer and subsoil and the properties of the drainage system. From the simulated course of the pressure head in the top layer, duration and frequency of inadequate playing conditions then can be derived with the aid of the density and pressure head limits for adequate playing conditions obtained from the field and laboratory measurements (Chapter 5).

In conclusion a number of recommendations for the practice of sports field construction and maintenance, derived from the field, laboratory and model investigations will be given (Chapter 6).

2 Soil physical properties determining playing conditions

2.1 Usage of sports fields

As the soccer competition in the Netherlands takes place from August to May inclusive, the playing season mainly coincides with a period having a precipitation surplus. Fig. 5 shows the yearly variation of precipitation and open water evaporation as monthly averages over 25 years. Only at the end of the playing season evaporation exceeds rainfall. Because of a mean precipitation surplus of about 2 mm · d^{-1} during the winter months, the soil water content of the top layer will predominantly be high. So at certain textures and bulk densities, the top layer will often be soft and slippery, thus reducing playing conditions. When constructing grass sports fields much attention therefore is paid to the texture of the top layer and to controlling the groundwater table depth (see Section 1.2.1). Mainly on basis of experience, standards have been set with regard to particle size distribution and highest acceptable groundwater level. The amount of particles <20 μm may not exceed 10%. The median particle diameter of the sand must be about 200 μm and the organic matter content between 2 and 5%. The groundwater level must not rise above 50 cm below the soil surface. When this occurs, a drainage system must be installed with a discharge capacity of 1.5 cm · d^{-1}.

Nevertheless, in many circumstances adequate playing conditions of grass sports fields constructed in accordance with these standards cannot be guaranteed. Playing conditions, in so far as depending on bearing capacity or soil strength, are not constant but regularly liable to change. Short term changes may occur in

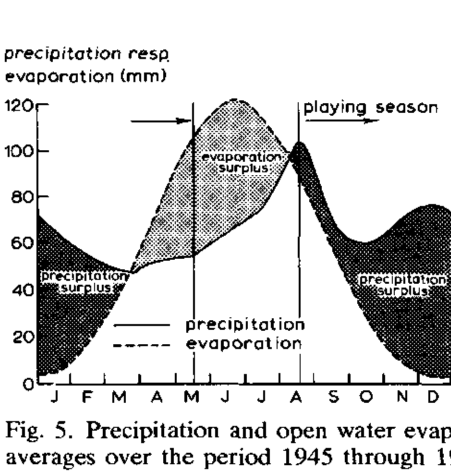


Fig. 5. Precipitation and open water evaporation at De Bilt, the Netherlands, as monthly averages over the period 1945 through 1969 (after Anonymous, 1971).

consequence of changes in water content of the top layer. In the long run accumulation of leaf clippings, thatch formation or earthworm activities may alter the prescribed grain size distribution by enriching the top layer with organic matter and fine particles.

The effect of playing depends, except on the conditions of the top layer, on the nature of actions such as rushing, scuffing, turning, etc. Because the effect of the forces exerted depends on the surface area on which these forces act, the type of sport shoe becomes of major importance. Compared with regular street shoes soccer boots have a very small contact area. They are supplied with studs, which must prevent sliding of the player by their light penetration into the turf. When stationary, a 75 kg heavy man wearing street shoes may exert a vertical pressure in the order of 0.025 to 0.040 MPa. When walking and placing the entire heel down first, this pressure may increase up to 0.12 MPa. For soccer two types of boots are used. The more professional type has six studs of which four are placed at the base of the front part of the boot. A 9.5 (U.K), equivalent to a 11.5 (USA), size boot has studs with a top Ø of 1.25 cm, base Ø of 1.40 cm and height of 1.30 to 1.50 cm. Another type with nine studs of which six at the front of the boot, has studs with a top Ø of 1.30 cm, base Ø of 1.60 to 1.70 and height of 0.95 to 1.00 cm. In standing position a 75 kg player wearing the six-studded boots exerts a pressure of 0.51 MPa and when wearing the nine-studded boots of 0.31 MPa. When walking he puts his weight on the studs at the front of one of his boots and exerts a pressure of 1.53 MPa or 0.94 MPa respectively. When running he may exert a pressure two to three times as large than when standing (Beard, 1973). When running or scrummaging the effective momentary pressure of a soccer player can increase up to about 4.0 MPa (Thornton, 1973).

At these large pressures it seems inevitable that damage to the surface and wear of the sward will occur. The damage to the turf will be the more severe, the more the studs penetrate the surface. This will lead to shearing and disruption of the turf.

2.2 Usage and soil physical properties

Because of playing, compaction of the top layer may occur. The susceptibility for compaction depends on a number of factors, such as soil texture, soil water content, frequency and severity of the pressures applied. In this context Beard (1973) points out the role of the vegetation cover in cushioning the effects of the forces exerted. Soil compaction alters the soil physical properties. Bulk density increases which implies a change of both total pore volume and pore size distribution and at the same time a change of the soil water characteristic, the hydraulic conductivity as well as the oxygen diffusion coefficient.

On the other hand an increase in bulk density also implies a change of the strength properties of the soil. The shear strength of granular soils is highly dependent on its degree of packing. The denser the packing the greater the energy input needed for shear distortion and volume change (Yong & Warkentin, 1975). To estimate at what pressure top layer failure occurs and which exerted pressures still are acceptable, the equation of Coulomb can be applied:

$$\tau = c' + \sigma' \operatorname{tg} \phi' \quad (1)$$

where

τ = soil shear strength (Pa)

c' = cohesion (Pa)

σ' = effective stress (Pa)

ϕ' = the angle of shear resistance (degrees)

According to this equation the resistance of the soil to deformation consists of cohesive and frictional forces. Cohesion represents that portion of soil strength that is not depending on the vertical load. The frictional forces at the interparticle contact areas counteract sliding of the particles. c' and ϕ' are soil constants which are related to texture, organic matter content and bulk density (Smith, 1964) (see also Section 3.4.6). If for various sands with different bulk densities data on c' and ϕ' would be available, it would in principle give the opportunity to forecast top layer deformation from the pressures exerted.

In this study it is attempted to derive the soil strength required for adequate playing conditions by measuring the in situ strength of top layers. Reasons for this are:

- data on c' and ϕ' are not available for top layer materials and conditions usual in the Netherlands. Moreover they only can laboriously be determined;
- the unknown contribution of grass roots to top layer soil strength;
- the experience of Smith (1964) and Green et al. (1964) who found that directly measured soil strength values such as vane shear strength, cone index and triaxial shear strength reflected changes in soil water content and bulk density with better precision than indirectly measured or derived values such as cohesion and angle of shear resistance.

2.3 Fields investigated and methods

2.3.1 *Experimental sites*

Field investigations were performed during the playing seasons from the second half of the winter of 1972–73 up to the playing season of 1975–76 inclusive, in first instance (1972–73 and 1973–74) on seven and later (1974–75 and 1975–76), as a consequence of a more intensified measuring program, mainly on four grass sports fields. The seven grass sports fields, all used for soccer, differ from each other in texture, top layer, profile, drainage and age. On each field three plots were chosen in such a way that three quite different playing intensities were encountered (Fig. 6). In sequence of increased playing intensity the Plots 1, 2 and 3 represent respectively an extensively, a moderate intensively and a very intensively used part of the field. Each field was visited about once in two weeks.

When selecting the fields for investigation it was taken into account that grass sports fields in the Netherlands occur on various profiles and almost all have an artificial sand cover or sand-mixed topsoil. A survey of the profiles of the seven

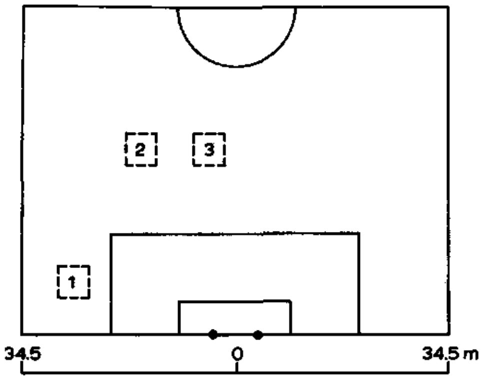


Fig. 6. Location of the 3 plots on half of each of the soccer fields investigated.

fields chosen is given in Fig. 7. Fields A and B both are situated on silty clay loam (creek ridge soils), Fields C and D on heavy clay soils over peat (back-swamp soils), Field E on a humous fine sand, Field F on a humous medium sand and Field G on a fine loamy sand almost without humus.

To characterize the different drainage of the various soil profiles, the highest, lowest and mean groundwater table depth as measured during the period of investigation are given. For Fields B, C and D this period lasted from December

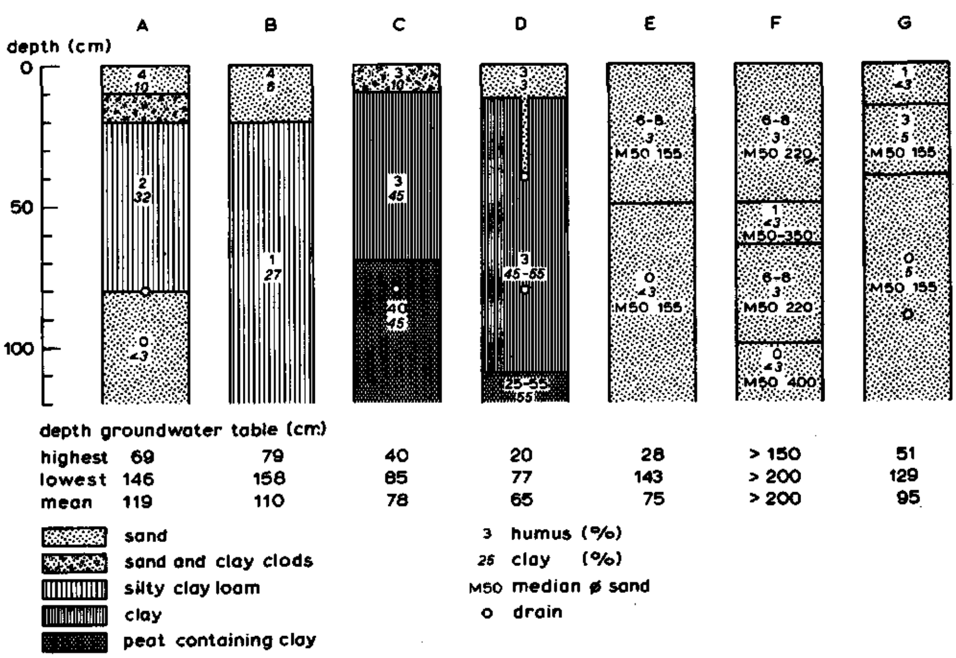


Fig. 7. Profile, texture and groundwater table depth of the 7 selected grass sports fields (for the top layer see Table 5).

1972 to April 1973 inclusive and from October 1973 to April 1974 inclusive. For Fields A, E, F and G the data are pertaining to the periods December 1972 to April 1973 and October to April 1973–74, 1974–75 and 1975–76.

The profiles of Fields A and B can be qualified as being well-drained. The subsurface drain of the profile of Field A seems to be superfluous, because the groundwater table depth very seldomly exceeds the subsurface drain level. Fields C and D are subsurface drained because they are located in areas with high ditch water levels. Field E can be considered as being representative of wet sandy soils, Field F representative of dry sandy soils. The drainage of Field E is intermediate to Fields E and F.

As already mentioned, playing conditions of a grass sports field directly depends on the composition of the top layer. Table 5 shows both the texture and organic matter content of the top layer of the 21 experimental plots at the start of the investigation.

Table 5. Texture, median particle diameter (M50) and organic matter content of the layer 0 to 2.5 cm of the 7 grass sports fields investigated (for the profiles see Fig. 7).

Field	Plot	Texture							M50	Org. m.
		<2 μm	2–16	16–50	50–105	105–150	150–210	>210 μm		(%)
A	1	12.4	8.3	7.9	2.2	3.0	11.1	55.1	306	7.6
	2	8.0	5.7	5.8	3.6	8.4	17.3	51.2	260	6.7
	3	5.9	3.5	4.4	4.7	8.7	15.6	57.2	280	6.1
B	1	5.7	4.9	7.1	10.4	15.5	25.9	30.5	185	5.7
	2	6.5	5.2	7.6	9.1	17.4	23.0	30.2	185	6.1
	3	4.5	3.3	5.8	9.8	24.0	27.0	25.6	171	5.5
C	1	14.3	6.6	3.8	1.6	2.6	7.1	64.0	316	7.7
	2	11.3	5.4	3.8	2.3	4.2	9.1	63.9	315	7.2
	3	10.4	4.7	3.5	2.1	3.8	9.1	66.4	313	7.4
D	1	2.7	1.1	3.0	7.5	19.0	30.4	36.3	170	5.2
	2	3.8	1.4	4.0	8.9	19.1	27.6	35.2	188	5.7
	3	7.9	4.0	4.3	7.9	16.4	24.1	35.4	193	6.4
E	1	2.8	1.4	2.5	14.6	26.7	28.2	23.8	161	8.8
	2	2.5	1.3	2.6	15.0	27.1	27.1	24.4	160	7.8
	3	2.5	1.3	2.7	14.2	25.1	25.0	29.2	168	7.7
F	1	2.8	2.0	3.8	6.8	13.8	19.4	51.4	241	8.8
	2	2.7	1.1	3.3	8.1	20.4	25.0	39.4	193	8.9
	3	2.1	1.4	2.3	9.2	23.4	27.9	33.7	181	7.5
G	1	1.9	0.7	1.8	13.6	31.5	29.0	21.5	156	2.6
	2	1.6	0.5	1.0	11.9	32.7	31.0	21.3	157	2.1
	3	1.5	0.5	1.5	11.3	31.2	31.9	22.1	161	2.1

2.3.2 *Measuring methods*

Simultaneously with sensory appraisals of the condition of the top layer, physical measurements were carried out as well as sward density appraisals.

During the playing season of 1974–75 and 1975–76 these measurements were supplemented on the four Fields A, E, F and G, with additional regular measurements of soil water pressure head along the depth of the profile and of oxygen diffusion rate and oxygen concentration (see Chapter 4). On these four fields from time to time measurements of bulk density of the top layer and observations about rooting depth and intensity were made.

2.3.2.1 Firmness appraisal

To be able to derive a true and reproducible criterion on playing conditions it is necessary to correlate physical measurements with practical appraisals of the actual playing condition. To this end, at the same time and place as the measurements, a sensory firmness appraisal was made to estimate the bearing capacity of the top layer from the penetration depth when kicking a shoe-heel into the turf (Pieters, 1961; Boekel, 1972). For this heel-method a scale was used ranging from 1 to 10. A score of 7 implies that the bearing capacity of the top layer is sufficient to allow intensive playing. At this score just perceptible imprints of the studs are observed on intensively played parts of a field, where the sward is generally thin. Lower scores given to such parts are coupled with increasing deformation of the top layer. Higher scores indicate a decreased grip because of increased hardness of the top layer. These appraisals were carried out in cooperation with professional turfmen and include their experience. Perceptible consequences in the course of time such as changes in smoothness and stiffness also were taken into account.

The disadvantage of the heel-method is that the reliability and reproducibility of the observations depend on the experience of the essayer. Therefore observations have to be carried out by the same person or by a few closely attuned persons.

2.3.2.2 Soil strength

In situ soil strength can be measured in several ways. In the experiments discussed here, two devices were used, a penetrometer and a vane shear apparatus (Fig. 8). The penetrometer applied is a hand-operated static cone type (manufactured by the Goudse Machinefabriek) registering the penetration resistance in $kg \cdot cm^{-2}$ met by the cone when slowly at a constant rate pushed into the top 2 to 3 cm of the soil. The penetration resistance depends on the size and shape of the cone applied (Freitag, 1968). The cone used had an apex angle of 60° and a base of 1 cm^2. The vane shear apparatus consisted of four blades (each 1×4 cm) at 90° intervals around a central shaft. The vane is pushed into the top layer till the upper side of the blades coincide with the soil surface. The torque applied to overcome the soil shear resistance at the surface then is measured. It can be

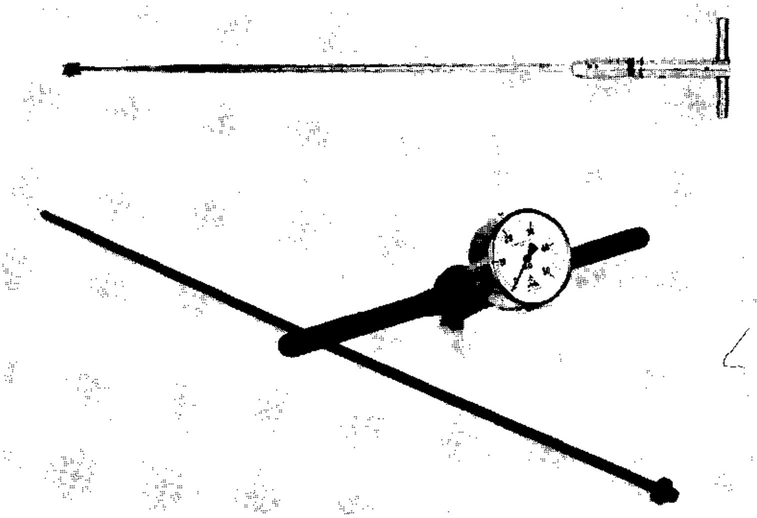


Fig. 8. Vane apparatus and penetrometer used in the field experiments.

converted to shear strength by applying the equation:

$$S_v = \frac{T}{2\pi r^2(u + \frac{1}{3}r)} \qquad (2)$$

where

S_v = vane shear strength (Pa)
T = torque applied (N · m)
r = radius of cylinder sheared (m)
u = height of cylinder sheared (m)

An extensive review on types, application and underlying theory of the penetrometer (especially with regard to the determination of the bearing strength of the soil to support foundations) is presented by Sanglerat (1972). Smith (1964) and Green et al. (1964) give soil strength measurements as obtained with the vane shear apparatus and correlations between vane readings and other soil strength parameters.

It is apparent that penetrometer and vane apparatus do not differentiate between the cohesion and friction component (Eq. (1)). Only in the case of a pure cohesive soil ($\phi' \approx 0$), such as a nearly saturated fine grained soil, or a cohesionless soil ($c' \approx 0$), as pure sand, the measured resistance may be interpreted in terms of a single strength parameter. This will be, however, a rather exceptional situation. Generally the penetration and vane shear resistance will be a composite parameter. Smith (1964) found for fine grained soils a distinct penetration resistance at a number of c' and ϕ' values. For practical application, however, a separation of these strength parameters is not necessary and penetrometer and vane apparatus are therefore convenient tools to evaluate the in situ mechanical strength of soil in a quick and reproducible way (Smith, 1964; Green et al. 1964; Freitag, 1968; Gill, 1968).

2.3.2.3 Bulk density

Data on bulk density of the top layer of the experimental plots were obtained by core sampling. Before sampling the sward was removed. It was performed by means of two stacked steel rings (height 2×2.5 cm, diameter 5 cm) which were separated after sampling to give information on bulk density of the layer 0 to 2.5 and 2.5 to 5.0. On Fields A, E, F and G the sampling was performed five times, on the other fields once only.

2.3.2.4 Soil water conditions

The state of water at a given temperature can be described by the Gibbs' function, often called the water potential, Ψ_{mass}. The water potential is an expression for the work capacity of a unit mass of water as compared to the work capacity of the same mass of pure free water. Pure free water at the same temperature is defined as having a potential of zero. Potentials thus are expressed on a unit mass basis ($J \cdot kg^{-1}$). They can also be expressed as energy per unit weight, Ψ_{weight}. Under the condition that the density of soil water is taken to be $10^3\ kg \cdot m^{-3}$ the relation holds:

$$\Psi_{weight} = \frac{\Psi_{mass}}{g} \quad (m) \tag{3}$$

where
g = the acceleration due to gravity ($m \cdot s^{-2}$)

g varies with the place on earth. In this paper a value $g = 9.813\ m \cdot s^{-2}$ was used. On a weight basis the potential has the dimension of length. Ψ_{weight} includes the matric potential (ψ) due to forces resulting from the attraction of soil matrix and water and the gravitational potential (z) due to the force of gravity. The first usually is measured by tensiometry, the second is the height above some reference level. When only dealing with the sum of matrix and gravitational potential, one usually speaks of the hydraulic head, H. Thus

$$H = \psi + z \quad (m) \tag{4}$$

with ψ now being the soil water pressure head (negative in unsaturated conditions) and z the gravitational head.

In this investigation the soil water pressure head was measured with tensiometers. During the winter of 1972–73 measurements were limited to the upper 3 cm of seven grass sports fields. Later on during the winters of 1974–75 and 1975–76 for Fields A, E, F and G they were extended to depths of 1, 5, 10, 20, 40, 60, 80 and 100 cm. Except for the 1 cm depth, all tensiometer cups were installed permanently. At each measurement these cups were connected to a strain gauge pressure transducer (Bakker, 1978) by means of thin nylon tubes, which were joined in a vertical hollow tube of which the top was buried directly under the turf.

Simultaneously with the pressure head measurements, the soil water content of the top 3 cm was measured gravimetrically. It is expressed as a volume fraction (cm^3 water · cm^{-3} soil).

2.4 Soil strength

2.4.1 Criterion for adequate playing conditions

Fig. 9 gives correlations between soil strength of the top layer characterized by the heel-method and that measured by penetrometer and vane shear apparatus for the 7 fields investigated. At a heel-method value of 7 (required for intensive playing) the penetrometer registers a resistance ranging between 1.2 and 1.4 MPa, for all 7 fields. At the same heel-method value the penetration resistance of sandy top layers on sandy soils tends to be somewhat lower than on clay soils. The vane readings show a lower correlation with the heel-method than the penetrometer readings and more variation at a heel-method value of 7. By the way they are measured, the vane readings are much lower than the penetrometer values.

Because the vane readings were less correlated with the soil strength estimations by means of the heel-method, and the vane apparatus is less easy to handle, the penetrometer is to be preferred for judging playing conditions in the field. The penetrometer resistance of 1.4 MPa will be used in this study as lower limit for the soil strength required for intensive playing of grass sports fields. At this value top layer deformation does not occur on the intensively played parts of the field.

On the non-intensively played parts (Plots 1 and 2) the score obtained with the heel-method was mostly below 7 in the wet season, while the penetration resistances were below 1.4 MPa. Because of the less intensive playing, serious injury to the top layer at these lower bearing capacities does not necessarily need to occur, however. From the data collected on the moderate intensively used parts (Plot 2), it could be derived that serious deformation of the top layer does not occur when the penetration resistance amounts to 1.0 MPa or higher. On the extensively played parts (Plot 1) serious deformation of the top layer was only observed locally in spite of the penetration resistances being often lower than 1.0 MPa. The assessment of a criterion for penetration resistance for extensively played parts therefore is rather difficult. A penetration resistance of 1.0 MPa on parts extensively played still seems to be desirable there too, because the lower the penetration resistance the heavier the playing character of the field.

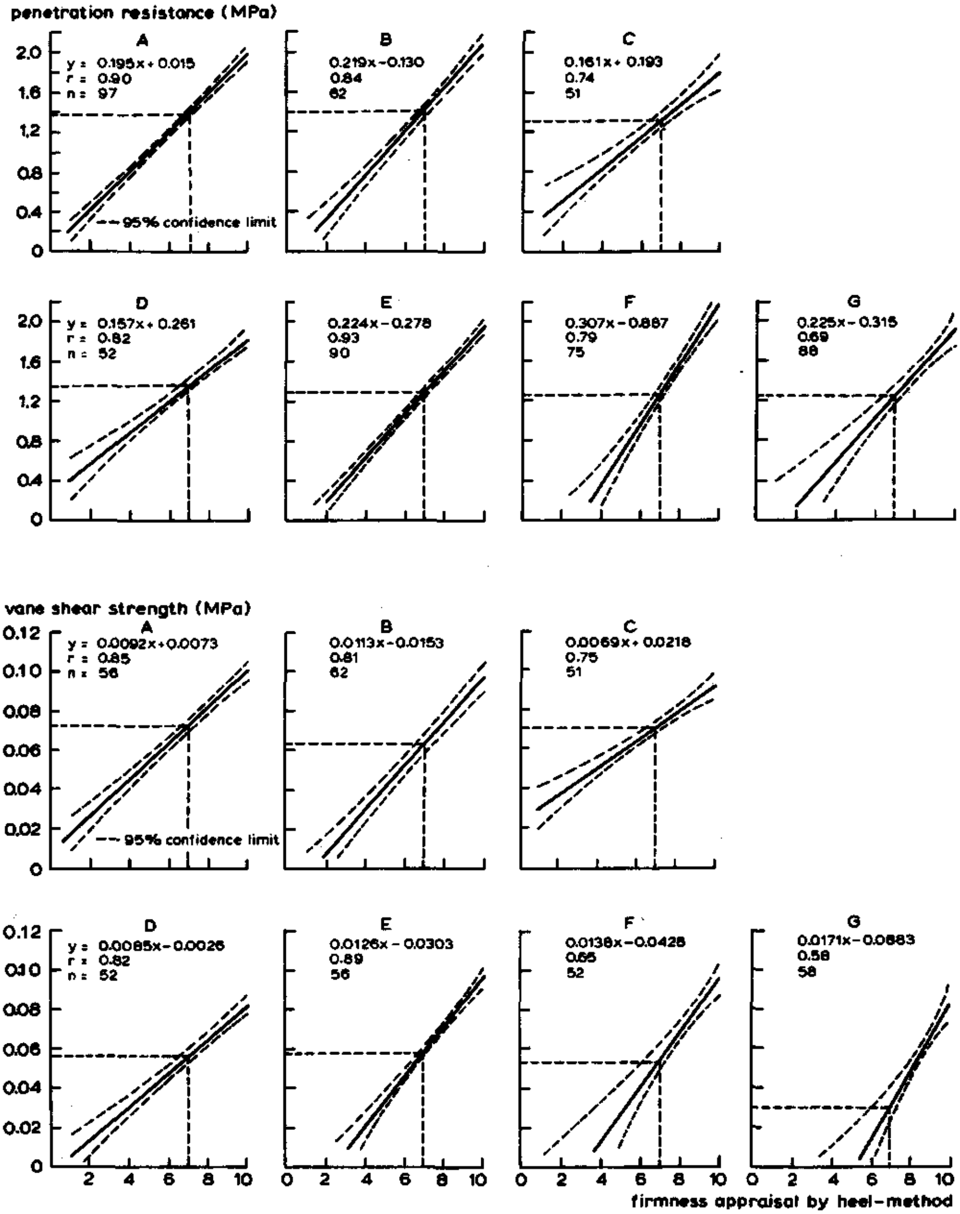


Fig. 9. Soil strength of the upper 2 to 3 cm of the top layer of 7 grass sports fields, as measured by penetrometer (upper part) and vane apparatus (lower part), versus appraisals of the playing conditions by the heel-method. *r*, correlation coefficient; *n*, number of observations. A heel-method value of 7 implies that the soil strength is sufficient for intensive playing.

2.4.2 *Penetration resistance, playing intensity and playing reliability*

When playing intensity is defined as the number of treads during a match on a spot of a sports field, playing intensity is not uniformly distributed over the field. Fig. 10 shows the results of a survey of the penetration resistance as measured on the Fields A and E in winter. Both fields were playable without serious damage being done. Each number on the maps is an average of 10 penetrometer readings, which consist each of 2 groups of 5 data taken around 2 corresponding points on both halves of the field. Isopenetration lines run in a more or less radial pattern from the goal to both sides of the field, i.e. going from the goal to the middle of a soccer field the top layer is compacted over an increasing width around the centre line of the field. This general pattern on soccer fields regularly played is both a result of the way of playing the field, and the maintenance measures taken according to this playing pattern. The more intensively a part of a field is played the more compacted the top layer is and the more attention it is given during maintenance operations. Extensively played sides are less compacted and have a smaller soil strength. The midfield of Field E satisfies the criterion of 1.4 MPa, while the extensively played parts at the sides meet the 1.0 MPa criterion. The sides of Field A, with a higher clay content, show more soft soil conditions.

If the penetration resistance at various parts of the field regularly falls below the critical value, the field can be characterized as being little reliable. A survey of

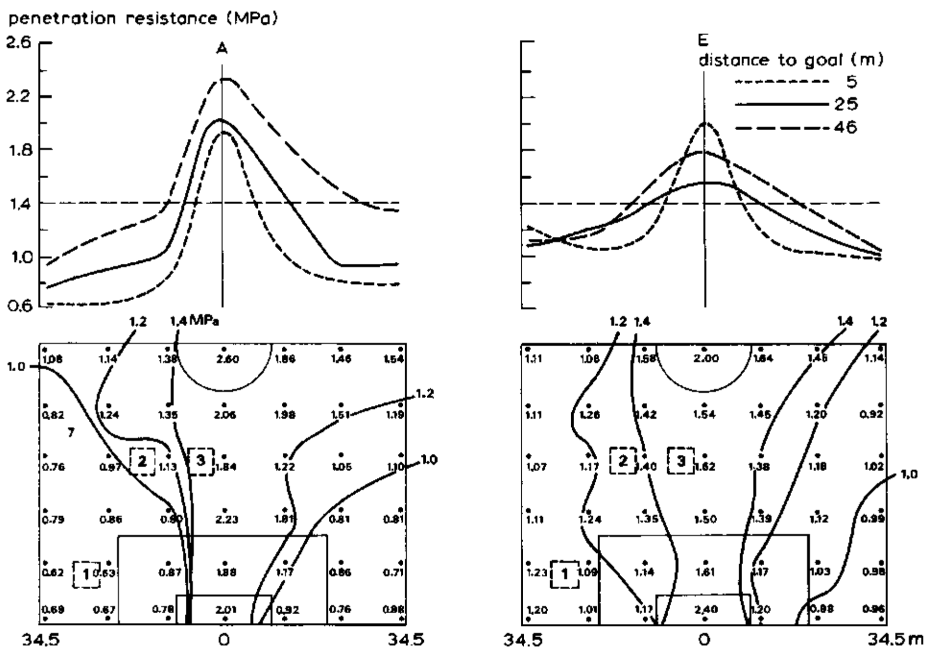
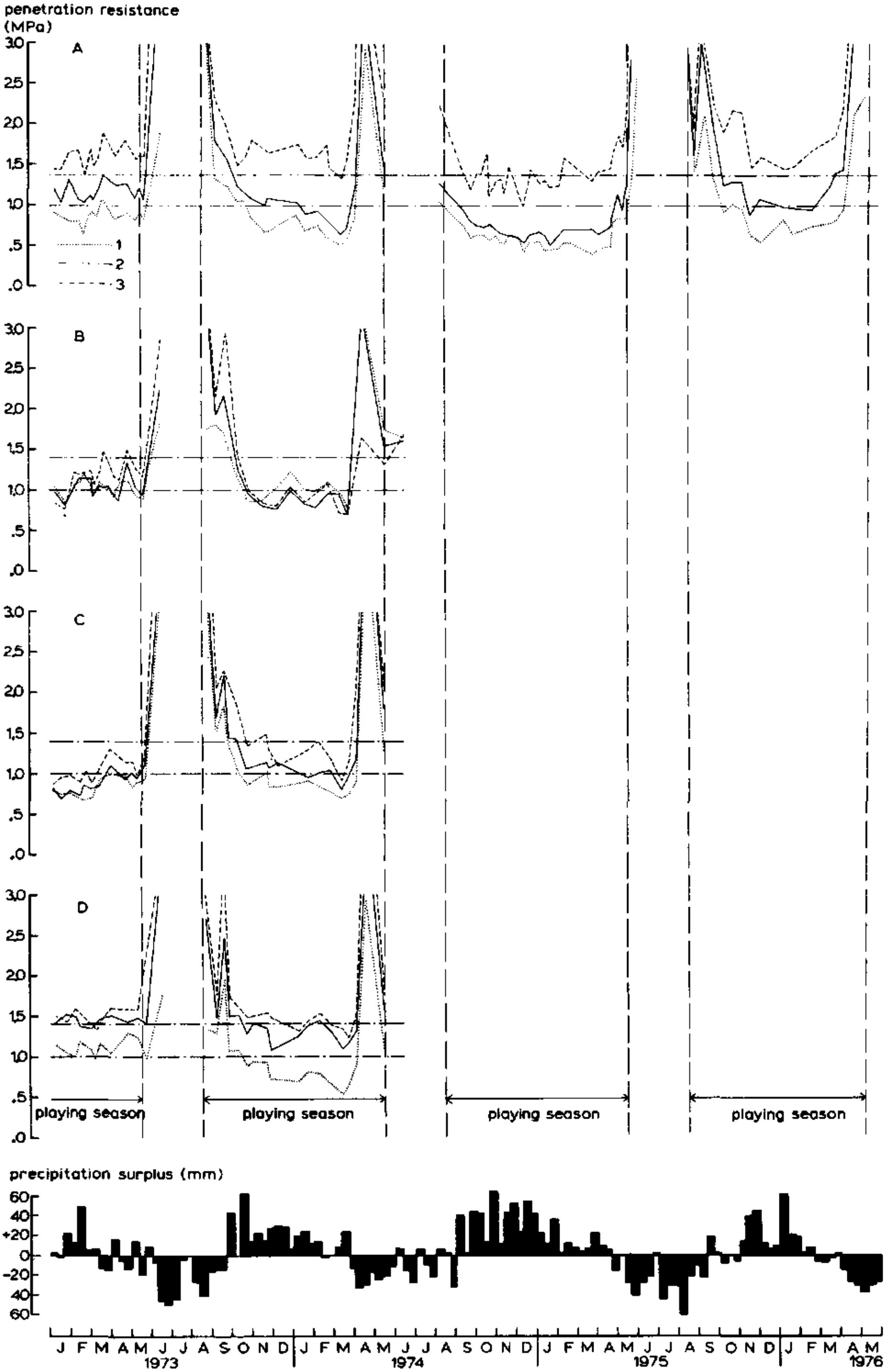


Fig. 10. Distribution of penetration resistance of the upper 2 to 3 cm of the top layer over Fields A, a sand covered clay soil and E, a humous sandy soil, at good playing conditions.

the reliability of the seven grass sports fields is given in Fig. 11. For Fields B, C and D the measured penetration values are plotted for the period January 1973 through April 1974. On the other 4 fields the measurements were taken throughout May 1976. The general course of the three lines shows that soil strength as characterized by the penetration resistance is not constant but varies between large boundaries. From the start of the playing season, in consequence of the precipitation surplus in August/September, the penetration resistances decrease to a low level and fluctuate within a rather narrow range. Then they are close to the limits for adequate playing conditions of 1.4 and 1.0 MPa. A sharp increase in soil strength is not observed before there is an evaporation surplus starting from about mid-March. From Fig. 11 it appears that the largest fluctuations of the penetration resistance, in spring and autumn, closely coincide with the change of precipitation to evaporation surplus or reversely. From a soil technological point of view the figure would point towards the necessity of a better adjustment of the playing season to the weather conditions prevailing in the Netherlands.

In general not only the soil water conditions are determining the soil strength of the top layer, the bulk density is also an important factor. This is demonstrated by the separate and parallel course of the curves of Fig. 11. The parallel sequence of the curves corresponds with differences in bulk densities because of differences in loading. Considered over a long period the bulk density is not a constant at all, but is liable to change. As mentioned earlier both bulk density and soil strength may be reduced by soil loosening activities of earth worms and root growth. This holds especially for the non-playing period in summer and for periods with low playing frequency. Regular playing (if necessary supplemented by dressing with sand and rolling) appears a useful measure to maintain the soil strength above the critical level of 1.4 MPa at the intensively and 1.0 MPa at the moderate intensively played parts. Temporary omittance of playing or temporarily less frequent maintenance of the entire field or some of its parts may reduce both soil strength and reliability. This pertained to Fields A and E during the seasons 1973–74 and 1974–75. Especially during the wet winter 1974–75 unplayable conditions very often were met. Field F is the only field with a high degree of reliability over all the consecutive years. During the first year of observation also Fields A, D and E mostly met the soil strength criteria and were reliable also in the opinion of the managers. Fields B and C were soft almost throughout the entire season and had undesirable underfoot conditions. Injury of the top layer occurred regularly.

The curves of Field E during the first year and of Field G during the consecutive years demonstrate a gradual adaptation of the density of the top layer to playing intensity. In the summer of 1972 the playing on Field E was changed in such a way that extensively played parts were switched with intensively played, compacted, parts. After the change, the smallest penetration values were measured on that part of the field now most intensively played on (Plot 3) but later, in autumn 1973, as is to be expected, the largest values were found there. At Field G, newly constructed at the beginning of the investigations, the curves show a sequence which fits more and more the playing intensity.



penetration resistance (MPa)
A
B
C
D
1
2
3
playing season
playing season
playing season
playing season
precipitation surplus (mm)
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M
1973
1974
1975
1976

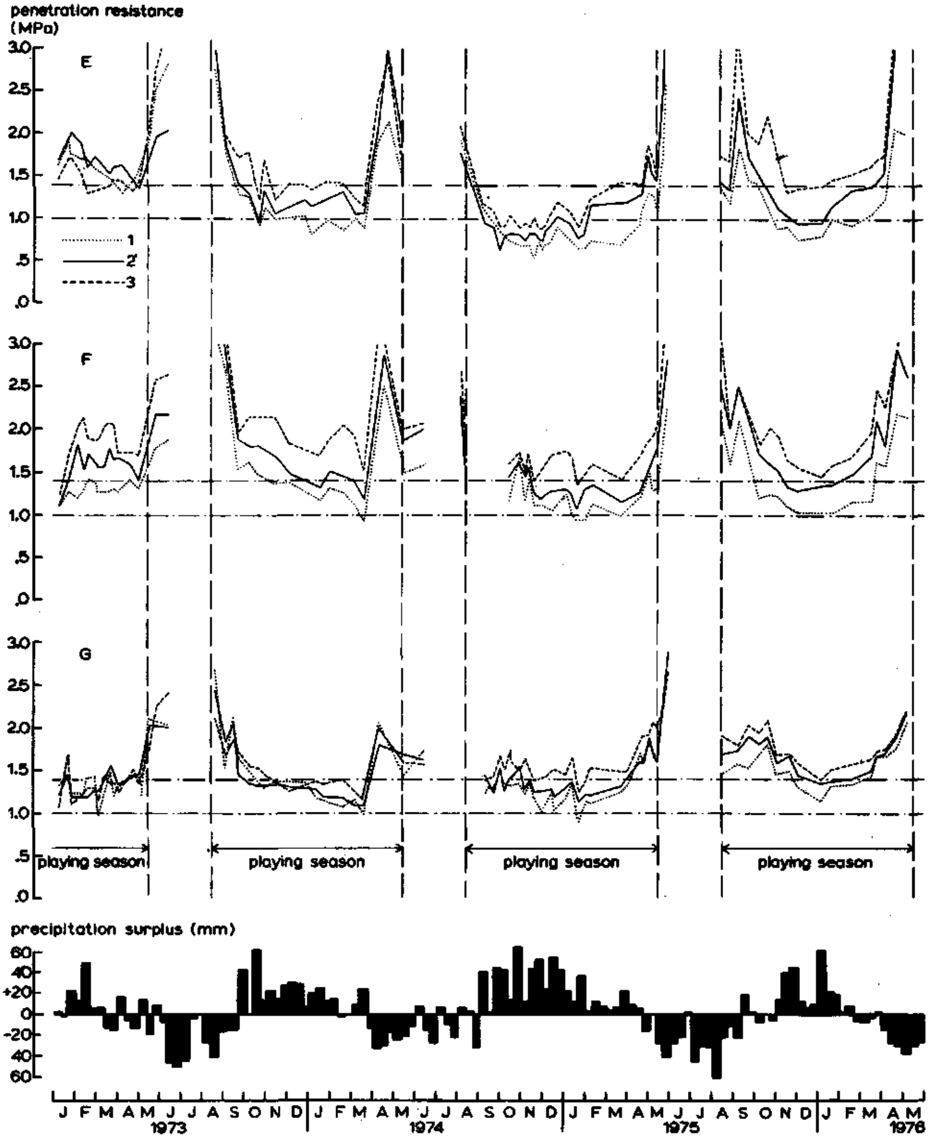


Fig. 11. Course of the penetration resistance of the upper 2 to 3 cm of the top layer at each of the 3 experimental plots of the 7 grass sports fields. Penetration resistances of 1.4 and 1.0 MPa were found to be required for intensive and moderately intensive playing, respectively. Course of the precipitation surplus ($P - E_0$) over the period considered is also given.

2.5 Bulk density

As shown above, the more intensively a part of a field is played, the more compacted the top layer. Table 6 gives a survey of bulk density, pore volume, organic matter content and relative density values of the top layers of the experimental plots on the 7 grass sports fields. The figures for Fields A, E, F and G are averages of 21 data collected on the core sampling dates in October 1973, September 1974, September 1975, January 1976 and March 1976. Those for Fields B, C and D are averages of 3 cores collected in autumn 1973. The values on organic matter were obtained from the soil mass after separation of the root mass by sieving.

Table 6. Bulk density ρ ($g \cdot cm^{-3}$), pore volume ε ($cm^3 \cdot cm^{-3}$), organic matter content (% by weight) and relative density ρ' of the layers 0 to 2.5 and 2.5 to 5.0 cm as measured at each of the experimental plots of the 7 grass sports fields.

Field		Depth					
		0 – 2.5 cm			2.5 – 5.0 cm		
	Plot	1	2	3	1	2	3
A	ρ	1.11	1.32	1.51	1.34	1.40	1.57
	ε	0.559	0.479	0.412	0.471	0.449	0.386
	org. m.	7.5	6.1	5.0	6.4	6.0	5.5
	ρ'	−0.12	0.21	0.52	0.25	0.36	0.68
B	ρ	1.24	1.31	1.40	1.41	1.48	1.55
	ε	0.512	0.486	0.455	0.445	0.410	0.385
	org. m.	6.1	5.7	4.4	5.3	7.0	6.5
	ρ'	0.09	0.16	0.22	0.33	0.61	0.71
C	ρ	1.15	1.33	1.31	1.48	1.57	1.55
	ε	0.536	0.466	0.476	0.418	0.377	0.373
	org. m.	9.3	8.0	7.4	5.3	6.5	9.0
	ρ'	0.04	0.37	0.29	0.48	0.75	0.91
D	ρ	1.13	1.28	1.36	1.50	1.63	1.69
	ε	0.549	0.486	0.454	0.419	0.369	0.337
	org. m.	7.2	8.1	7.9	3.2	3.3	4.9
	ρ'	−0.09	0.26	0.43	0.32	0.64	0.90
E	ρ	1.14	1.25	1.40	1.31	1.40	1.47
	ε	0.544	0.502	0.447	0.477	0.448	0.419
	org. m.	8.3	7.9	6.8	7.9	6.9	6.7
	ρ'	−0.02	0.18	0.43	0.31	0.43	0.55
F	ρ	1.16	1.34	1.45	1.32	1.37	1.50
	ε	0.539	0.471	0.431	0.475	0.456	0.408
	org. m.	7.8	6.2	5.7	7.8	7.8	7.0
	ρ'	0.0	0.25	0.45	0.32	0.42	0.63
G	ρ	1.42	1.47	1.54	1.59	1.64	1.70
	ε	0.453	0.433	0.408	0.392	0.378	0.354
	org. m.	3.7	3.0	3.2	2.2	1.6	1.7
	ρ'	0.19	0.21	0.38	0.42	0.49	0.69

The data show remarkable differences in bulk densities and pore volumes for the 3 plots of each field. These differences must be ascribed to differences in playing intensity. Moreover, during maintenance more attention is usually paid to the intensively used parts; more frequent rolling and a measure as selective dressing with sand result in a higher bulk density. It appeared that on intensively played parts of the fields, the organic matter content of the upper 2.5 cm has a tendency to be lower than elsewhere. This is partly due to selective dressing with sand. Moreover, it may be assumed that the supply to the top layer of organic matter originating from clippings and root production is the lower the more frequently a part of the field is trodden.

When comparing the bulk densities and pore volumes it is to be noted that they are a measure for the degree of compaction only then, when soil materials are considered that have equal organic matter content. For an objective comparison of the degree of compaction of soils differing in organic matter content, the concept of relative density will be used. Then the actual density is considered with respect to the most dense and the most loose packing. On the basis of Fig. 22 (Section 3.3.2), yielding the maximal and minimal bulk density of fine sand, the relative densities of Table 6 have been calculated. A relative density of 0 indicates no compaction and of 1 maximal compaction.

Noteworthy are the differences in relative density between the layers 0 to 2.5 and 2.5 to 5.0 cm. The relative density of the upper layer generally is much lower than of the lower one. Both layers show an increase in relative density with increasing playing intensity. The relative density of the 2.5 to 5.0 cm layer is considerable, especially on the more intensively used plots. The compaction of this layer appears to be more than twice as severe as that of the upper 2.5 cm. The presence of a structured root mass, much more in the upper than in the lower layer (see Table 11, Chapter 4), prevents severe compaction. The very low or even negative density values found on the extensively used sites of the field, emphasize that a dense root structure keeps the density at a level lower than experimentally could be determined from loosely poured air dry sands (see Fig. 22). When the root mass is reduced by an increased playing intensity, the soil becomes more compacted. The fields which have in the long run a penetration resistance predominantly sufficient for intensive use of the midfield (Plot 3), showed a compaction to a relative density of about 0.45 or higher in the upper layer and of more than 0.60 in the lower layer. The relative density of 0.45 for the upper 2.5 cm later will be used as the lower density limit for grass sports fields.

2.6 Soil water conditions

2.6.1 Pressure heads prevailing in the top layer

For the characterization of soil water conditions in situ, soil water pressure head has been preferred above soil water content. This choice has been made because at equal soil water pressure heads the soil water contents measured at the same experimental plot did show a certain variability with time. The main reason for this behaviour are small variations of the bulk density.

Changes of soil water conditions influence soil strength and therefore playing conditions of the top layer. In Fig. 12 the distribution of the penetration resistance across Fields A and E at different soil water pressure heads (ψ) of the top layer is shown for some soil water conditions in spring 1974. The distributions of 28 February pertain to a mean winter situation with ψ-values in the top layer being about −40 and −60 cm. The playing conditions were good on both fields. The distributions measured on 3 and 26 April, after preceding spring periods with an evaporation surplus, show much firmer conditions of the top layer with ψ-values of −200 and −450 cm respectively. After a few days of heavy rain, completely unplayable field conditions were observed on 12 March on Field A and on 21 March on Field E with ψ-values of −15 and −20 cm respectively. Rather small increases in soil water pressure head from −40 and −60 cm to −15 and −20 cm respectively cause a decrease in penetration resistance to such an extent that the field becomes unplayable. This decrease in penetration resistance is most serious on the intensively played mid-fields, where the highest penetration resistances are measured. In wet periods insufficient soil strength conditions occur mostly at the intensively played parts of a field. Other indications about the influence of the soil water conditions on soil strength are the already mentioned

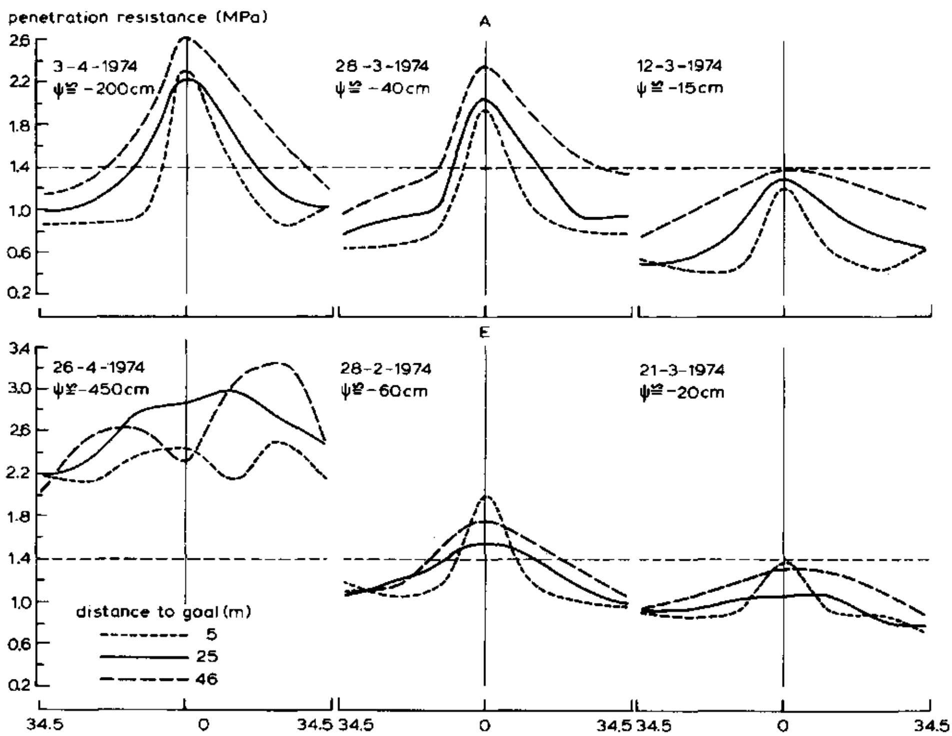


Fig. 12. Distribution of penetration resistances of the upper 2 to 3 cm of the top layer measured across Fields A and E at 3 pressure head (ψ) situations. The criterion for intensive playing, a penetration resistance of 1.4 MPa, is indicated.

sharp increase of the penetration resistance in spring and the decrease in autumn coinciding with the start respectively end of the evaporation surplus (see Fig. 11).

Data on soil water pressure head as measured during the winter 1972–73 on three sand covered clay soils and three sandy soils are presented in Fig. 13. In this figure precipitation surplus per decade and the groundwater table depth characterize the weather circumstances and the drainage. From December to the beginning of March soil water pressure heads remained continuously at a high level. The group of the sand covered clay soils shows somewhat wetter soil water conditions in the top layer than the sandy soils. High pressure heads occur in spite of deep groundwater tables. The equilibrium state between pressure head in the top layer and depth of the groundwater table as sometimes assumed (Boekel, 1979) for periods with zero precipitation and evaporation has not been encountered on the clay soils and some sandy soils, because of the low hydraulic conductivities of these soils. Therefore a highest admissible groundwater table

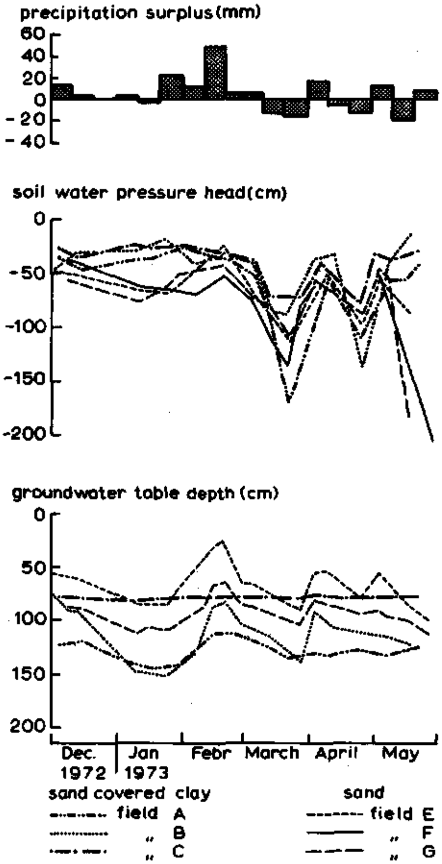


Fig. 13. Precipitation surplus per decade, soil water pressure head in the top layer and groundwater table depth for 6 grass sports fields on clay respectively on sandy soils, during winter and spring of 1972–73.

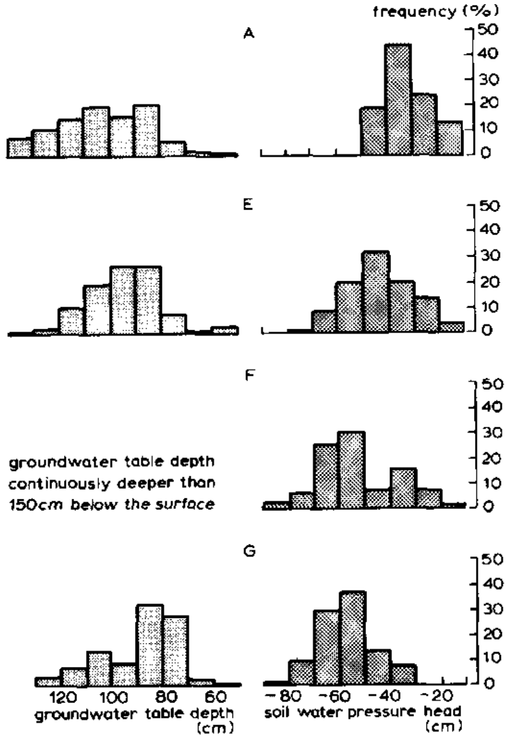


Fig. 14. Frequency of occurrence of pressure heads in the top layer and groundwater table depths of Fields A, E, F and G in periods with a precipitation surplus.

depth as generally used for the design of subsurface drainage of grass sports fields can hardly be a guarantee for dry conditions of the top layer.

A more complete survey of pressure head variations in periods with a precipitation surplus is given in Fig. 14. The frequency diagram is based on all available data on pressure heads in the top layer (about 80 per field), as measured twice a month during the period of investigation. The data originated from one exceptionally wet (1974–75) and two rather dry (1972–73 and 1975–76) winter periods. In spite of rather deep groundwater tables the pressure head in the top layer of Field A (a sand covered clay soil) does not decrease below −50 cm. On the sandy soils of Fields E, F and G the lowest pressure heads are about −70 to −80 cm.

2.6.2 *Pressure head profiles*

The influence of top layer compaction, subsoil and groundwater depth on the soil water conditions of the top layer is clearly reflected in the measured pressure head profiles. Examples of such profiles are given in Fig. 15. Curves 1 and 2 represent a wet situation and Curves 3 a mean winter situation. Curves 4 were measured during a rather dry period on the second day with thaw, following a seven day frost period. Curves 5 show the influence of the evapotranspiration

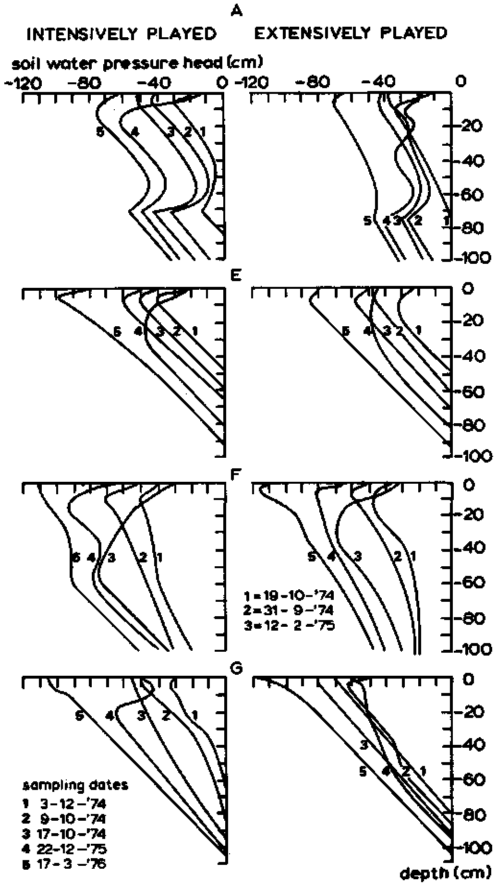


Fig. 15. Pressure head profiles for various soil water conditions of Fields A, E, F and G.

starting in spring.

From in situ measured ψ-profiles qualitative information can be obtained on the direction of flow in and hydraulic conductivity of the various soil layers. For an analysis of the ψ-profiles the Darcy equation for vertical flow of water in soil is used, which reads:

$$v = -k \frac{\partial H}{\partial z} \tag{5}$$

where

v = the volumetric flux ($cm^3 \cdot cm^{-2} \cdot d^{-1}$)

H = the hydraulic head (cm)

z = the vertical coordinate (cm), having its origin at the soil surface and taken positive upwards

Substituting Eq. (4) in Eq. (5) yields:

$$v = -k(\psi)\left(\frac{d\psi}{dz}+1\right) \qquad (6)$$

where
$k(\psi)$ = the hydraulic conductivity ($cm \cdot d^{-1}$) depending on ψ

When $d\psi/dz = -1$, $v = 0$. At values of $d\psi/dz > -1$ respectively < -1 the flow direction is downward respectively upward. The slopes of the ψ-profiles in Fig. 15 are > -1 with exception of the ψ-profiles 5 in some cases. Assuming steady-state conditions, i.e. v = constant, the larger the gradient of ψ over a soil layer, the smaller the hydraulic conductivity and reversely. Noteworthy are the large gradients measured over the upper 10 cm. This implies a high flow resistance in this layer. The highest flow resistance is concentrated in the layer 0 to 5 cm. From this behaviour it may be concluded that the deteriorating effect of playing on the hydraulic conductivity is mainly limited to the upper 10 cm. Therefore maintenance measures, aiming at improvement of top layers compacted by playing should be extended to a depth of at least 10 cm.

With regard to the ψ-profiles in the subsoils (Fig. 15) the high pressure head gradients over the layer 20 to 70 cm of Field A indicate a small hydraulic conductivity of the silty clay loam. This was confirmed by measuring the hydraulic conductivity of this layer, as given in Section 5.2.2. The consequence of the lower conductivity of the silty clay loam is higher pressure heads in the top layer (Fig. 14).

2.6.3 Phase distribution in the top layer

Compaction causes an increase of the portion of fine pores at the expense of pores with a larger diameter. This shift changes the soil water characteristic. Fig. 16 shows the soil water characteristics (ψ-θ relations) of the upper 5 cm of the top layer of the 3 experimental plots of 6 grass sports fields. Core sampling was performed in the spring of 1973. With the aid of the pressure head data of Fig. 14 the distribution of solids, water and air in the upper 5 cm of the top layer of 4 fields is derived from the ψ-θ relations at the mean and lowest (driest) pressure head over the winter period (Table 7). The table shows rather low air contents. The differences in air content between the dense and less compacted plots are rather small. The highest air contents are found on Field G with a sandy top layer low in organic matter with a soil water characteristic showing a sharp decrease in the water content at pressure heads lower (drier) than about −40 cm. With respect to the aeration of the soil this argues for a low organic matter content of the top layer. With regard to stability, however, then also disadvantages appear (see Chapter 3). Loosening of the top layer as sometimes suggested to improve the grass growth conditions (Beard, 1973), does not always improve soil air content (Fig. 17). The three soil water characteristics are from the same plot but sampled at three different dates. In spite of different pore volumes the air contents at equal pressure heads hardly differ because of the similar slopes of the curves.

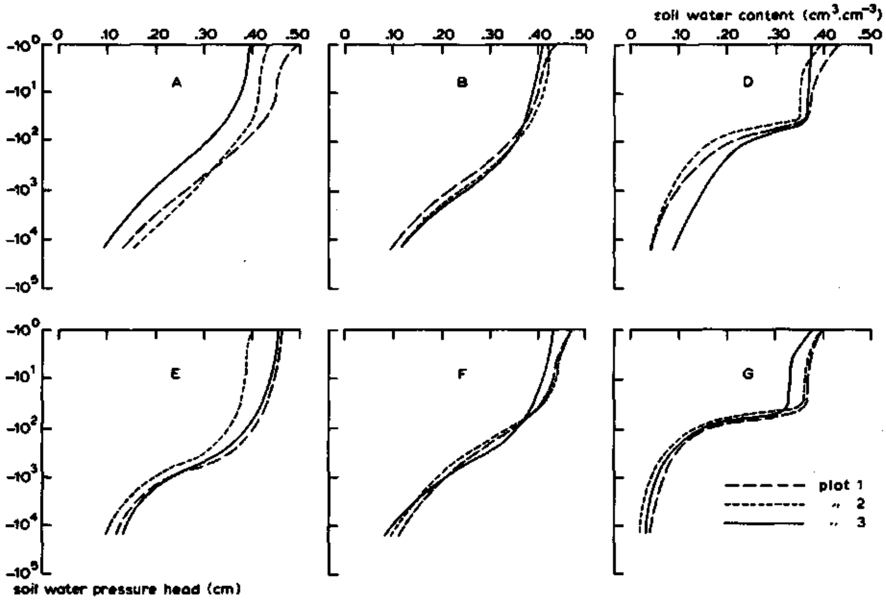


Fig. 16. Soil water characteristics of the top layer of the 3 experimental plots (see Fig. 6) on 6 fields (see also Table 5).

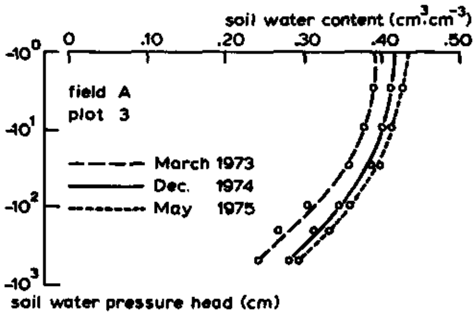


Fig. 17. Soil water characteristics measured on 3 different sampling dates at Plot 3 on Field A.

Table 7. Solids, water and air content ($cm^3 \cdot cm^{-3}$) and saturation degree S_R of the upper 5 cm of the top layer at the mean and lowest soil water pressure heads (ψ) during the period with a precipitation surplus (October through February).

Field	Plot	ψ	Solids	Water	Air	S_R
A	1	mean	0.509	0.425	0.066	0.87
		lowest	0.509	0.412	0.079	0.84
	2	mean	0.568	0.402	0.030	0.93
		lowest	0.568	0.392	0.040	0.91
	3	mean	0.608	0.348	0.044	0.89
		lowest	0.608	0.335	0.057	0.85
E	1	mean	0.535	0.417	0.048	0.90
		lowest	0.535	0.412	0.053	0.89
	2	mean	0.600	0.370	0.030	0.93
		lowest	0.600	0.360	0.040	0.90
	3	mean	0.542	0.424	0.034	0.93
		lowest	0.542	0.405	0.053	0.88
F	1	mean	0.531	0.378	0.091	0.81
		lowest	0.531	0.372	0.097	0.79
	2	mean	0.527	0.385	0.088	0.81
		lowest	0.527	0.372	0.101	0.79
	3	mean	0.568	0.385	0.047	0.89
		lowest	0.568	0.372	0.060	0.86
G	1	mean	0.604	0.260	0.136	0.66
		lowest	0.604	0.210	0.186	0.53
	2	mean	0.604	0.240	0.156	0.61
		lowest	0.604	0.180	0.216	0.45
	3	mean	0.621	0.270	0.109	0.71
		lowest	0.621	0.200	0.179	0.53

2.7 Soil strength – pressure head – bulk density

In Section 2.4.1 it was found that playing conditions can be characterized by soil strength as measured with a penetrometer. At a soil strength of 1.4 MPa deformation of the top layer does not occur on intensively played parts. For the moderate intensively played parts a soil strength of 1.0 MPa is required. For extensively played parts, a soil strength of 1.0 MPa is desirable. The soil strength depends on bulk density and the soil water conditions. From Section 2.5 it appears that the penetration resistance is almost always sufficient for intensive playing if the top layer of intensively used parts is compacted to a relative density of about 0.45. If the top layer is compacted enough, only high pressure heads can limit the playing conditions. From relationships between penetration resistance and pressure head simultaneously measured, pressure heads critical for the required soil strength can be derived. Fig. 18 shows such relations for the intensively and extensively played plots of the Fields A, E, F and G. Because of changes of bulk density in time, data were grouped per playing season. The soil

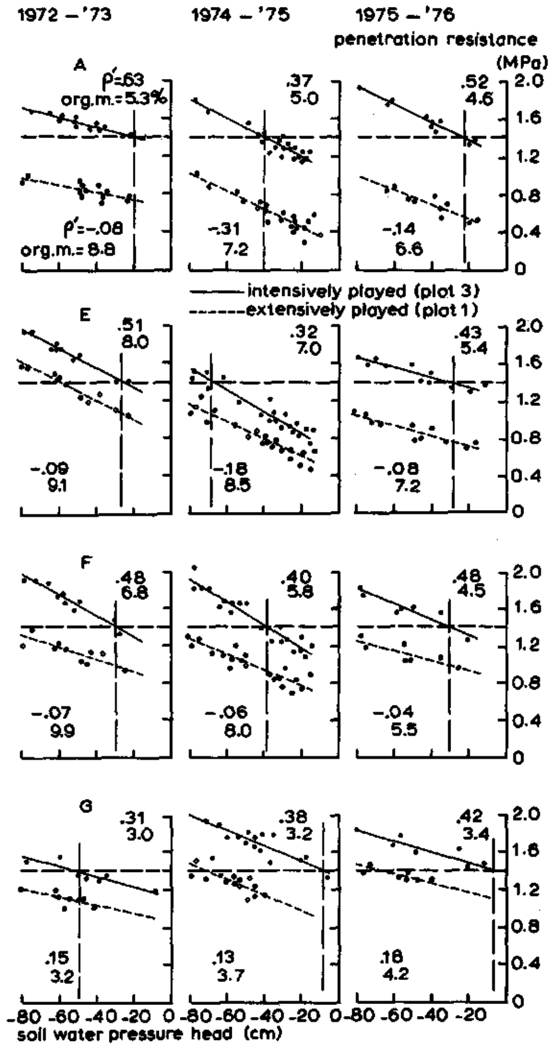


Fig. 18. Penetration resistance versus soil water pressure head, simultaneously measured in the top layer of intensively and extensively played parts of Fields A, E, F and G during the wet part of 3 playing seasons. Relative densities (ρ') and organic matter contents (%) of the top layers are given.

strength of 1.4 MPa required for intensively played parts is indicated in Fig. 18. The 3 playing seasons considered represent two rather dry (1972–73 and 1975–76) and an extremely wet (1974–75) season. The best fitting curves through the points measured during the seasons 1972–73 and 1975–76 on the intensively played plots, intersect the 1.4 MPa line of Field A at pressure heads of −20 and −22 cm, of Field E at −26 and −28 cm, of Field F at −20 and −22 cm and of Field G at −49 and −5 cm. As compared with the other fields, Field G shows in the season 1972–73 a lower pressure head at the intersection because it was a newly constructed field with still little compaction in the top layer. In the following seasons the bulk density increased as is indicated by its relative density. The curves then move towards a higher level and intersect the 1.4 MPa line at a pressure head of −8 and −5 cm.

In the playing season 1974–75 the intersection with the 1.4 MPa line occurred for Fields A, E and F at lower pressure heads. Because of the extreme wetness from the start of the playing season in autumn 1974, fields were played over a long period at a low frequency giving less compaction and lower bulk densities. In the years 1972–73 and 1975–76 the relative densities on the plots played intensively vary between 0.43 and 0.63, while the intersection with the 1.4 MPa line is found in the pressure head range of −28 to −20 cm. At lower relative densities such as occur in 1974–75, the 1.4 MPa line is intersected at heads of −40, −67 and −39 cm. When the bulk density is lower, also the pressure head must be lower to satisfy a soil strength of 1.4 MPa. However, the lower the required head, the greater the frequency and duration that this head is exceeded and the more frequently and the longer the field is insufficiently playable. Considering field G with a low organic matter content, pressure heads of −8 and −5 cm are found in 1974–75 and 1975–76 at relative densities of 0.38 and 0.42. This indicates that a top layer with a low organic matter content but well compacted still yields sufficient soil strength at saturation. Then only ponding can limit the playing conditions. From this behaviour it can be concluded that at a relative density of about 0.45 a pressure head higher (wetter) than −30 cm is limiting the playing conditions at organic matter contents in the range from 5 to 8%. At an organic matter content in order of 3% the pressure head must be < -10 cm at this compaction level.

In addition also the relation between penetration resistance and pressure head for the extensively played parts are given in Fig. 18. Because of the low compaction level these curves lie at much a lower level. At equal pressure heads as found for the intensively played parts, the penetration resistance of 1.0 MPa desired for extensively played sites is not always reached. More compaction then is the only means to improve the soil strength at these sites.

2.8 Discussion

From the field investigations presented it appears that the most important measures to assure sufficient soil strength for intensive playing are: maintaining a relative density of at least 0.45 and keeping such soil water conditions that certain pressure head limits (see Section 5.3) are exceeded as infrequently as possible. Therefore an examination has been made about the behaviour of different types of sand under compaction and on the effect of increase in bulk density on soil strength over the range of pressure heads prevailing during the playing season (Chapter 3).

However, high bulk densities could be disadvantageous for the growth conditions of grass. In Chapter 4 attention will be given to the controversial requirements for soil strength versus grass viability.

The ways the pressure head of top layers of different composition and compaction can be managed properly will be described in Chapter 5.

3 Compactability and strength of differently composed and wetted sands

3.1 General

In Chapter 2 it was made clear that bulk density and soil water conditions of the top layer are the main factors affecting the soil strength required for good playing conditions. Reduction of the soil water pressure head and increase in bulk density of the top layer are coupled with larger soil strength, diminishing the chance of injury to the top layer by playing.

When wanting to improve playing conditions of grass sports fields it therefore is necessary to study the compaction behaviour and the interrelationships between soil strength, pressure head and bulk density of sands used for top layer construction. To this purpose a number of detailed experiments were carried out in the laboratory.

3.2 Materials and methods

Three types of sands generally applied in the Netherlands for top layer construction of grass sports fields were used. The first two types were fine sands: an aeolian Upper Pleistocene sand and a dune sand. The third one was a river sand of medium texture. The textures are indicated according to the nomenclature of Soil Survey Staff (1975) (see Fig. 1).

Once established, the composition of the top layer changes with time. Over the years a slow increase in organic matter content and also in fine particle content, when it concerns top layers overlying clayey subsoils., will change the mechanical behaviour of the sandy top layer. Therefore the mechanical behaviour of sands was studied at both different organic matter and fine particle contents. By mixing two natural fine sands with 0.4 and 8.6% organic matter respectively and similar particle size distributions a standard series of sands with organic matter contents of 0.4, 2.3, 4.3, 6.6 and 8.6% was obtained (Table 8).

Of grass sports fields constructed on clayey or loamy soils the top layer usually consists of 10 to 15 cm poor sand. This layer then often is slightly mixed with the underlying soil. Over the years the top layer becomes often enriched further with fine particles from the subsoil as a result of worm activity (Stuurman & Kamp, 1971). To similate this situation, a fine sand and a medium sand were mixed with increasing quantities of a clay soil (Table 8).

The organic matter contents of the fine sands roughly represent the range which is being found in practice. Numbers 6, 7, 11 and 12 of the sand–clay mixtures are regarded in practice as favourable and Numbers 8, 9, 10, 13, 14 and 15 as too rich with respect to clay content.

Table 8. Organic matter content (%), particle size distribution (%) and median particle diameter (M50 in μm) of fine sands as well as fine and medium sand - clay mixtures.

Nr	Organic matter	Clay	Silt		Sand						M50
		<2 μm	2–16	16–50	50–105	105–150	150–210	210–300	300–420	>420 μm	
Fine sand mixtures											
1	0.4	2.0	0.3	0.2	12.3	27.3	30.9	16.2	7.9	2.9	168
2	2.3	2.6	0.7	1.9	13.5	26.2	30.3	15.2	7.0	2.6	166
3	4.3	3.1	1.2	3.7	14.7	25.1	29.6	14.2	6.1	2.3	163
4	6.6	3.8	1.7	5.8	16.2	23.7	28.9	13.1	5.0	1.8	159
5	8.6	4.4	2.2	7.6	17.4	22.6	28.2	12.1	4.0	1.5	156
Fine sand–clay mixtures											
6	0.4	4.0	2.1	5.2	2.9	14.4	37.8	29.9	3.5	0.1	193
7	0.6	7.0	3.9	9.3	4.4	13.4	33.0	26.1	3.0	0.1	190
8	0.7	10.0	5.6	13.3	6.0	12.3	27.9	22.3	2.5	0.1	187
9	0.8	13.0	7.3	17.4	7.6	11.3	23.0	18.5	2.0	0.1	182
10	1.0	17.0	9.8	23.4	9.8	9.9	15.7	12.8	1.3	0	169
Medium sand–clay mixtures											
11	0.4	4.0	2.0	4.7	2.3	5.1	12.9	29.1	25.0	14.9	285
12	0.6	7.0	3.8	8.8	4.0	5.4	11.4	25.3	21.5	12.8	279
13	0.7	10.0	5.5	13.0	5.6	5.7	10.0	21.6	18.0	10.7	270
14	0.8	13.0	7.2	17.1	7.3	6.0	8.5	17.9	14.5	8.6	258
15	1.0	17.0	9.8	23.2	9.7	6.4	6.3	12.4	9.3	5.5	228

The behaviour of these sand mixtures was studied at increasing soil water contents and compacting efforts of 0.2, 0.4, 0.8 and 1.2 MPa, pressures found to be exerted upon grass sports fields (see Section 2.1). Successive soil portions of 2.5 cm thickness were weighed, put into a column of five stacked stainless steel rings of 10 cm inside diameter and 5 cm height each. Layer for layer was compressed by means of a compression equipment. Compression times of 1 minute were used. Then the rings were separated and weighed. From these weights and the water content after compaction of the soil samples, the bulk density was calculated. Because of small deviations of the top and bottom samples the mean value of the three intermediate samples was used to determine the bulk density versus soil water content curve. In the case of wet sandy top layer materials drainage of water from the sample may occur during compaction. This behaviour may influence the compaction degree. To allow drainage, porous plates were applied at the bottom of the samples.

To investigate the effect of pressure head and bulk density on soil strength, the relation between soil strength and pressure head was determined at different bulk densities. A pressure head range varying from 0 to −100 cm was taken which corresponds with soil water conditions during the main part of the playing season (see Fig. 14).

In order to have soil samples with the same bulk density, columns with 110 cm length were built by stacking steel rings and filling them with soil layers of 2.5 cm thickness, which were compacted as described before. In this way a uniform compaction was obtained over the entire soil column, except for the two end rings which were discarded.

After saturating the column from the bottom upward, a water table was

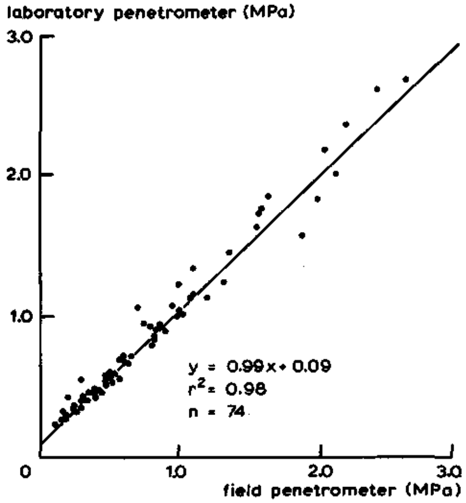


Fig. 19. Penetration resistances as measured with a laboratory penetrometer versus those measured with a hand-operated field penetrometer, using the same cone. r^2 is variance and n the number of observations.

established at a height of 2.5 cm above the bottom. When an equilibrium situation was reached the samples were separated, weighed and the penetration resistance was measured. To save time the samples rings of the columns with the fine and medium sand–clay mixtures were separated before saturation. After saturation these samples were brought to the desired pressure heads.

With the aid of a soil test penetration apparatus, the penetration resistance was measured to a depth of 2.5 cm and the highest value encountered taken. The same cone as used in the field measurements was applied (base 1 cm^2, top angle 60°). The penetration speed used was 1 $cm \cdot min^{-1}$. This speed was considerably lower than that of the hand-operated penetrometer used in the field. Therefore a comparison between the measurements with the apparatuses was made (Fig. 19). The differences between both types of measurements were negligible. Only at very low penetration resistances the hand-operated penetrometer is somewhat less sensitive.

3.3 Compactability of sand

3.3.1 Influence of water content and pressure exerted

Results of the compression tests are shown in Fig. 20, where bulk density is plotted versus soil water content before compaction. Because the water content at the beginning and end of the compression process is not necessarily the same, soil water contents before compaction were used. The influence of the water content on compactability (change of bulk density) can be read from the slope of the compression curves. The influence of pressure is given by the distances between the curves. At each compaction level the bulk density increases the more, the

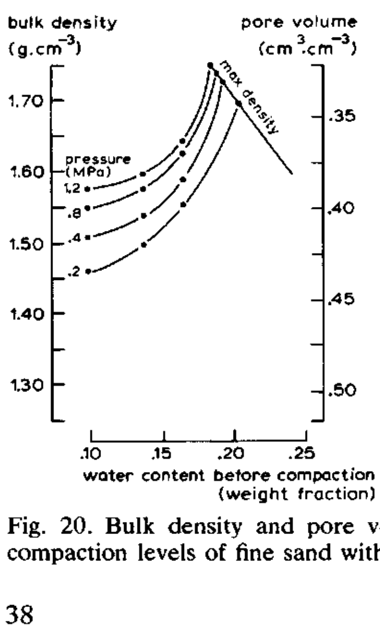


Fig. 20. Bulk density and pore volume versus water content before compaction, at 4 compaction levels of fine sand with 4.3% organic matter.

more water the soil contains. Compressing at low water contents yields lower densities because of a high shear resistance between the sand grains. With increasing water contents the shear resistance decreases and the bulk density increases up to a certain maximum when the sand is compressed. At the applied pressures and compression time, compaction beyond this maximum is not possible. The differences in bulk density due to differences in pressures exerted are the greatest at drier soil conditions. At wet soil conditions sand can already be severely compacted by applying small pressures. A small pressure exerted on a wet soil causes much more compaction than a higher pressure exerted under drier circumstances.

It appears that the compactability of sand is much more sensitive for changes in water content than for pressure increments. Fig. 20 also shows that a certain bulk density can result from a number of combinations of pressure and water content.

3.3.2 Influence of organic matter content

Fig. 21 shows bulk density versus soil water content curves at four compaction levels for sands with 0.4, 2.3, 4.3, 6.6 and 8.6% organic matter content. The higher the organic matter content the stronger the increase in bulk density per pressure increment and the larger the differences in bulk density between the four compaction levels. This behaviour was already demonstrated in Fig. 11, where the three curves relating to Field G remain much closer together than the curves for the other fields, which have a higher organic matter content in the top layer. When wet enough, compaction of poor sands will occur at low pressures, while compaction of humous sand mainly occurs at high pressures. An increase in organic matter content is generally coupled with a decrease in bulk density. When dealing with sands with different organic matter contents it is therefore difficult to judge degrees of compaction. Then a comparison on the basis of bulk densities cannot be made. In such cases the concept of relative density must be used, where actual density is compared with the most dense and the most loose packing. The relationship between relative density, ρ', and actual density, ρ, is:

$$\rho' = \frac{\rho_{min} - \rho}{\rho_{min} - \rho_{max}} \qquad (7)$$

where ρ_{min} and ρ_{max} are the minimum and the maximum bulk densities respectively. ρ' varies between 0 and 1; $\rho' = 0$ indicates no compaction and $\rho' = 1$ maximal compaction.

Fig. 22 gives ρ_{min} and ρ_{max} for fine sand with different organic matter contents. The minimum density was determined by pouring air dry sand into a sample ring, carefully avoiding to disturb the samples. As maximum densities were taken the highest values found at pressures of 1.2 PMa in the compression test (see Fig. 21). However, the maximum bulk densities found at 0.4 and 2.3% organic matter content respectively were lower than those found for naturally packed dense sands. The conditions during the compression test apparently are not optimal to reach the closest packing of the grains at low organic matter contents. Therefore

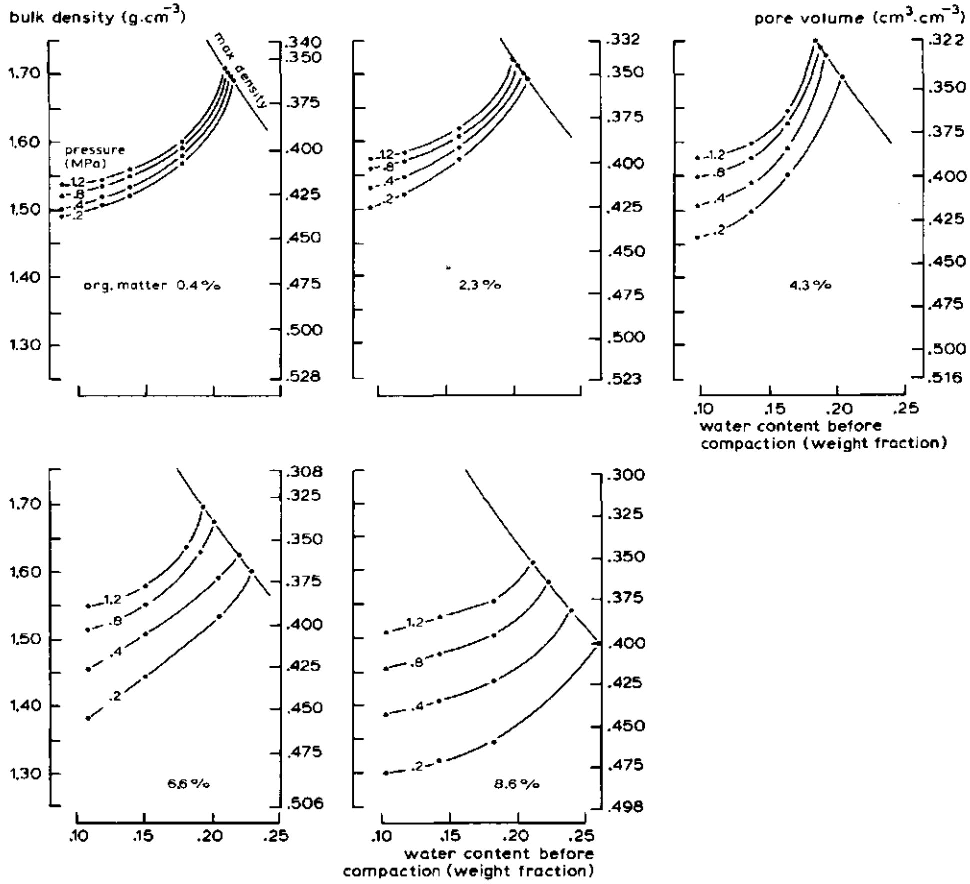


Fig. 21. Bulk density and pore volume versus water content before compaction, at 4 compaction levels of fine sand at increasing organic matter contents.

the maximum density curve was drawn on basis of the maximum densities found at 4.3, 6.6 and 8.6% organic matter and on basis of an extrapolation to a bulk density of $1.85 \, g \cdot cm^{-3}$ mentioned by Schothorst (1968) as the maximum for humusless fine sand.

From Fig. 22 it is obvious that for sands with different organic matter contents bulk density is not a good measure for the degree of compaction. Fig. 23 shows relative density versus bulk density for the fine sand at various organic matter contents as derived from Fig. 22. A bulk density of for example $1.60 \, g \cdot cm^{-3}$ corresponds at 0.4 and 8.6% organic matter content with a relative density of 0.19 and 0.92 respectively.

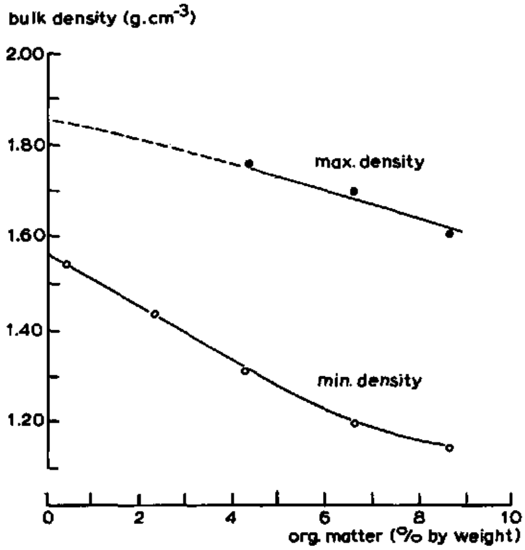


Fig. 22. Relation between bulk density and organic matter content of maximally respectively minimally compacted (at 1.2 MPa pressure respectively air dry poured) fine sand.

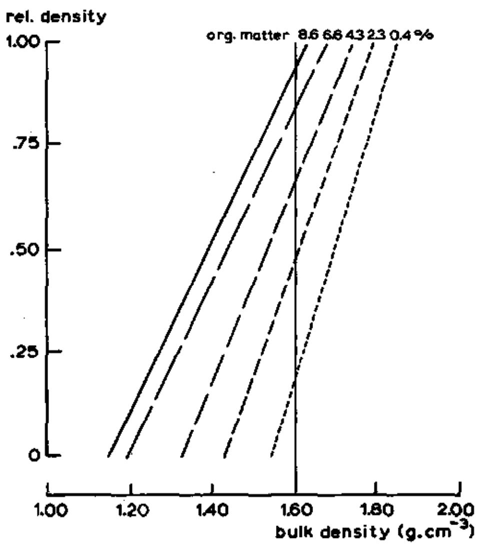


Fig. 23. Relative density (i.e. degree of compaction) versus bulk density at different organic matter contents of fine sand.

3.3.3 Influence of clay content and coarseness of sand

The bulk density of sand–clay mixtures increases considerably with higher clay content as is shown in Fig. 24. From about 13% clay content bulk density increases hardly any further. The initially strong increase in bulk density may partly be caused by a filling up of the intergranular spaces with fine particles and partly by acting of the finest particles as a lubricant between the coarser sand grains. The increased resistance against compression at higher clay contents, as expressed by only slightly changing bulk densities, may be the consequence of the increased cohesion of the sand–clay mixtures. An increase in clay content of the sand advances the compactability the more, the higher the soil water content. Then small pressures already can cause severe compaction. The influence of pressure increments is small, as compared with the influence of an increase in clay and soil water content. Comparison of the compression curves in Fig. 24 with those found at higher organic matter contents (see Fig. 21) shows large differences. The compactability of sand with more organic matter appears to be less sensitive for increasing water contents than poor sands or sand–clay mixtures.

The influence of coarseness of the sand is illustrated in Fig. 25, which is derived from Fig. 24. Compaction of the medium sand–clay mixtures results in higher bulk densities than compaction of the fine sand–clay mixtures. With increasing coarseness the total surface of the sand grains and the total contact area between the grains is smaller per unit of volume and therefore the shear resistance

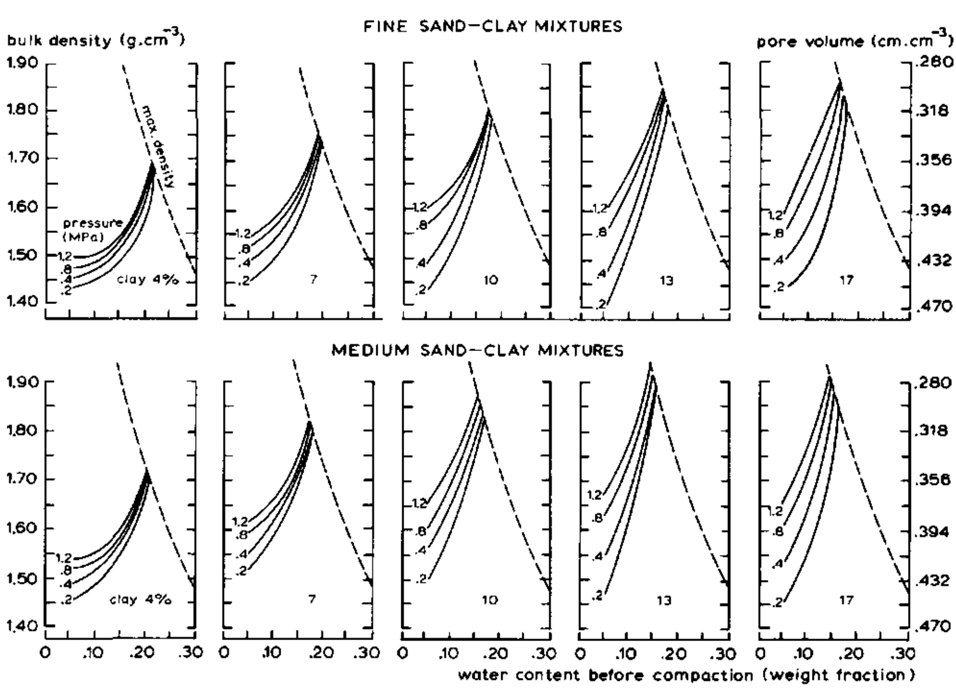


Fig. 24. Bulk density and pore volume versus water content before compaction, at 4 compaction levels of 5 fine sand and 5 medium sand-clay mixtures.

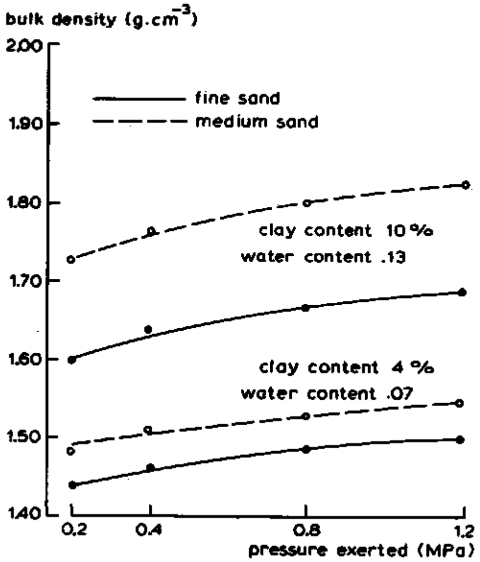


Fig. 25. Bulk density versus pressure exerted on samples of both fine sand-clay mixtures and medium sand-clay mixtures, each at 2 different clay respectively water contents.

between the grains also is smaller. Because of this lower shear resistance the coarser sand is more compacted at equal compaction conditions. Fig. 25 also shows that within the given range of pressures for both types of sand–clay mixtures a certain pressure increment results in a more or less similar bulk density increment.

3.4 Soil strength of sand

3.4.1 *Influence of compaction and organic matter content*

Fig. 26 shows the effect of compaction on soil strength of fine sands containing various organic matter contents at four different soil water contents. In this figure penetration resistance is plotted versus relative density. The slope of each curve gives the effect of compaction on soil strength, while the distances between the curves indicate the influence of organic matter content. Compaction does increase soil strength and the more the higher the organic matter content. Compaction of poor sands favours soil strength only a little. However, for sands containing more organic matter compaction appears to be a very effective measure to improve soil strength and thus playing conditions. Compaction to a relative density of 0.50 yields at a soil water content of 0.10, a soil strength of 0.32 MPa at 2.3% and 1.43 MPa at 8.6% organic matter respectively. When soil water content increases, soil strength decreases. This reduction can be compensated by stronger compaction. To obtain a soil strength of 1.43 MPa of the sand with 8.6% organic matter a relative density of 0.50 is required at a water content of 0.10, while the relative density must be 0.70 at a water content of 0.19.

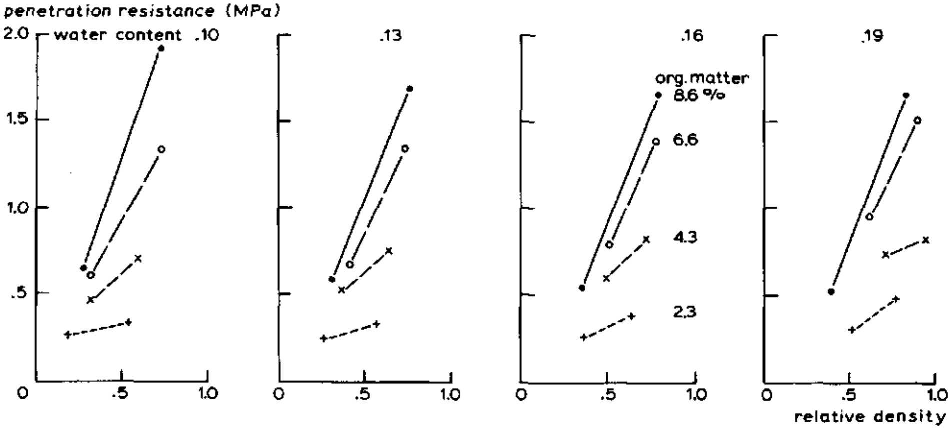


Fig. 26. Penetration resistance versus relative density (see also Fig. 23) at 4 organic matter contents of fine sand, each at 4 water contents.

3.4.2 *Influence of compaction and clay content*

Fig. 27 shows the effect of different bulk densities on soil strength of fine sand–clay mixtures at four soil water contents. The slopes of the curves indicate that the effect of an increase in bulk density is greater when the sand contains more clay. When the clay content amounts to 10% and the water content to 0.07

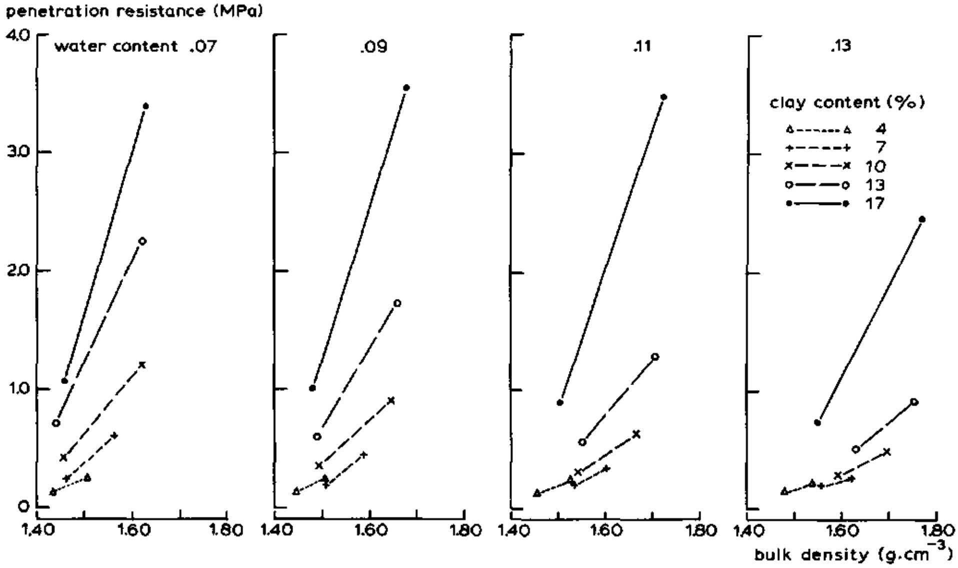


Fig. 27. Penetration resistance versus bulk density at 5 clay contents of fine sand, each at 4 water contents.

an increase in bulk density with 0.1 $g \cdot cm^{-3}$ results in an increase in soil strength of 0.48 MPa. For 17% clay this increase amounts to 1.35 MPa. This also implies that clay particles contribute more to soil strength when the sand is compacted to higher bulk densities.

Fig. 26 as also Fig. 27 indicate that poor sands possess little soil strength. This feature is connected with the small cohesion between the grains themselves and with the way of measuring the penetration resistance. In the present study this resistance was measured in the upper 2.5 cm of the samples. The little-cohesive grains surrounding the penetrating cone may then easily be displaced. When this displacement is prevented, for instance by overlying soil layers as occurs in soil profiles, much higher penetration values are observed.

Within the range considered the effect of increasing water contents is rather small. A reduction in penetration resistance is most obvious at higher bulk densities.

3.4.3 Influence of compaction and coarseness of sand

As shown in Fig. 25, at an equal compaction effort medium sand–clay mixtures were compacted to higher bulk densities than fine sand–clay mixtures. In other words, at equal bulk densities the fine sand has considerably more soil strength than the medium sand (Fig. 28). Independent of water content the penetration resistance of fine sand with 13% clay is some 0.7 MPa higher than of medium sand with the same clay content. At 7% clay content this difference amounts to some 0.2 MPa. To obtain the same soil strength as fine sand the medium sand must have a higher bulk density. In practice this will be the case when both sands are trodden with about equal intensity (see Fig. 25). However, the higher bulk

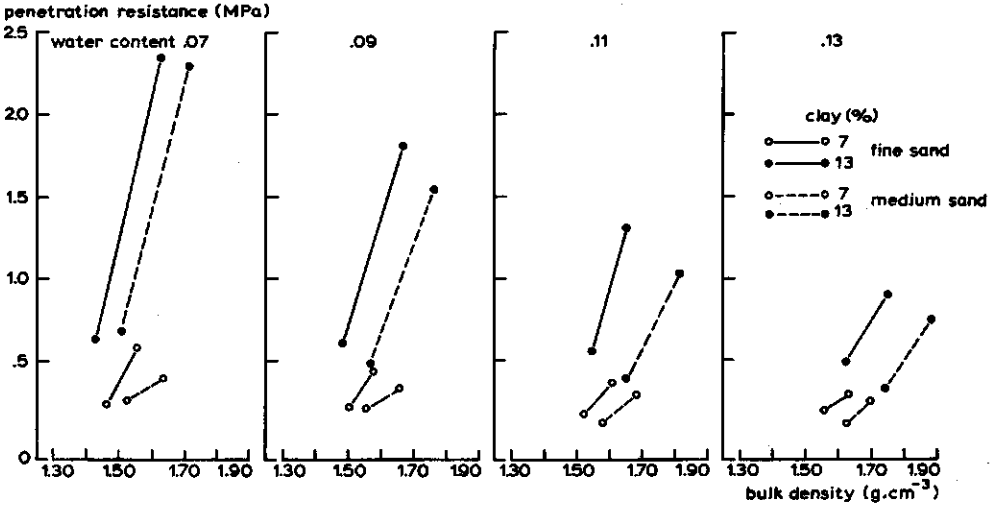


Fig. 28. Penetration resistance versus bulk density at clay contents of 7 and 13% of fine respectively medium sand-clay mixtures, each at 4 different water contents.

density of the medium sand required to reach similar soil strengths generally is disadvantageous for the hydraulic conductivity and air filled pore space (storage capacity, oxygen diffusion).

3.4.4 Influence of compaction, pressure head and organic matter content

In the preceding sections the relations between penetration resistance and bulk density in dependency of organic matter, clay content and coarseness of sand, were considered within a rather wide range of water contents. Measurements in the field indicate that during winter when grass sports fields are vulnerable, soil water conditions vary within a rather narrow range of pressure heads (Fig. 14). From the same measurements it also appeared that in the very wet range soil strength of the top layer of sports fields is strongly affected by rather small changes in pressure head (Figs. 12 and 18). Fig. 29 shows the relation between soil strength, measured as penetration resistance, and soil water pressure head for fine sands with different relative densities and organic matter contents. The relative densities of the sands given in Fig. 29 represent compaction levels which can be found on sports fields regularly played. At low compaction levels the penetration

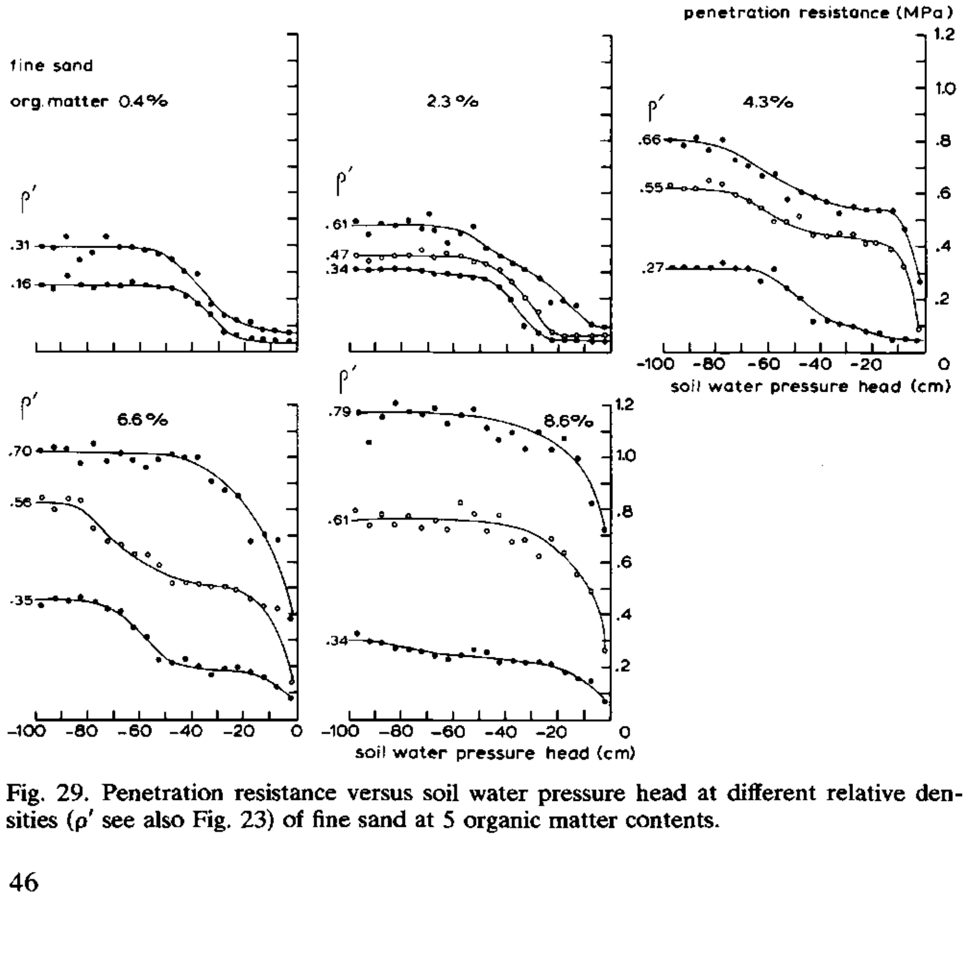


Fig. 29. Penetration resistance versus soil water pressure head at different relative densities (ρ' see also Fig. 23) of fine sand at 5 organic matter contents.

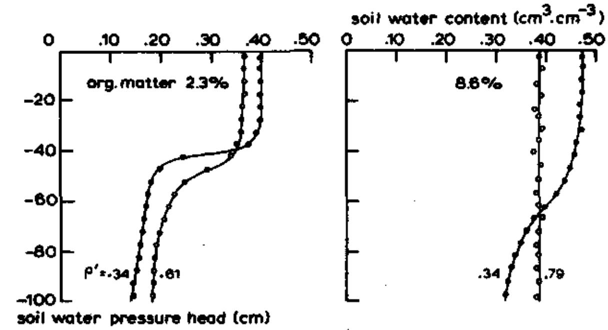


Fig. 30. Soil water characteristics of sand with 2.3 and 8.6% organic matter (see also Fig. 29) at light and severe compaction levels. ρ' is relative density.

resistance is small at each organic matter content. At low organic matter contents the penetration resistance is increased only a little by compaction. At higher organic matter contents an increase in relative density goes with a considerable increase in penetration resistance. So within the investigated range, compaction to improve soil strength is more effective at higher organic matter contents.

The effect of soil water pressure head on penetration resistance gradually changes going from lower to higher organic matter contents. A reduction of soil strength occurs at pressure heads higher (wetter) than about −50 cm and is smaller at higher organic matter contents and compaction levels. Sands with 0.4 and 2.3% organic matter show this reduction most clearly. This reduction coincides with a strong increase of the volumetric water content over the same range of pressure heads in the soil water characteristic (see Fig. 30). When the increase in soil water content is more gradual, the relationship between penetration resistance and pressure head also shows a more gradual course.

Noteworthy in Fig. 29 is the strength behaviour in the pressure head range close to saturation. Here the more compacted sands with 4.3, 6.6 and 8.6% organic matter respectively show a sharp drop of the penetration resistance. This drop occurs over a pressure head range in which the soil water content hardly changes (see Fig. 30). At 6.6 and 8.6% organic matter content the penetration resistance sharply decreases at ψ-values higher (wetter) than −30 cm, while this occurs above −15 cm at 4.3% organic matter content. These values confirm the findings from the field experiments (see Figs 12 and 18).

3.4.5 Influence of compaction, pressure head and clay content

With regard to the effect of clay content on soil strength over the wet range, Fig. 31 gives some information. The soil strength of the fine sand–clay mixtures was measured at two bulk densities 1.54 and 1.65 $g \cdot cm^{-3}$ respectively. Within a soil water pressure head range from 0 to −70 cm (prevailing during the main part of the playing season) soil strength at a bulk density of 1.54 $g \cdot cm^{-3}$ is practically not improved by adding increasing quantities of clay to the sand. As compared with sand practically without clay and organic matter (see Fig. 29), addition of 4

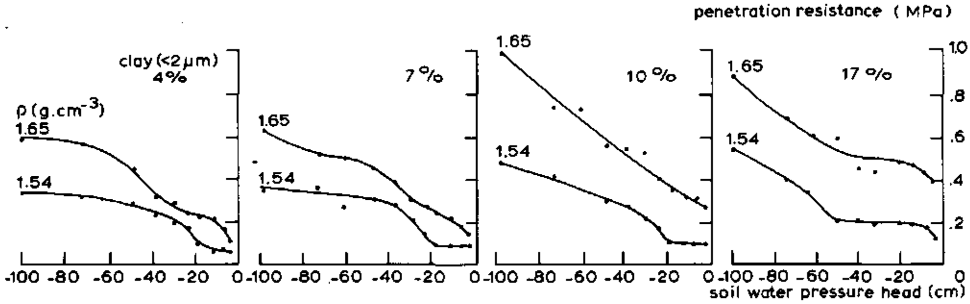


Fig. 31. Penetration resistance versus soil water pressure head at 2 bulk densities (ρ) of fine sand–clay mixtures with increasing clay contents.

to 7% clay and compaction to $1.65\ g \cdot cm^{-3}$ barely improves soil strength. Even additions of 10 to 17% clay do but slightly increase it. As compared with the contribution of a few per cent of organic matter, the contribution of clay to soil strength is nearly negligible.

For soil conditions drier than those occurring during the main part of the playing season, soil strength increases the more the higher the clay content and the drier the soil (Fig. 32). Under wet soil conditions differences in clay content hardly cause differences in soil strength. For dry soils, however, the penetration resistance increases with higher clay contents to such high values that the top layer becomes unpleasantly hard. This happens when the penetration resistance exceeds values of some 3.0 MPa (Van Wijk & Beuving, 1975b).

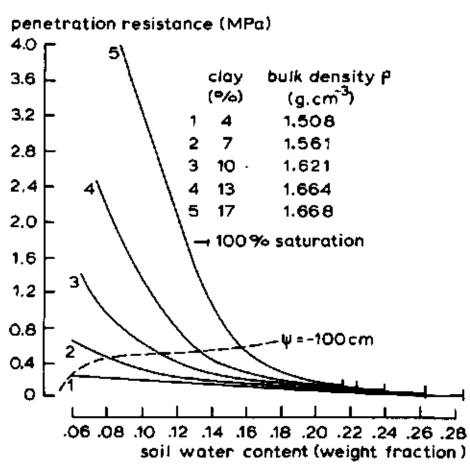


Fig. 32. Penetration resistance versus soil water content at increasing clay contents of fine sand. The bulk densities result from equal compaction conditions. The range of water contents prevailing during the playing season is defined by the area below the $\psi = -100$ cm curve.

3.4.6 *Theoretical interpretation of penetration test results*

Freitag (1968) qualifies the penetration test as a surprisingly accurate and efficient means of measuring strength of soils in situ. At the same time he emphasizes the lack of directly applicable solutions for describing the penetration resistance of a cone in terms of stress–strain properties. It is therefore necessary to rely heavily upon experimentation and practical experience to interprete the cone penetration test results.

An increase in bulk density as well as a decrease in soil water pressure head improving penetrometer soil strength has also been found by Taylor & Gardner (1963), Smith (1964), Green et al. (1964), Barley et al. (1965), Farrell & Greacen (1966) and Taylor et al. (1966).

The influence of soil water pressure head on soil strength is commonly explained in terms of contribution to the effective stress operating between solid soil particles (Aitchison, 1961; Jennings, 1961; Skempton, 1961; Williams & Shaykewich, 1970). The maximum shear resistance in any plane in the soil is a function of the difference between the total stress (σ) acting on the plane and the water pressure ($\rho_w g\psi$). The effective stress (σ') is given by the expression:

$$\sigma' = \sigma - \rho_w g\psi \quad \text{(Pa)} \tag{8}$$

In a partially saturated soil, water pressure is acting over a part χ and the air pressure over a part $(1-\chi)$ of the plane. The proportionality factor χ is a function of the saturation degree (S_r). For a saturated soil $S_r = 1$, $\chi = 1$ and for a oven dry soil $S_r = 0$, $\chi = 0$. When the pores are open to the atmosphere, Eq. (8) then can be written as

$$\sigma' = \sigma - \chi|\rho_w g\psi| \quad \text{(Pa)} \tag{9}$$

Taking into account the contribution of soil water pressure to soil strength, the shear strength at failure (Eq. (1)) can be written as:

$$\tau = c' + (\sigma - \chi|\rho_w g\psi|)\text{tg}\phi' \quad \text{(Pa)} \tag{10}$$

The results of Fig. 29 can now be interpreted in terms of this effective-stress theory. At the lower organic matter contents the change in penetration resistance occurs within a range of pressure heads within which also the volumetric water content, and therefore S_r and χ, sharply change. On the other hand at higher organic matter contents, especially at higher bulk densities, a sharp drop of the penetration resistance was observed at pressure heads close to saturation where the soil water content hardly changes. The same behaviour was found from field measurements (see Fig. 12). This change in strength behaviour may be interpreted in terms of effective-stress theory too. During the penetration of the cone in soils with high pressure heads, water cannot flow fast enough away from the cone surface to the surrounding soil. Then an increase in pore water pressure even to positive values arises around the penetrating cone. These increased or positive pore water pressures lower the effective stress and the shear strength.

3.4.7 *Influence of grass roots*

According to the field investigations, reported in Chapter 2, a penetration resistance of the top layer of 1.4 MPa implies a soil strength that is adequate for intensive playing. Despite the high relative or bulk densities obtained in the laboratory experiments, the required penetration resistance was not reached. The lower the relative density and the organic matter content, the larger the discrepancy between measured values and required values (see Fig. 29). Nevertheless, penetration resistances of 1.4 MPa are measured indeed in the turf of sports fields under texture and water conditions of the same kind as present in the laboratory experiments. These high resistances suggest that grass roots must considerably contribute to the penetration resistance of the top layer. This behaviour is illustrated in Fig. 33. The upper part of this figure shows some of the relations between penetration resistance and pressure head, as measured in the field and earlier presented in Fig. 18. The lower part shows results of laboratory measurements with the same materials, compacted to the same densities as found in the field, but without a grass cover. The contribution of the grass roots to soil strength, indicated by the distance between the corresponding curves is considerable and varies between 0.8 and 1.6 MPa for the pressure head range considered. The field measurements were performed during autumn and winter on intensively played parts. During this period sward density at these sites shows a strong decrease (see Fig. 35). In spite of thinning of the sward as a result of intensive playing the underground parts are able to reinforce the top layer. Although the

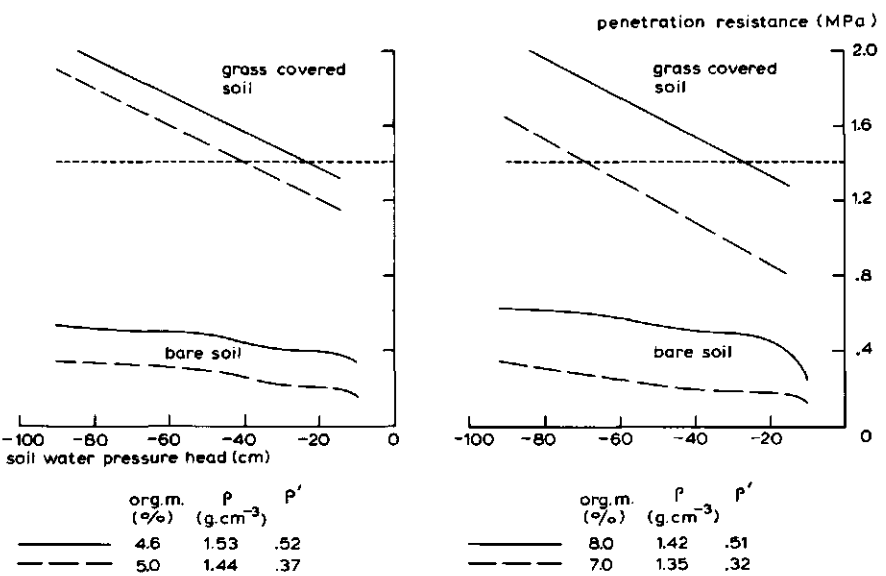


Fig. 33. Penetration resistance versus soil water pressure head for sands with different organic matter contents and densities (ρ and ρ') both with and without a grass cover.

grass makes an essential contribution to soil strength, short term variations in penetration resistance and playing conditions result from changes of bulk density and pressure head.

The reinforcing action of the grass roots can be explained from the high root intensities in the top layer and the tensile strength of the roots. In Table 11 a root intensity is given of 116 roots per cm^2 in the upper 2.5 cm of the top layer at intensively played parts. This implies a mean distance between the roots of 0.7 mm. Schubert (1978) has measured for a number of grass species the force required for tearing roots. For perennial rye grass, the dominating species on grass sports fields in the Netherlands he found an average tensile strength of 290 grams for roots with a diameter of 0.2 mm. When a cone of a penetrometer or a stud of a boot is inserted into the root zone, the soil material surrounding the cone or under the stud is displaced upwards and in lateral directions along certain shear planes (Fig. 34). The tensile strength of the roots crossing the shear planes will hinder this lateral displacement.

The contribution of grass roots is different for soils with different mechanical behaviour. In case of less compressible soils cone penetration is only possible when lateral displacement of soil segments occurs. Then the shear strength of the soil and the tensile strength of the roots crossing the shear planes must have been exceeded. Unstable poor sandy top layers without grass show, because of easily possible lateral displacement of the sand grains, little soil strength both in a loose and a dense state (see Fig. 29). But because of their low compressibility (see Fig. 21) these sands reinforced by grass roots show high penetration resistances and hardly deform. Sands of low bulk density with a high organic matter content are more compressible and show only lateral displacement after an initial compaction. Therefore they show in a loose state little soil strength in spite of the presence of grass roots. A prerequisite for adequate soil strength then is compaction to a higher bulk density. In that case the soil itself gains considerable strength and depends less on the reinforcing function of grass roots.

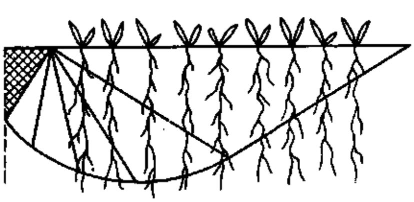


Fig. 34. Shear planes around a penetrating cone.

3.5 Discussion

From field measurements (Chapter 2) it appeared that playing conditions of grass sports fields can be improved by increasing the bulk density and decreasing the soil water pressure head in the top layer. The present chapter dealt with compaction behaviour of sand as far as depending on organic matter and clay content, coarseness of sand, water content, pressure head and the pressures exerted. The higher the organic matter and clay content, the greater the increase in bulk density with increasing compacting actions. Sand low in organic matter and clay content react only little on differences in pressure exerted. For compaction of these sands high water contents are required. Under equal compaction conditions medium sand–clay mixtures are compacted to higher bulk densities than fine sand–clay mixtures.

Within the framework of improving playing conditions compaction is only significant when it promotes top layer soil strength. It appears that even when compacted, poor sands show little soil strength. Increase in organic matter content may contribute considerably to soil strength, but only after compacting the soil to higher bulk densities. The contribution of clay particles to the strength of unstable poor sands is small in the range of pressure heads prevailing during the main part of the playing season. In spite of the higher densities of medium sand–clay mixtures at equal compaction conditions, the soil strength of these types of mixture is not greater than of fine sand–clay mixtures. In the case of compacted humous fine sands water pressure heads within the range between 0 and −30 cm are disadvantageous. This confirms the findings from field experiments (see Fig. 18). Grass roots considerably contribute to soil strength. This contribution is most essential in the case of unstable poor sands.

With respect to the desired composition of top layers the following conclusions can be made:

- Clay particles hardly contribute to the stability of sands under the soil water conditions prevailing during the main part of the playing season. In fact the presence of clay induces disadvantageous effects, such as increased slipperiness and a decrease in hydraulic conductivity (Fahmy, 1961; Koenigs, 1964). So it is expedient to construct sports field top layers mainly intended for winter use with a clay content of the top 5 to 7 cm as low as possible.
- From the point of view of soil strength fine sand is more preferable than medium sand.
- In the case of compacted sands, the contribution of grass roots to soil strength is more essential at low than at higher organic matter contents. As far as the latter is concerned an important part of the soil strength originates from the material itself.
- Because of the effects of organic matter content and compaction on the soil strength of sand, the playing conditions can be improved best by increasing the organic matter content and the bulk density of the top layer. Both measures go, however, at the expense of soil aeration and hydraulic conductivity. The next chapter deals with the effect of compaction on soil aeration and the resulting

response of the grass. Reduction in hydraulic conductivity can only be accepted as far as it does not result in soil water conditions that limit playing conditions. This aspect will be discussed in Chapter 5.

4 Grass viability and soil aeration

4.1 General

In the previous Chapters it was shown that playing conditions of grass sports fields depend on bulk density and soil water conditions of the top layer. The higher the bulk density, the higher the soil strength and penetration resistance. Compaction, however, is said to reduce soil aeration, to impede root penetration and to decrease overall grass quality, growth and vigor (Beard, 1973). To what extent top layer compaction required for a playable field leaves viable conditions for grass has been investigated on 4 grass sports fields. It concerned the regularly used Fields A, E, F and G (see Section 2.3.1) being little compacted at the extensively and severely compacted at the intensively trodden parts (see Table 6).

With regard to grass growth, data were collected on:

- the course of sward density during 3 playing seasons;
- the root distribution over the year.

With regard to possible factors limiting grass viability, measurements were performed on soil aeration:

- oxygen diffusion rate (ODR);
- O_2-concentration in the soil gas phase.

These measurements were compared with the oxygen demand of grass as reported in literature.

4.2 Grass viability

4.2.1 Density and composition of the sward

The main function of a grass cover on sports fields is to reinforce the upper centimeters of the sandy top layer and to prevent a direct contact between player and soil surface. This implies that the sward must retain a certain density. Standards on sward density, for instance formulated as minimally required number of shoots per cm^2 cannot be found.

The ability of grass to withstand the injurious effect of forces exerted upon it, is generally called wear tolerance. The severity of the wear depends on a number of factors, such as the mode of use (intensity, frequency, type of footwear, nature of actions), the composition of the sward and the actual condition of the top layer.

A number of factors affecting turfgrass wear tolerance are known (see reviews of Beard, 1973, and of Canaway, 1975) such as management practices (cutting height, cutting frequency and fertilization). Diseases and environmental factors reducing grass growth may generally affect wear tolerance adversely. Recently more attention has been paid to various physiological, morphological and anatomical characteristics which are thought to determine differences in wear tolerance between grass species (Shearman & Beard, 1975b, 1975c).

The wear tolerance is the main characteristic by which sports turfgrass species and varieties are judged (Shildrick, 1974). Rate of establishment, competitive ability and recuperative potential are second-ranked criteria in variety selection (Duivendak & Vos, 1974). As appears from a number of artificial wear treatments combined with regular cutting, the wear tolerance of turfgrasses may differ widely (Youngner, 1961, 1962; Van der Horst, 1970, 1974; Shildrick, 1971, 1974; Bourgoin et al., 1975; Shearman & Beard, 1975; Skirde, 1975). Under Dutch climatic conditions perennial ryegrass (*Lolium perenne* L.) and Kentucky bluegrass (*Poa pratensis* L.) have shown the best performance on sports fields and under artificial wear treatments (Van der Horst, 1970, 1974; Descriptive list, 1980). Many other investigators (Adams & Bryan, 1974; Shildrick, 1974; Bourgoin et al., 1975; Shearman & Beard, 1975a; Skirde, 1975) give a ranking order in wear tolerance of turfgrass species, with perennial ryegrass being unanimously qualified as the most wear tolerant species of the cool season grasses.

The density and composition of the sward of the fields investigated in this study, as present in June 1976, is given in Table 9. Sward density is given as the fraction of the ground surface covered by grass. Because of the very dry conditions during the early summer of 1976 the sward was still fairly open on the intensively played parts.

From the table it can be concluded that with increasing use intensity the number of grass species in the sward decreases to two dominating species, perennial ryegrass and annual bluegrass (*Poa annua* L.) Only on the less trodden places some other species are present, although for a minor part. Because of the good conformity of these data with findings of the Working group (1970) on 9 fields and of Kraak (1974) on 15 fields, the botanical composition of the sward can be considered as being representative for regularly used fields in the Netherlands. A further natural shift in botanical composition in favour of perennial ryegrass is not to be expected because of the about equal competitative power of perennial ryegrass and annual bluegrass (Kraak, 1974).

Fig. 35 shows the sward density on 4 grass sports fields from January 1973 through May 1976. The course of sward density in time and its reaction on playing intensity show the same tendency on all fields. The changes in sward density on Field G are less pronounced as it was recently constructed and hardly used during the season 1972–73. Also, later on it was used at a lower frequency than the others.

The general shape of the sward density curves follows that of the curves describing the dry matter production of grass in time. In spite of continued playing, regrowth of grass in spring overcomes the mechanical injury done to it. In summer the degree of recovery of the sward depends on climatic conditions and

Table 9. Density and botanical composition of the sward on the 3 experimental Plots 1, 2 and 3 on Fields A, E, F and G (see Section 2.3.1) in June 1976. Playing intensity increases from Plot 1 to 3.

	Field											
	A			E			F			G		
Plot	1	2	3	1	2	3	1	2	3	1	2	3
Sward density	1.00	0.80	0.35	1.00	0.70	0.40	1.00	0.80	0.60	0.90	0.80	0.75
Lolium perenne L.	0.59	0.88	0.95	0.83	0.75	0.53	0.55	0.65	0.75	0.44	0.55	0.35
Poa annua L.	0.20	0.12	0.05	0.15	0.25	0.40	0.25	0.30	0.25	0.45	0.37	0.65
Poa trivialis L.	0.10	+		+	+		0.02	0.01		0.02	0.01	
Phleum pratense L.	0.02	+						0.04		0.03	0.02	+
Poa pratensis L.							0.02			0.01	0.05	+
Holcus lanatus L.							0.01			0.03		
Agrostis tenuis Sibth.	0.08											
Agrostis canina L.							0.15					
Plantago major L.	+		+	+	+	0.02	+	+	+	+		
Taraxacum spp.	0.01	+		0.02	+			+	+	0.02	+	+
Trifolium repens L.		+		+	+	+		+		+	+	
Polygonum aviculare L.					+	0.05			+	+		
Bellis perennis L.	+	+					+					
Ranunculus acris L.	+			+								
Ranunculus repens L.		+		+								
Cerastium holosteoides Fr.	+											
Capsella bursa-pastoris Med.			+									

management. Although the water supply from the subsoil is mostly insufficient to cover the precipitation deficit in a 'normal' summer and sprinkling irrigation of grass sports fields is not yet common in the Netherlands the sward recovers, but in a number of cases recovery of the sward during the summer is deficient and full sward density is not reached. Nowadays application of sprinkling irrigation on grass sports fields increases because sod seeding of heavily played areas becomes a more common management practice in spring. In addition the use of irrigation equipment could have been advanced in consequence of the dry summers of 1975 and 1976.

From the start of the playing season a decrease of the sward density is observed. This decrease is rather sharp in autumn when frequent use coincides with growth retardation of the grass.

Differences in sward density induced by differences in playing intensity are obvious. On regularly used sports fields (4 to 5 matches per weekend) the decrease in sward density goes down to very low levels. At the most intensively

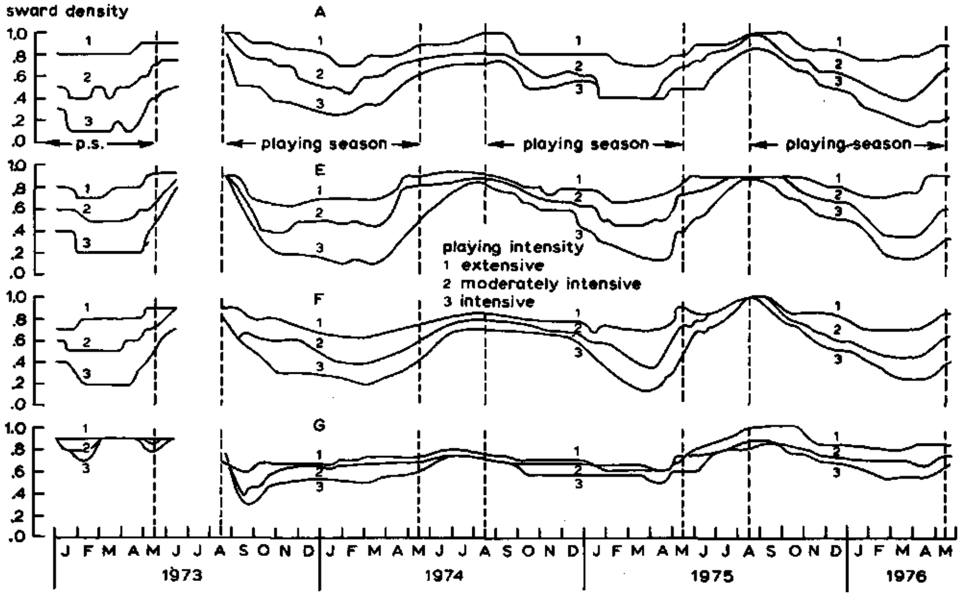


Fig. 35. Course of sward density, as a cover fraction, on the 3 experimental plots with different playing intensities, on Fields A, E, F and G (see Section 2.3.1).

used parts reduction in sward density amounts to 0.7 to 0.9 while the extensively played parts are reduced only with 0.2 to 0.3. The relationship between sward density and playing intensity can also be illustrated when comparing the course of the sward densities in the autumns of 1973, 1974 and 1975. Contrary to 1973 and 1975, the autumn of 1974 was characterized by continuous very wet weather conditions. During this wet autumn a large number of matches was cancelled. This resulted in less mechanical injury to the grass plants and a slower decrease of the sward density than during the autumns of 1973 and 1975.

The main conclusion drawn from this section is that direct mechanical injury to grass plants severely affects sward density.

4.2.2 Root intensity and distribution

Information on the intensity and distribution of the roots of the 4 grass sports fields is presented in Table 10. This information was obtained by counting the number of living roots per 5×5 cm area in a vertical soil section of 10 cm width and 1 cm thick. Observations have been performed in twofold on three various dates, October 1974, April 1975 and August 1975 on both an extensively (Plot 1) and an intensively (Plot 3) used part of the field. The table shows a regular decrease of the root intensity from the surface to a depth of 50 to 60 cm below surface. Below this depth roots do not occur. Differences in root intensity between the profiles are small. They all show the tendency of lower root intensities under more intensive use.

Table 10. Vertical distribution of roots (number $\cdot$ cm^{-2}) and sward density (cover fraction) of Fields A, E, F and G.

Field		Extensively played			Intensively played		
		Oct. 1974	Apr. 1975	Aug. 1975	Oct. 1974	Apr. 1975	Aug. 1975
A	sward density	0.80	0.75	1.00	0.55	0.40	0.85
	depth 5–10 cm	0.96	0.82	0.98	0.19	0.76	0.83
	10–20	0.31	0.44	0.45	0.07	0.25	0.44
	20–30	0.24	0.23	0.30	0.07	0.07	0.22
	30–40	0.17	0.16	0.15	0.12	0.06	0.15
	40–50	0.12	0.08	0.11	0.07	0.04	0.16
	50–60	—	0.005	0.04	—	0.01	0.07
E	sward density	0.80	0.70	1.00	0.60	0.20	0.90
	depth 5–10 cm	0.79	0.85	0.88	0.62	0.39	0.75
	10–20	0.39	0.29	0.34	0.42	0.11	0.30
	20–30	0.34	0.16	0.16	0.23	0.08	0.17
	30–40	0.35	0.09	0.08	0.13	0.04	0.07
	40–50	0.26	0.05	0.03	0.07	0.01	0.04
	50–60	—	—	0.03	—	—	—
F	sward density		0.75	1.00		0.20	1.00
	depth 5–10 cm		0.80	1.00		0.54	0.67
	10–20		0.36	0.37		0.20	0.40
	20–30		0.25	0.23		0.09	0.13
	30–40		0.09	0.14		0.03	0.10
	40–50		0.02	0.03		0.01	0.03
	50–60		0.01	—		—	—
G	sward density	0.70	0.60	1.00	0.65	0.50	0.90
	depth 5–10 cm	0.80	0.47	0.63	0.58	0.63	0.27
	10–20	0.33	0.14	0.22	0.13	0.12	0.14
	20–30	0.08	0.09	0.09	0.03	0.01	0.05
	30–40	0.07	0.14	0.01	—	—	0.03
	40–50	—	0.04	—	—	—	0.01

Counting the number of roots in the root mass concentrated in the upper 5 cm was not possible, but information could be obtained from the fresh root mass sieved from cores taken for bulk density determinations. Assuming a mean root diameter of 0.2 mm (Schubert, 1978) and a vertical growth direction, root intensity could be estimated from the volume occupied by the fresh root mass. The cores originated from the same experimental plots as the countings. Table 11 gives the calculated mean root intensities in the layers 0 to 2.5 and 2.5 to 5.0 cm together with the mean values of the figures from Table 10.

Noteworthy is the very high concentration of roots in the layers 0 to 2.5 and 2.5 to 5.0 cm below the surface, together some 99%. With regard to root distribution the table shows a situation also generally found under pastures. Klapp (1943) found below a weekly grazed or mowed mixed sward a root concentration of 95%

Table 11. Vertical distribution of roots as number · cm^{-2} and percentage on an extensively and intensively used part of the field. The figures for the upper 5 cm were calculated, those of deeper layers were obtained from countings.

Layer	Extensive		Intensive	
	number · cm^{-2}	%	number · cm^{-2}	%
0–2.5	200	81.4	116	77.8
2.5–5	44	17.9	32	21.5
5–10	0.89	0.4	0.60	0.4
10–20	0.37	0.2	0.28	0.2
20–30	0.24	0.1	0.13	0.1
30–40	0.15	—	0.08	—
40–50	0.11	—	0.05	—
50–60	0.02	—		

in the 0 to 5 cm layer. When the frequency of cutting decreased the root concentration decreased in the shallow layers and increased in the deeper layers. From an experiment with 21 varieties of perennial ryegrass with a mowing regime of once a week, Boeker (1974) reports a mean portion of the roots in the upper 5 cm equal to 84% of total root mass. Data of Klapp (1943), as well as of a number of authors cited by Troughton (1957) and Boeker (1974) show almost unanimously that the frequency and height of cut are supplementary in diminishing the total root mass and in promoting the accumulation of roots in the upper layer. So an accumulation of roots in the top layer seems inevitable on grass sports fields under the prevailing management practice of mowing weekly.

To what extent (in addition to the management practice) compaction of the top layer influences root distribution is difficult to derive from the field observations presented here. On the one hand the proportional distribution with depth is nearly the same on extensively and intensively played parts. On the other hand the quantity of roots averaged over the year is greatest on the extensively played parts of the field. But the same is also valid for the sward density and the number of shoots. Compaction may influence the root distribution through soil strength and soil aeration. Barley (1963) found that soil strength is a controlling factor in root growth: when soil strength increases, root penetration decreases. Taylor et al. (1966) found that penetration resistances of 2 to 3 MPa impede root penetration completely. In the Netherlands such values (and much higher ones) are measured only under rather dry circumstances, during summer, in the upper layer of grass sports fields. In that period differences in root intensity between more or less compacted (i.e. intensively and extensively trodden) parts are the smallest (see Table 10), in spite of the wide differences in bulk density of the top layers.

Assuming that the presence of the major part of the root mass in the top layer is induced by cutting practices, deterioration of oxygen diffusion by the top layer compaction further can unbalance the root distribution. That is to say if a high oxygen consumption rate (high root activity) in the top layer goes with a low oxygen diffusion rate, temporarily very low oxygen concentrations (see Figs 38 and 39) and possibly reduced root growth in the subsoil will occur.

With respect to water uptake of the roots the unbalanced root distribution of sports fields is unfavourable. Water must be supplied to the roots partly from water stored in the root zone and partly from the inflow from the subsoil. Apart from factors such as soil hydraulic conductivity, soil water characteristic, presence of a water table and meteorological conditions, root properties like depth, density and distribution determine the water extraction pattern. At shallow rooting depths the amount of water available in the root zone is limited. Moreover the inflow from the subsoil must go over a longer distance and therefore will occur at lower rates. Rooting density is important for the rate and amount of water uptake. Wind (1960) estimated for arable soils in the Netherlands that a density of 1 to 2 roots per cm^2 is required to deplete the root zone down to wilting point. Only the upper 5 to 10 cm of our grass sports fields satisfy this requirement. Also Newman (1974) and Flühler et al. (1975) showed that the soil is dried out more when rooting density increases. Although not specifically measured in the field, extensive depletion from the layer where the bulk of the roots are present may cause also a drought front at the lower boundary of this layer, thus making the major part of the root system ineffective with respect to water uptake.

When no water is present near the soil surface then plants may extract it from greater depths where a rather small percentage of roots may provide for the water uptake (Feddes, 1971; Rice, 1975). For grass sports fields it is questionable to what extent the water uptake of the sparse root system below the 10 cm layer can cover the transpiration demand of the turf. During the dry summers of 1975 and 1976 grass sports fields appeared to suffer more from drought than surrounding grasslands on the same soils. The unfavourable root distribution as compared with that of grasslands (Goedewaagen & Schuurman, 1950) and also the presence of the sandy top layer may explain the greater drought susceptibility of grass sports fields.

4.3 Soil aeration

4.3.1 Grass response to soil aeration

Investigations about the response of grass species to oxygen diffusion rate (ODR) and O_2-content of the soil gas phase are not numerous. More attention is given to the tolerance of grasses to flooding (see Beard, 1973). Letey et al. (1964) found that the vegetative growth of Newport Kentucky bluegrass was not restricted by a soil oxygen content as low as 0.02. Root growth was only affected at an O_2-concentration of 0.01. A similar figure was reported by Waddington & Baker (1965) with regard to Pencross creeping bentgrass (*Agrostis palustris* Huds.). Letey et al. (1964) report an ODR of $20 \times 10^{-8}\ g \cdot cm^{-2} \cdot min^{-1}$ as required for root growth of Newport Kentucky bluegrass. A value of about $15 \times 10^{-8}\ g \cdot cm^{-2} \cdot min^{-1}$ appeared to be the lower limit for root growth of the, warm season, common bermudagrass (*Cynodon dactylon* L.) (Letey et al., 1966). Waddington & Baker (1965) found that root growth of Merion Kentucky bluegrass was reduced only at an ODR below 5 to 9×10^{-8} g·cm^{-2}. min^{-1} and that Pencross creeping bentgrass grows well in soils having an ODR down to 3×10^{-8} g·cm^{-2}·min^{-1}. Gradwell (1965, 1967) found a consistent relationship between the growth of perennial ryegrass and ODR. The above-ground growth was reduced at an ODR below 10×10^{-8} g·cm^{-2}·min^{-1} and the root growth at values below 7.5×10^{-8} g · cm^{-2} · min^{-1}.

Most of the ODR-values mentioned as reducing growth of various grass species are considerably lower than the 20×10^{-8} g·cm^{-2}·min^{-1}, mentioned as limiting root growth of most crop species (Wiersma & Mortland, 1953; Bertrand & Kohnke, 1957; Letey et al., 1961, 1962a, b; Stolzy et al., 1961). Compared with other crops, grass has a good tolerance for a low oxygen availability. The low critical O_2-concentrations and ODR-values aforementioned and the tolerance of most grasses to flooding indicate this.

4.3.2 Measuring methods

To judge whether soil aeration is limiting grass growth, in this study both O_2-concentrations in the soil gas phase and oxygen diffusion rates (ODR) were measured under field conditions and compared with the oxygen demand of grass reported in literature (see Section 4.3.1). In addition to measurements of the O_2-concentration of the soil supplementary measurements of the oxygen diffusion rate are required, because for plant growth the rate of supply is as important or even more than the O_2-concentration itself.

The ODR was measured according to the method of Lemon & Erickson (1952). This method is based on the reduction of oxygen on the surface of a platinum micro-electrode inserted in soil when a certain voltage is applied between the platinum micro-electrode and the silver-silver chloride reference electrode. In the here presented cases the platinum micro-electrode had a diameter of 1 mm and was 7 mm long. The applied voltage was 0.7 Volt. The current resulting from the O_2-reduction is a measure for the oxygen diffusion rate to the platinum electrode acting as an O_2-sink. The ODR-measurements were performed at depths of 1, 5, 10, 15, 20, 30 and 40 cm below the soil surface.

To record the O_2-concentration with depth, soil gas samples were taken from small diffusion chambers burried at 5, 10, 20 and 40 cm below the surface. The oxygen content of these gas samples was measured by a Johnson & Williams Oxygen Analyser.

4.3.3 Oxygen diffusion rate

A survey of the ODR-measurements at the depths of 1, 5, 10 and 15 cm on Fields A, E and G is presented in Fig. 36. On the investigated fields the course in time of the ODR was rather similar: a gradual decrease in autumn and a, sometimes very sharp, increase in spring. Because the ODR is affected by soil water content, texture and bulk density, the measurements will vary when these soil properties change. The increasing soil water contents in autumn and the decreasing ones in spring may explain the picture shown in Fig. 36. Moreover, an

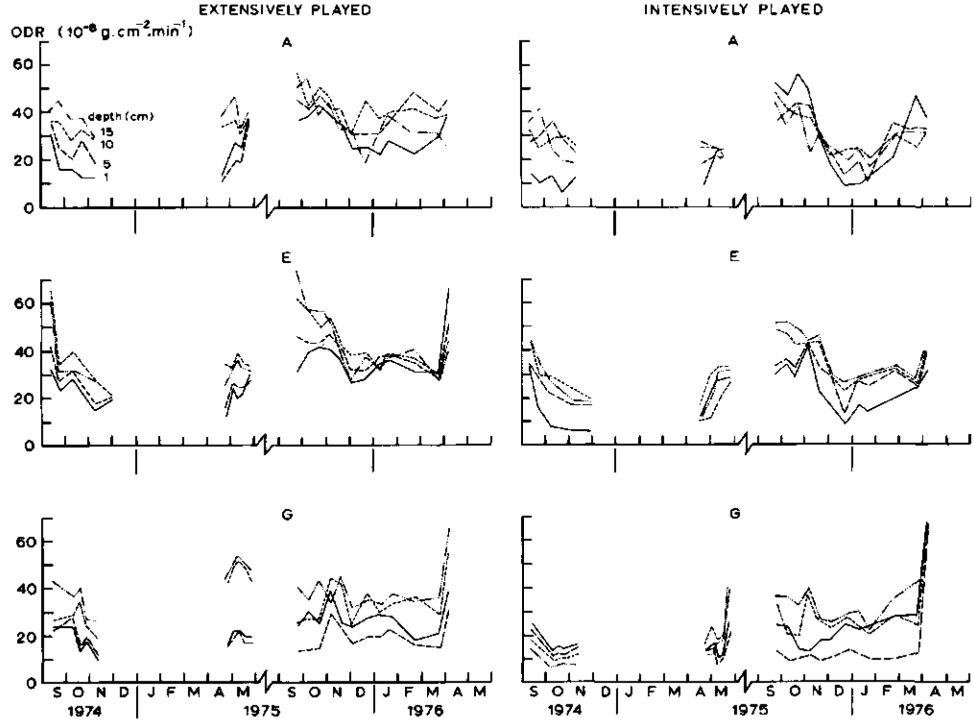


Fig. 36. Oxygen diffusion rates (ODR) as measured on extensively and intensively played plots on Fields A, E and G during the playing seasons 1974–75 and 1975–76.

increase in bulk density in the upper centimeters of the top layer after the start of the playing season may also contribute to a reduction in ODR. In soils a reduction in ODR with depth is generally observed (Lemon & Erickson, 1955; Doyle & McLean, 1958). This reduction is connected with a gradual increase in soil water content and bulk density with depth. However, the here presented ODR-measurements show that the ODR at 1 cm and to a less extent also the one at 5 cm depth were often considerably lower than those at greater depths. This points towards a higher diffusion resistance in the upper centimeters of the top layer, which must have been caused by compaction and blocking of the pores.

The difference in compaction between the extensively and intensively played parts is only reflected in the temporarily strongly lower ODR-values at the 1 and 5 cm depths on the intensively used parts of the fields.

4.3.4 Measured oxygen distribution profiles

The results of the oxygen concentration measurements of the soil gas phase during the playing seasons of 1974–75 and 1975–76 are summarized in Fig. 37. It appears that the oxygen status of the soil during the seasons was quite different. The period September 1974 up to January 1975 inclusive was an excessively wet

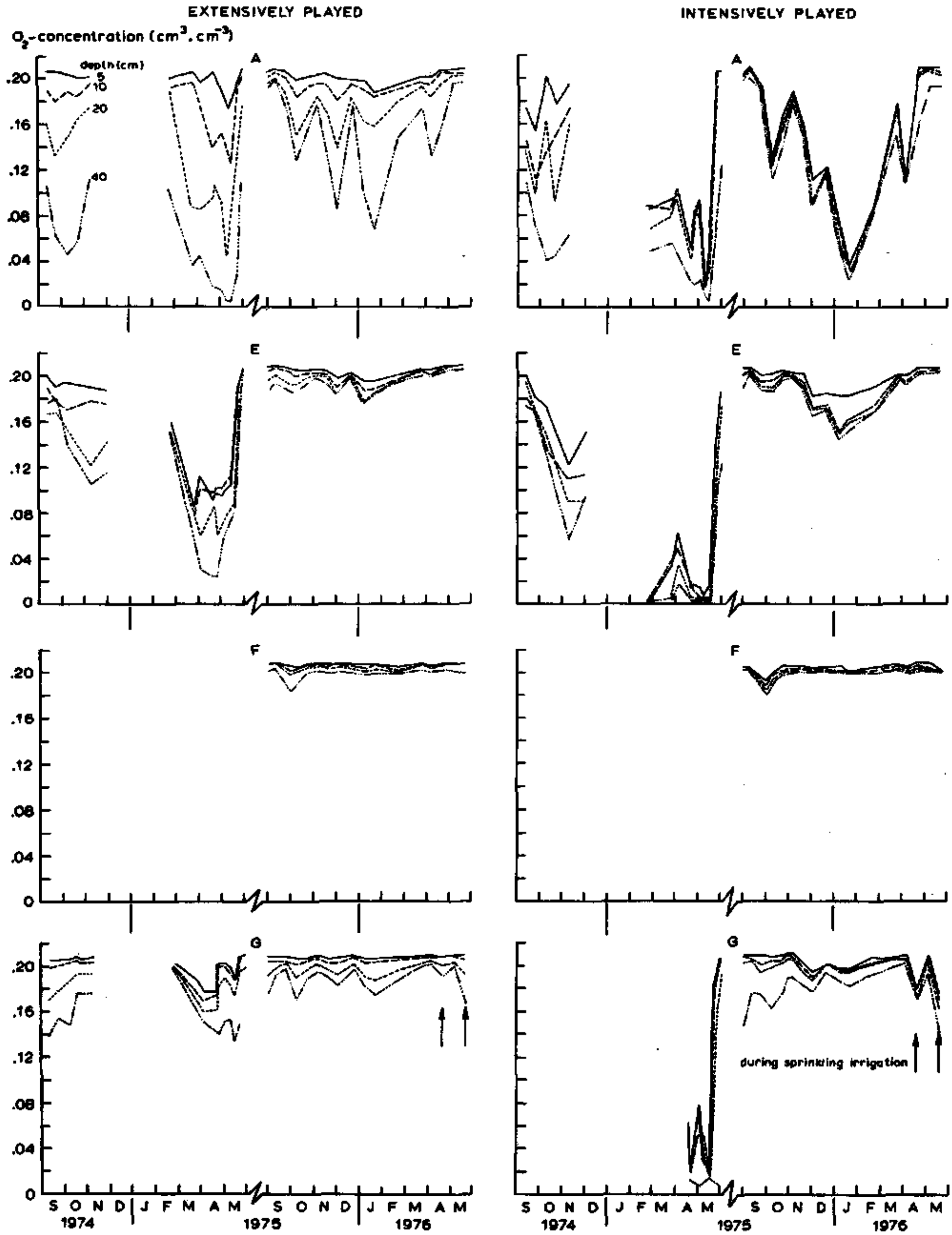


Fig. 37. Oxygen concentration in the soil gas phase of extensively and intensively played plots on the fields A, E, F and G during the playing seasons of 1974–75 and 1975–76. Measurements on field G were not possible in autumn 1974 because of continuously near saturated conditions of the profile.

period and also the spring of 1975 was rather wet (see Fig. 11). During the playing season of 1975–76 a continuous period with a precipitation surplus did not start before November and continued only up to the middle of February; January 1976 was very wet.

The measurements over 1974–75 show that the O_2-concentrations are reduced even at depths of 40 cm. This indicates a soil gas exchange limited by wet soil conditions. It is noteworthy that in autumn the O_2-content of the soil gas fluctuated around a higher level than in spring. From February 1975 onwards oxygen concentrations decreased sharply at all depths. This decrease was most pronounced on the intensively played parts, where O_2-concentrations tended to practically zero values. A sharp rise of the O_2-concentration was observed at all depths from mid-May. From the second decade of May onwards considerable evaporation started, with at the same time a sharp decrease in soil water pressure head. On 15 May 1975 still very low O_2-concentrations were measured in the upper 5 cm of the intensively played parts of the fields A and E at soil water pressure heads of -150 and -110 cm respectively. This may point to a discontinuity of the greater part of the air-filled pores by water-blocking. A decrease in soil water pressure head down to -350 and -300 cm respectively, as measured on 23 May, apparently removed this discontinuity as O_2-concentrations on that date were high.

In the next playing season only during the very wet month of January 1976 on the intensively played part of Field A a sharp decrease of the O_2-concentration over the upper centimeters occurred, while on field E a small decrease was present. This behaviour may have been caused by a lessening of oxygen diffusion through the top layer due to an omittance of adequate maintenance, such as timely dressing with sand. On the other fields such a decrease in O_2-concentration was not measured, although also there a compacted top layer was present. The reason for this favourable O_2-status, contrary to the 1974–75 season, was the drier weather and the therefore drier soil conditions during that winter period.

When a decrease in O_2-concentration was measured, than the greater part of the drop in concentration occurred in the upper 5 centimeters of the sandy top layer. Fig. 38 shows the O_2-measurements over 1974–75 averaged over autumn and spring separately, with the area of scatter around the mean values. The high values measured at the end of May 1975 have been excluded.

In spite of continuously very wet conditions, the O_2-concentrations in autumn 1974 were at a higher level than during spring 1975. The O_2-profiles in spring show a sharp decrease in O_2-concentration over the upper 5 cm of the top layer, particularly on the intensively played parts. On the extensively played parts the drop in O_2-concentration is less pronounced (Field E) or not present (Fields A and G). Below the depth of 5 cm a gradual decrease in O_2-concentration was observed.

The occurrence of the lowest ODR-values at 1 and 5 cm depths and the sharpest drop in O_2-concentration over the upper 5 cm, indicates that the compaction by playing is limited to a depth of about 5 cm. From pressure head profiles about the same compaction depth was found (see Section 2.6.2).

In explanation of the differences in O_2-distribution between autumn and spring

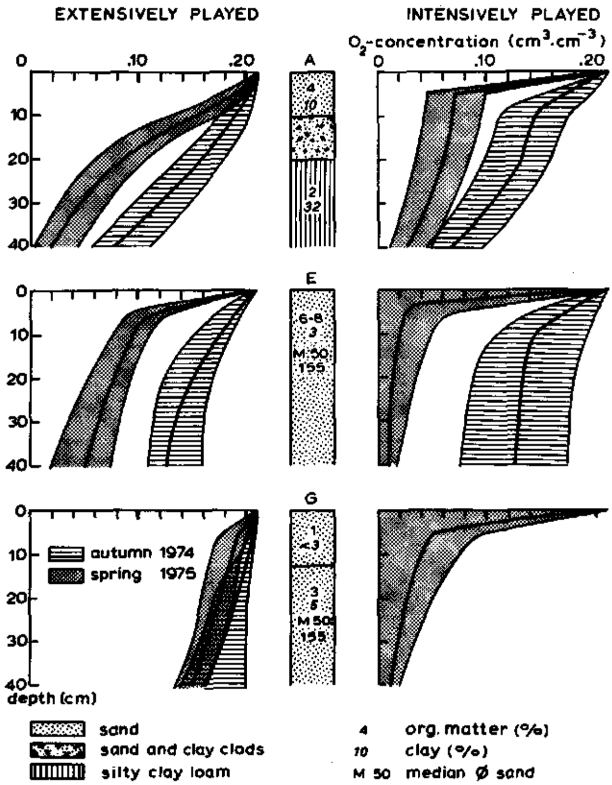


Fig. 38. Averaged oxygen profiles in autumn 1974 and spring 1975 on extensively and intensively played plots of Fields A, E and G.

the following can be said:

- During autumn and the first part of winter the O_2-consumption of the soil (respiration of roots and micro-organisms) decreases to a low level. Increasing acitity of the roots preceding the regrowth of the above-ground parts of grass and of micro-organisms leads to a higher O_2-uptake in spring.
- With the advance of the playing season the compaction of the top layer increases. Therefore the conditions for gas exchange between atmosphere and soil are in spring often more unfavourable than in autumn and winter.
- The drop in O_2-concentration, such as measured during the spring of 1975, may be caused by a high uptake of the grass roots, concentrated for more than 90% in the upper 5 cm, while the ODR in this layer will be reduced by compaction and wet soil conditions.
- Because of poor weather conditions a number of matches was cancelled in the autumn of 1974, so the competition programme had to be performed more intensively from January 1975 onwards. Therefore compaction was possibly more severe in spring than in autumn. This may have enlarged the differences between the oxygen status in autumn 1974 and spring 1975.

A similar reduction in O_2-concentration in the soil gas phase during spring was reported by Boynton & Compton (1944) for orchard soils (silty clay and light silty clay loam). A sandy loam did not show this spring reduction. Comparison of the O_2-distributions measured in 1974–75 and 1975–76 shows that the extent in which these seasonal fluctuations occur will depend on the combination of soil type and prevailing weather conditions.

4.3.5 Calculated oxygen distribution profiles

A better physical understanding of the effect of top layer compaction on the O_2-distribution in the soil can be obtained from a more theoretical approach of soil aeration. When dealing with the interchange of O_2 and CO_2 between soil and atmosphere, molecular diffusion is generally assumed as being the main process governing the transport of these soil gas components.

For the diffusion of a soil gas Fick's first law holds:

$$F = -D\frac{\partial C}{\partial z} \tag{11}$$

where

F = the flux ($cm^3 \cdot cm^{-2} \cdot s^{-1}$)

D = the diffusion coefficient of the gas ($cm^2 \cdot s^{-1}$)

$\frac{\partial C}{\partial z}$ = the driving force of the diffusion process with C the concentration ($cm^3 \cdot cm^{-3}$)

z = the length of the diffusion path (cm; taken positive downwards)

During the process of diffusion through the soil medium O_2 and CO_2 may be consumed respectively produced. This 'activity of the soil', originating from the respiration activity of roots and micro-organisms, is designated with the symbol β ($cm^3 \cdot cm^{-3} \cdot s^{-1}$). It acts as a sink in the case of O_2-consumption (negative sign) and as a source in the case of CO_2-production (positive sign).

Combination of Fick's law and the equation of continuity yields:

$$\frac{\partial G}{\partial t} = -\frac{\partial F}{\partial z} + \beta_z \tag{12}$$

where

G = the concentration of the gas ($cm^3 \cdot cm^{-3}$)

t = time (s)

z = the depth below the soil surface (cm)

If ε_g is the air-filled pore volume of the soil then $G = \varepsilon_g C$ and Eq. (12) can be written as:

$$\varepsilon_g \frac{\partial C}{\partial t} = \frac{\left(D\frac{\partial C}{\partial z}\right)}{\partial z} + \beta_z \tag{13}$$

At known diffusion coefficients and activity rates it is possible with Eq. (13) to forecast the vertical distribution of O_2-concentration in the soil. One-dimensional steady-state solutions of the diffusion equation were performed by Van Bavel (1951), Van Duin (1956), Currie (1962), Wesseling (1962) and Papendick & Runkles (1965, 1966), while Hoeks (1972) gives solutions for some non-steady state problems.

The factors responsible for the shape and differences between the O_2-concentration profiles measured in autumn 1974 and spring 1975 (see Fig. 38) can now be analyzed. If the change of O_2-concentration tends to be diurnal then the term $\partial C/\partial t$ in the diffusion equation may be set equal to zero (Currie, 1962). In that case the O_2-concentration and soil activity are independent of time. When the diffusion coefficient is considered to vary stepwise in the layers distinguished, Eq. (13) can be reduced to:

$$-\beta_z = \frac{\partial}{\partial z}\left(D\frac{\partial C}{\partial z}\right) \tag{14}$$

A grass sports field soil can be schematized as an active top layer of thickness λ, overlying an active subsoil of thickness $(Z-\lambda)$. Because of the uniformly dense root distribution in the top layer the O_2-consumption rate of this layer is set constant, i.e. $\beta_z = \beta$ for $0 < z < \lambda$. Rooting density (see Table 11) as well as microbiological activity decrease with depth, so for the subsoil a linear decrease of the O_2-consumption rate can be assumed according to Van Duin (1956) and Wesseling (1962):

$$\lambda < z < Z \quad \beta_z = \beta\left[1-\left(\frac{z-\lambda}{Z-\lambda}\right)\right] \tag{15}$$

or

$$\beta_z = \beta\left(\frac{Z-z}{Z-\lambda}\right) \tag{16}$$

To obtain a solution, Eq. (14) must be supplemented by appropriate boundary conditions:

$$\text{at } z=0 \quad C=C_0 \tag{17}$$

$$\text{at } z=Z \quad \frac{dC}{dz}=0 \tag{18}$$

$$\text{at } z=\lambda \quad D_1\frac{dC}{dz}=D_2\frac{dC}{dz} \tag{19}$$

with D_1 and D_2 the diffusion coefficients of the top layer and of the subsoil respectively. For the specified sink function, Eq. (16), integration of Eq. (14) yields the following solutions:

for the top layer:

$$C = C_0 + \frac{\beta}{D_1}\left[\frac{-z^2+(Z+\lambda)z}{2}\right] \tag{20}$$

for the subsoil:

$$C = C_0 + \frac{\beta Z\lambda}{2D_1} + \frac{\beta}{D_2}\left[\frac{z^3-3z^2Z+3zZ^2-\lambda^3+3\lambda^2Z-3\lambda Z^2}{6(Z-\lambda)}\right] \tag{21}$$

Calculations with Eqs (20) and (21) were carried out for various situations. The thickness of the active top layer (λ) was fixed at 5 cm and of the total active layer (Z) at 50 cm, except for one case where Z was variable.

Consumption of O_2 by grass roots depends on factors as temperature, air content, organic matter, soil fertility, prevailing O_2-concentrations, etc. A large variation exists in O_2-consumption rates (β) reported in literature (Wesseling, 1974). Greenwood (1969) reported an average O_2-uptake under United Kingdom conditions of $1.3\times10^{-7}\,cm^3\cdot cm^{-3}\cdot s^{-1}$ for soils carrying a mature crop and a highest value of $4.0\times10^{-7}\,cm^3\cdot cm^{-3}\cdot s^{-1}$ (cf. Wesseling, 1974). Bakker (personal communication, 1979) measured a β-value of $3.9\times10^{-7}\,cm^3\cdot cm^{-3}\cdot s^{-1}$ under pasture on a fertile clay soil in spring. In the present study β-values were taken to vary between 0.7 and $4.0\times10^{-7}\,cm^3\cdot cm^{-3}\cdot s^{-1}$.

The diffusion coefficients were derived from a power function, as reported by Bakker & Hidding (1960) and Bakker et al. (1980) for a number of soils:

$$\frac{D}{D_a} = a\varepsilon_g^b \tag{22}$$

where

D and D_a are diffusivities in soil and air ($cm^2\cdot s^{-1}$) respectively
ε_g is air-filled pore volume ($cm^3\cdot cm^{-3}$)
a and b are soil constants depending on pore geometry and aggregation degree

Bakker et al. (1980) concluded that below $D = 1.5\times10^{-4}\,cm^2\cdot s^{-1}$ deficient aeration conditions always exist. This D-value can be reached at different soil air contents depending on the type of soil. For the range where $1.5\times10^{-4} < D < 3.0\times10^{-3}\,cm^2\cdot s^{-1}$ the upper limit must be taken into account at high and the lower limit at low O_2-consumption rates.

For the top layer D-values of 4×10^{-3} and $4\times10^{-4}\,cm^2\cdot s^{-1}$ have been taken. The first value represents a well-structured and the second one a bad-structured sandy loam, both having an air-filled pore volume of $0.10\,cm^3\cdot cm^{-3}$. The subsoil was a well-structured humous sandy loam with D-values of 6.5×10^{-4} and $1.7\times10^{-3}\,cm^2\cdot s^{-1}$ at ε_g-values of 0.05 and $0.10\,cm^3\cdot cm^{-3}$ respectively. A summary of the situations considered is given in Table 12, while the results of the calculations are shown in Fig. 39.

Comparison of Situations A and B shows the effect of reduction of the

Table 12. Values of the input parameters from Eqs (20) and (21) used for the calculation of the O_2-distributions presented in Fig. 39.

Situation	Curve Fig. 39	λ (cm)	Z (cm)	D_1 ($cm^2 \cdot s^{-1}$)	D_2 ($cm^2 \cdot s^{-1}$)	β ($cm^3 \cdot cm^{-3} \cdot s^{-1}$)
A	1	5	50	4×10^{-3}	1.7×10^{-3}	0.7×10^{-7}
	2					1.5×10^{-7}
	3					3.0×10^{-7}
	4					4.0×10^{-7}
B	1	5	50	4×10^{-4}	1.7×10^{-3}	0.7×10^{-7}
	2					1.5×10^{-7}
	3					3.0×10^{-7}
	4					4.0×10^{-7}
C	1	5	50	4×10^{-4}	6.5×10^{-4}	0.7×10^{-7}
	2					1.5×10^{-7}
	3					2.0×10^{-7}
	4					2.5×10^{-7}
	5					3.0×10^{-7}
D	1	5	20	4×10^{-4}	1.7×10^{-3}	3.0×10^{-7}
	2		30			
	3		40			
	4		50			

O_2-diffusion coefficient of the top layer on the O_2-distribution in the profile at different rates of O_2-uptake. In the case of a well-structured soil covered by a well-structured top layer (Situation A) a reduction in O_2-concentration is observed at high O_2-uptake rates only. Examples of this situation can be found on recently constructed fields or on extensively played parts of established fields. Situation B demonstrates the effect of a deteriorated structure of the top layer. The similarity in shape with the measured O_2-profiles in Fig. 38 is obvious: a low D-value in the top layer with high O_2-uptake rates gives O_2-distribution curves which correspond well with the O_2-profiles measured in spring 1975. The effect of

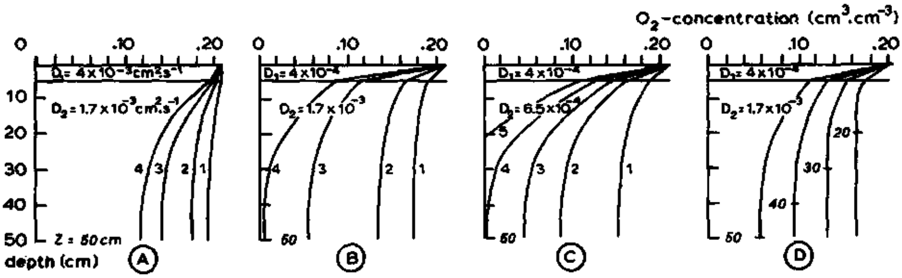


Fig. 39. Effect of differences in diffusion coefficients of top layer and subsoil, rate (1 through 5) and depth (Z) of oxygen consumption (see Table 12) on the oxygen distribution in soil.

an increased diffusion resistance of the subsoil, for instance as a result of heavy textures or high soil water contents, is illustrated by Situation C. High O_2-uptake rates lead towards very low oxygen concentrations at shallow depths. Situation D shows the influence of the thickness of the active layer on the O_2-distribution. The greater the rooting depth the stronger the drop in O_2-concentration at equal activity. Reduction of rooting depth may possibly be interpreted as a reaction of the plant to compensate for insufficient soil aeration.

4.4 Discussion

Cool season turfgrasses mostly applied on sports fields in the Netherlands are perennial ryegrass and Kentucky bluegrass. On the grass sports fields involved in the investigation, perennial ryegrass and annual bluegrass dominated for 90 to 100%. The portion of perennial ryegrass amounted to about 65% (see Table 9).

As appears from the measurements shown in Sections 4.3.3 and 4.3.4, playing affects the aeration status of grass sports fields as characterized by the oxygen diffusion rate (ODR) and the O_2-concentration of the soil gas phase.

The incomplete measurements of ODR during the 1974–75 playing season give rise to the assumption that ODR-values may temporarily have occurred near or below the critical value of $7.5 \times 10^{-8}\ g \cdot cm^{-2} \cdot min^{-1}$, found by Gradwell (1967) as limiting root growth of perennial ryegrass. During the 1975–76 playing season this value never was found. During spring 1975 low O_2-concentrations were observed, being near the level of 0.01 mentioned by Letey et al. (1964) as limiting root growth of Newport Kentucky bluegrass. How far the dominating perennial ryegrass suffered from these temporarily low ODR and O_2-levels is difficult to establish.

Some information with regard to the reaction of the sward on the measured ODR and O_2-concentration may be obtained from the course of the sward density on three differently played experimental plots of the four involved grass sports fields (Fig. 35). In spite of completely different aeration conditions during the playing seasons 1974–75 and 1975–76, on the four fields the course of the sward density during both seasons is rather similar. The poorer aeration conditions during part of the playing season 1975–76 on Field A apparently did not result in a sward density deviating from those on Fields E and F, both having much better O_2-concentrations. From the beginning of April 1975 a rather vigorous recovery of the sward was observed despite poor aeration conditions. After the start of each playing season the sward density decreases because the abrasion of the grass exceeds the growth rate. From about mid-March, at the start of regrowth, the recovery of the sward exceeds the abrasion caused by playing.

The only perceptible effect of the less favourable aeration in spring 1975 was a slight yellowing of the grass during a short period around mid-May on the intensively played areas of some fields. This yellowing may be attributed to a nitrogen deficiency caused by impaired nutrient uptake. Some investigators (Van Hoorn, 1958; Cline & Erickson, 1959; Sieben, 1974; Feddes & Van Wijk, 1976) found that increasing the nitrogen dressing reduces to a high degree the adverse effects of low oxygen supply encountered when high groundwater levels are present.

The general impression gained both from comparison of the measured ODR and O_2-concentrations with values reported in literature as limiting for root growth and from the reaction of the sward on the measured oxygen status of the soil, does not suggest seriously injurious effects of deficient soil aeration on grass viability on grass sports fields. This despite the rather high bulk densities of the sandy top layers giving the soil strength necessary for good playing conditions. It appears that direct injury to the sward by playing, widely overshadows the indirect consequences of playing such as an increased mechanical resistance for root growth and a reduced soil aeration.

5 Optimizing top layer, subsoil and drainage combinations

5.1 General

In Chapters 2 and 3 it was found that playing conditions can be improved by increasing the density and organic matter content and decreasing the water pressure head of the top layer. Increase in density and organic matter content are generally at the expense of the hydraulic conductivity. A compaction too severe and hence a decrease in hydraulic conductivity can induce too wet and therefore too soft top layer conditions.

When dealing with the influence of compaction and organic matter content on the soil water conditions of the top layer, factors other than its soil hydrological properties also must be taken into consideration. In this chapter attention will be paid to which extent the soil water status of the top layer, under the prevailing weather conditions, is influenced by:

- compaction of top layers that differ in organic matter content;
- thickness of the top layer;
- type of subsoil;
- subsurface drainage;
- a sandy drainage layer constructed between the top layer and subsoils of poor permeability.

Once the influence of these factors is quantified, it is possible to indicate how they best can be combined under different conditions.

To be able to evaluate these influences the soil hydrological properties (hydraulic conductivity and water characteristic) for differently composed and compacted top layers as well as various subsoils were determined. For the shortcoming of these properties the resulting soil water conditions are decisive. To establish the soil water conditions, two approaches for soil water flow have been applied, a steady-state respectively a non-steady-state one.

Taking steady-state conditions for the soil water flow, an estimate of duration, frequency and depth of ponding has been made from amount–duration–frequency precipitation curves. From ponding depths and soil water characteristics it then is possible to derive the thickness a certain top layer must have to prevent ponding. To illustrate the effects of top layer, subsoil and subsurface drainage upon soil water conditions in top layer and subsoil, pressure head profiles have been calculated. In this manner such a steady-state approach can be a valuable tool to sports fields constructors to evaluate in a rather simple way the effects of the measures intended.

Water flow through soils, however, occurs almost never under steady-state conditions. Therefore the effects have also been studied under non-steady-state conditions. To that purpose models can be used that simulate the variation in time of the pressure head in the top layer as a combined effect of precipitation, hydrological characteristics of top layer and subsoil and the characteristics of the drainage system. With the aid of the density and pressure head limits obtained from the field and laboratory measurements, duration and frequency of inadequate playing conditions then can be derived from the simulated course of the pressure head.

5.2 Soil materials used

5.2.1 Top layers

As top layer materials the fine sand mixtures given in Table 8 were chosen. For each level of organic matter content the soil water characteristic, $\psi(\theta)$, and hydraulic conductivity, $k(\psi)$, curves were determined for three different densities. To this purpose samples with a height of 30 cm and a diameter of 10 cm were prepared.

To measure the $\psi(\theta)$ and $k(\psi)$-curves, an evaporation method described by Boels et al. (1978) was applied. The procedure of this method is that during evaporation at the top of the sample the soil water pressure head is measured with tensiometers at various depths and at fixed time intervals. Simultaneously the loss of weight of the sample is registered. From the measured data in first instance the $\psi(\theta)$-relationship was calculated with the iteration procedure described by Wind (1969). The $k(\psi)$-relationship was calculated from the measured data with Eq. (6). The flux v at any depth z was obtained from the amount of water evaporated per unit time through the top of the sample (that is the loss of weight of the sample) plus the amount of water extracted over depth z per unit time (having a negative value). The hydraulic head gradient was obtained from the ψ-readings at different depths and times. Hence $k(\psi)$ could be found as the ratio of the flux over the hydraulic head gradient.

The $\psi(\theta)$-relationships obtained clearly show the effect of compaction of sand with increasing organic matter contents (Fig. 40). Compaction increases the slope of the curves and the more, the higher the organic matter content. The increase in slope illustrates the proportional increase of the fine pores, at the expense of hydraulic conductivity and storage capacity (see Table 13). From measurements in the field, as reported in Chapter 2, it appeared that during the main part of the playing season the actual soil water pressure head varies within a range from 0 down to about -80 cm. It should be kept in mind that the sands with higher organic matter contents when compacted to high densities can store only a few mm of rain within this range.

The $k(\psi)$-curves are given in Fig. 41 and presented as an exponentional relationship between k and ψ, such as suggested by Gardner (1958) and Rijtema (1965):

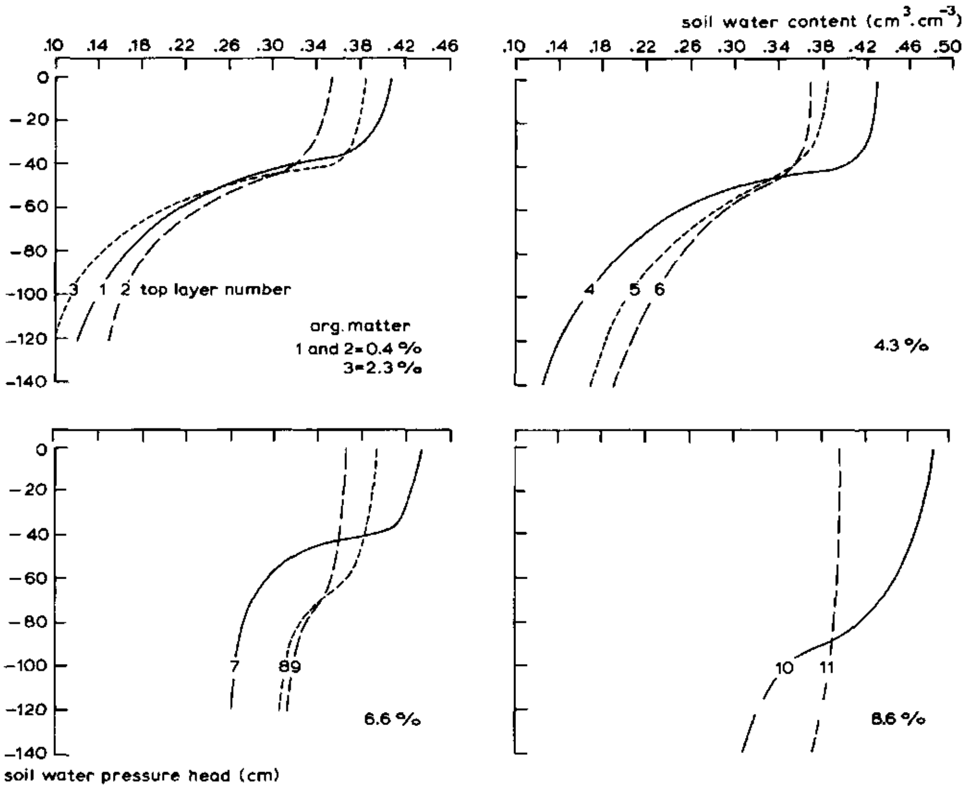


Fig. 40. Soil water characteristics of 11 fine sands with different organic matter contents at various compaction levels, used as top layers (see also Table 14 and Fig. 41).

$$k = k_0 \, e^{\alpha\psi} \tag{23}$$

where

k = hydraulic conductivity ($cm \cdot d^{-1}$)
k_0 = hydraulic conductivity at $\psi = 0$ ($cm \cdot d^{-1}$)
ψ = pressure head (cm)
α = soil constant (cm^{-1})

Through the measured points the best fitting exponential curve has been calculated, giving a straight line when the $k(\psi)$-relationship is plotted on a semi-logarithmic scale. Values for α and k_0, obtained from the exponential-curve fit, are represented in Fig. 41 by the slope respectively the intersection of the curves with the ordinate and are given in Table 14. This Table gives a conspectus of the densities of the used sands together with the hydraulic conductivity characteristics k_0 and α. Because of failure of some tensiometers in some samples, the objective to determine the $k(\psi)$ and $\psi(\theta)$-relationships at three densities for each organic matter content level could not fully be realized. In the following text

Table 13. Storage capacity (in mm per 10 cm layer thickness) within the range of soil water pressure heads (ψ) from 0 down to -100 cm of the 11 top layers used (see also Table 14).

ψ	Top layer										
(cm)	1	2	3	4	5	6	7	8	9	10	11
0 to −20	1.1	0.8	0.5	0.6	0.4	0.4	1.0	0.5	0.4	0.6	0.0
0 to −30	2.6	1.6	1.3	1.3	1.0	0.6	1.8	0.8	0.6	1.0	0.0
0 to −40	9.6	3.4	3.5	3.6	3.0	1.8	5.6	1.1	0.8	1.6	0.1
0 to −60	19.2	11.9	18.8	18.0	10.4	8.4	14.4	2.6	1.4	3.3	0.2
0 to −80	24.0	16.8	24.5	23.2	15.2	11.7	16.2	6.6	3.9	6.5	0.5
0 to −100	26.7	18.9	26.7	26.7	18.4	14.4	17.2	8.2	4.8	13.1	0.9

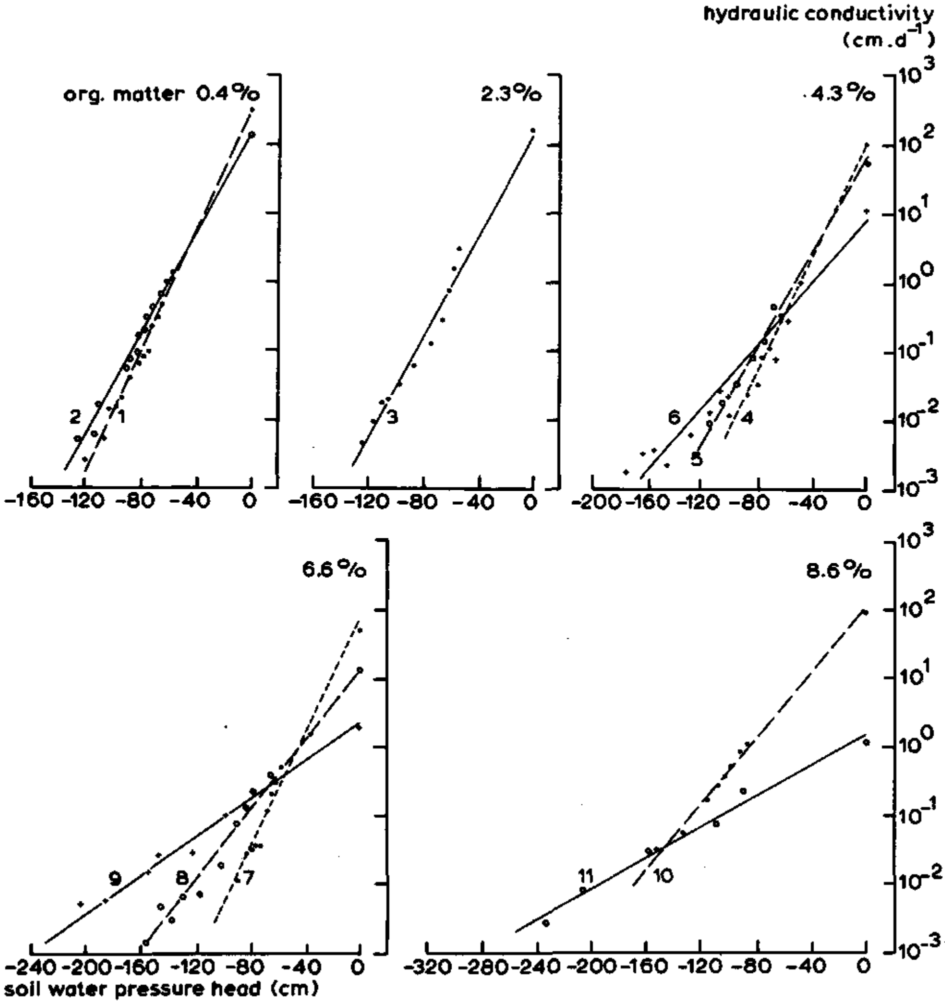


Fig. 41. Unsaturated hydraulic conductivity of 11 fine sands with different organic matter contents at various compaction levels, used as top layers (see also Table 14 and Fig. 40).

Table 14. Organic matter content, relative density (ρ') and bulk density (ρ), pore volume (ε) and the hydraulic conductivity characteristics k_0 and α of the 11 top layers used.

Top layer	Org. m. (%)	ρ'	ρ ($g \cdot cm^{-3}$)	ε ($cm^3 \cdot cm^{-3}$)	k_0 ($cm \cdot d^{-1}$)	α (cm^{-1})
1	0.4	0.10	1.571	0.407	323.2	0.100
2	0.4	0.59	1.716	0.353	155.6	0.085
3	2.3	0.47	1.604	0.383	146.3	0.085
4	4.3	0.45	1.510	0.426	118.6	0.096
5	4.3	0.61	1.577	0.385	65.1	0.079
6	4.3	0.72	1.626	0.367	8.4	0.053
7	6.6	0.46	1.423	0.436	72.3	0.095
8	6.6	0.60	1.531	0.394	13.1	0.058
9	6.6	0.80	1.592	0.370	2.5	0.029
10	8.6	0.29	1.285	0.483	105.7	0.054
11	8.6	0.73	1.495	0.399	1.5	0.026

the various top layers will be indicated by the numbers mentioned in this table. Fig. 41 and Table 14 show that an increase in bulk density (compaction) is coupled with a decrease in k_0. This decrease is the more pronounced, the higher the organic matter content. The slopes α are also affected by change in either organic matter content or bulk density or both. At lower organic matter contents the slopes are steeper and change less at increasing bulk densities. This implies that the hydraulic conductivity decreases more strongly with decreasing soil water pressure heads and is less affected by compaction, at low than at higher organic matter contents.

5.2.2 Subsoils

Subsoils that have different hydrological properties will affect the water conditions in the top layer also differently. Therefore three subsoils with different hydraulic conductivities were chosen: a humous medium sand, a sandy clay loam and a silty clay loam. The silty clay loam and the humous medium sand are the subsoils of Fields A and F described in Chapter 2. The $\psi(\theta)$ and $k(\psi)$-relationships of these subsoils (Fig. 42) were determined by a so-called instantaneous profile method. This method consists of a simultaneous measurement of the change in water content as well as of the pressure head distribution during drainage of soil profiles in situ (Hillel et al., 1972). In addition a third subsoil, a sandy clay loam used by Wind (1976), was chosen as an intermediate between the two other ones with regard to hydraulic conductivity. The main properties of the three subsoils are summarized in Table 15. The subsoils more or less span the range from well to poorly permeable soils. The difference in storage capacity between the sandy and the silty clay loam as given by the $\psi(\theta)$-relationship is small, while the hydraulic conductivities of the two subsoils widely differ. The humous medium sand has a more favourable $\psi(\theta)$ as well as $k(\psi)$-relationship than the two other ones.

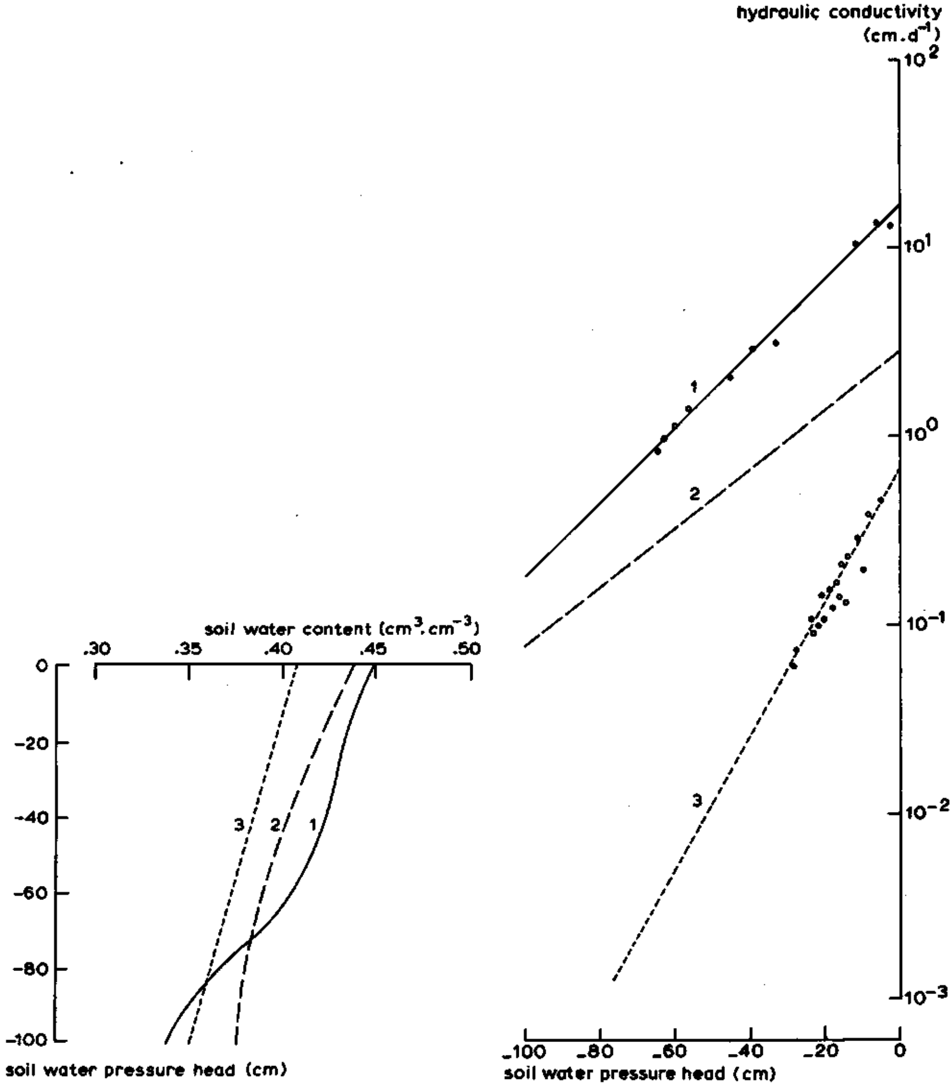


Fig. 42. Soil water characteristics (left) and unsaturated hydraulic conductivity (right) of the 3 subsoils used (see also Table 15).

Table 15. Clay and organic matter content, bulk density (ρ) and the hydraulic conductivity characteristics k_0 and α of the subsoils used.

	Clay (%)	Org. m. (%)	ρ ($g \cdot cm^{-3}$)	k_0 ($cm \cdot d^{-1}$)	α (cm^{-1})
1. humous medium sand	4	5.9	1.26	16.40	0.045
2. sandy clay loam				2.78	0.035
3. silty clay loam	32	5.1	1.28	0.65	0.082

5.3 Density and pressure head limits for adequate playing conditions

In Chapter 2 it was found that playing conditions can be characterized by the soil strength as measured with a penetrometer. At a soil strength of 1.4 MPa deformation of the top layer does not occur on intensively played parts. It appeared from Section 2.5 that top layers of grass sports fields satisfying over the years to a large extent this soil strength requirement, are compacted to a relative density of 0.45 or higher. In that case the playing conditions may still be insufficient because of soil conditions being too wet. As such can be considered from a play-technical point of view the occurrence of ponding or a too high soil water pressure head with regard to soil strength. From relationships between penetration resistance and pressure head at different bulk densities, obtained from field and laboratory measurements (see Sections 2.7 and 3.4.4) pressure heads critical for soil strength and for adequate playing conditions could be derived. The field measurements did show that top layers with an organic matter content in the range from 5 to 8% and a relative density of 0.45 or higher have a penetration resistance below 1.4 MPa at pressure heads higher (wetter) than −30 cm. At organic matter contents of about 3% (Field G, Fig. 18) the penetration resistance falls below 1.4 MPa if the pressure head is about −10 cm at a relative density of about 0.45. The laboratory findings showed a sharp decrease in penetration resistance at pressure heads higher than −30 cm for compacted sands with 6.6 and 8.6% organic matter content. For compacted sand with 4.3% organic matter an obvious decrease in soil strength was observed at heads higher than −15 cm. Sands with 0.4 and 2.3% organic matter showed a limited decrease in penetration resistance over the pressure head range from −50 to −30 cm, while the soil strength hardly decreased over the range from −30 to 0 cm. On basis of these data the following values of relative density, bulk density and soil water pressure head can be formulated as required for adequate playing conditions (Table 16).

Table 16. Minimal relative density (ρ') (i.e. degree of compaction), minimal bulk density (ρ) and maximal soil water pressure head (ψ), required for a soil strength sufficient for intensive playing of grass covered sandy top layers with different organic matter contents.

Org. m. content (%)	ρ'	ρ ($g \cdot cm^{-3}$)	ψ (cm)
1	0.45	1.65	0
2	0.45	1.61	0
3	0.45	1.56	−10
4	0.45	1.52	−20
5	0.45	1.47	−30
6	0.45	1.44	−30
7	0.45	1.41	−30
8	0.45	1.38	−30

To reach a relative density of 0.45 for sands with the given organic matter contents the bulk densities mentioned in Table 16 must be obtained. These bulk densities were derived from Fig. 23. To judge whether the top layers presented in Table 14 have adequate playing conditions the limits given in Table 16 have been used. With exception of the top layers 1 and 10 they all satisfy the density limits. They have insufficient soil strength only then, when the pressure head exceeds the limits given. The top layers 1 and 10 have relative densities and bulk densities lower than required. According to Fig. 18 they will have a ψ-limit lower than the more compacted top layers. For top layer 1 the ψ-limit estimated from Fig. 18 is −40 cm and for top layer 10, −60 cm.

Considering these ψ-limits it should be kept in mind that the lower the pressure head limit, the longer the total duration and the higher the frequency of the occasions on which this limit is exceeded during the wet season, and the more lastingly and frequently the field will be unplayable.

5.4 Steady-state approach of soil water conditions

5.4.1 Water balance approach of ponding

Playing conditions of grass sports fields can adversely be influenced by ponding. Assuming that water flow through the soil occurs under steady-state conditions, estimation of duration, frequency and depth of ponding is possible. This assumption implies that both flow rate and water content in the soil do not change with time. Examples of such a determination of ponding have been given earlier by Van Duin (1955) for arable land and by Van Wijk (1973) for grass sports fields.

Ponding will occur when over a certain period the amount of precipitation (*P*) exceeds the sum of the amount of water that infiltrates into the soil (*I*) and of the amount that can be stored in the top layer (*S*):

$$P > I + S \tag{24}$$

5.4.1.1 Prospective precipitation amounts

Amounts of precipitation which can occur or are exceeded over certain time intervals at certain frequencies are presented in Fig. 43. The figure gives the amounts of precipitation which can be expected over the entire year once in 1, 2, 5, 10 and 20 years and over the wettest part of the playing season (September through November, indicated by autumn) once in 0.2, 0.5, 1, 2 and 5 years. The amount–duration–frequency precipitation curves for the entire year are based on precipitation amounts over time intervals of 20, 30, 60, 90 and 120 minutes and 1 day (KNMI, 1978). The curves for autumn are calculated from frequency distributions (KNMI, 1966a) of amounts of rain in that three monthly period for time intervals of 5, 15, 30, 45, 60 and 90 minutes. In a double logarithmic plot the relationship between amount and duration of precipitation seems to be linear. Extrapolation to longer periods (dashed part of the lines) have been made. The amounts of rainfall in short periods given by the lines for the entire year are larger

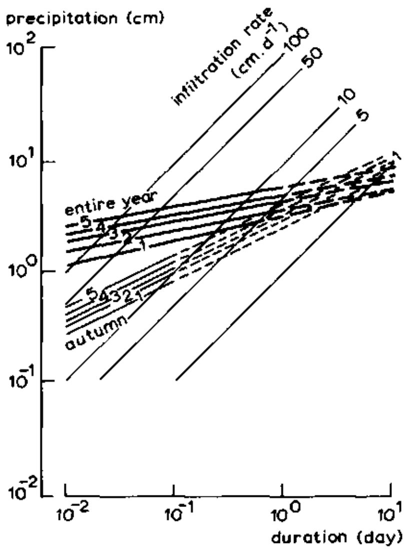


Fig. 43. Amount–duration–frequency (1 through 5) precipitation curves for the entire year and for autumn (see also Table 17), as well as curves of cumulative amounts of infiltration corresponding with different infiltration rates.

Table 17. Values of P_1 and n in Eq. (26) describing the amount–duration–frequency precipitation curves given in Fig. 43.

Curve	Frequency	P_1 (cm)	n
Entire year			
1	once per 1 year	3.09	0.225
2	once per 2 years	3.58	0.203
3	once per 5 years	4.34	0.203
4	once per 10 years	4.84	0.193
5	once per 20 years	5.59	0.190
Autumn			
1	5 times per year	2.51	0.506
2	2 times per year	2.99	0.491
3	once per 1 year	3.30	0.447
4	once per 2 years	3.60	0.449
5	once per 5 years	4.15	0.450

than those given by the lines for autumn. This is caused by the fact that over the entire year summer showers of high intensities are included. At a duration of 1 day the prospective amounts of rain at frequencies of once per 1, 2 and 5 years are of the same order for the entire year and autumn.

According to Fig. 43 the relationship between amount of precipitation P (cm), and duration t (day), satisfies:

$$\log P = n \log t + \log P_1 \tag{25}$$

or

$$P = P_1 t^n \tag{26}$$

where P_1 is the amount of precipitation (cm) which is reached or exceeded in one day with a certain frequency of occurrence and n is the slope of the curve. Values of P_1 and n for the curves presented in Fig. 43 are summarized in Table 17.

5.4.1.2 Maximal amount of precipitation to be stored

In Fig. 43 also curves of cumulative infiltration are drawn corresponding to infiltration rates of 1, 5, 10, 50 and 100 $cm \cdot d^{-1}$. When an infiltration curve lies below an amount–duration–frequency precipitation curve, ponding occurs. The frequency of ponding is the same as the frequency of the precipitation curve involved.

The amount of water to be stored in the top layer to be put on the soil to prevent ponding, can be derived from the simplified water balance equation for the soil:

$$S = P - I \tag{27}$$

Substitution of Eq. (26) into Eq. (27) and writing for $I = it$, yields:

$$S = P_1 t^n - it \tag{28}$$

where
i = the infiltration rate ($cm \cdot d^{-1}$)

If evaporation diminishes ponding, this can be accounted for in the precipitation term. With Eq. (28) the relation between depth and duration of ponding can be calculated for various frequencies of occurrence. Fig. 44 gives an example for a soil with an infiltration rate of 5 $cm \cdot d^{-1}$. The maximum of the curves yields the amount of rain that is to be stored in the top layer to be put on the soil to prevent ponding.

The duration of ponding on the soil without top layer can be read from the intersection of the precipitation and infiltration curves, thus where:

$$P_1 t^n = it \tag{29}$$

or when:

$$t = \left(\frac{i}{P_1}\right)^{1/n-1} \tag{30}$$

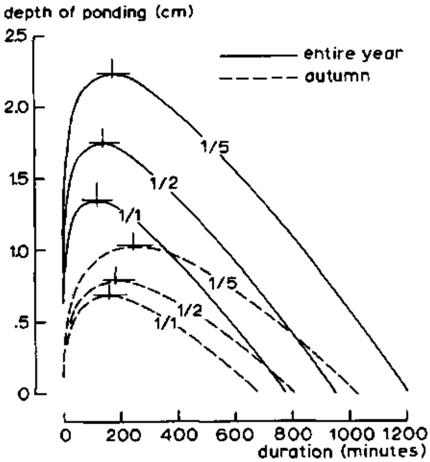


Fig. 44. Depth versus duration of ponding at frequencies of occurrence of once per 1, 2 respectively 5 years, for the entire year as well as for autumn for a soil with an infiltration rate of $5\,cm \cdot d^{-1}$.

Eq. (28) represents a second degree curve with a maximum at $\frac{dS}{dt} = 0$. The critical duration at which the amount of precipitation to be stored is maximal, thus is found as:

$$t = \left(\frac{i}{nP_1}\right)^{1/n-1} \tag{31}$$

Combining Eqs (28) and (31) yields:

$$S = P_1 \left(\frac{i}{nP_1}\right)^{n/n-1} - i\left(\frac{i}{nP_1}\right)^{1/n-1} \tag{32}$$

With Eq. (32) the maximal amount of precipitation to be stored in the to be designed top layer can be calculated (Fig. 45). The lower the allowed frequency of occurrence of ponding the larger the maximal amount of rain to be stored in the top layer for a given infiltration rate of the subsoil. Especially in the range of low infiltration rates the maximal amount of rain to be stored increases sharply with decreasing frequency. From Fig. 45 can be read for example, that on a soil with an infiltration rate of $5\,cm \cdot d^{-1}$ at least 1.8 cm of rain must be stored in an added top layer to prevent ponding more frequently than once per 2 years as based on amount–duration–frequency precipitation curve for the entire year. When the autumn precipitation curves are used the required storage capacity amounts to 0.8 cm. Therefore when designing storage capacities of top layers amount–duration–frequency precipitation curves should be used that are appropriate for the playing season considered.

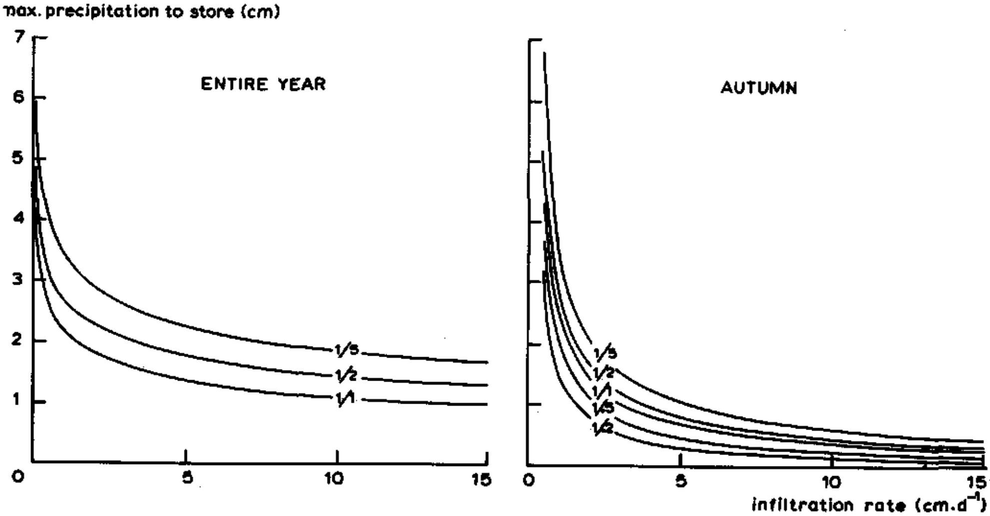


Fig. 45. Maximal amounts of precipitation to be stored in the to be added top layer to prevent ponding more frequently than once per 1, 2 respectively 5 years for the entire year and once per 0.2, 0.5, 1, 2 respectively 5 years for autumn, versus the infiltration rate of the subsoil.

5.4.1.3 Required thickness of the top layer

If a criterion for acceptable duration and frequency of ponding is known, it is possible to determine the required infiltration rate of the subsoil and storage capacity of the top layer to be applied. For example, the criterion is set that ponding must not occur longer than 2 hours once in two years. Inserting in Eq. (29) $t = 0.083$ day (= duration of 2 hours) and the constants (see Table 17) describing the amount–duration–frequency precipitation curve for once per 2 years (entire year curve) it is found that the subsoil must have an infiltration rate of $25.9\,\text{cm}\cdot\text{d}^{-1}$ to satisfy the criterion. The maximal ponding depth which must be accepted than is 1.15 cm, reached or exceeded after a rainfall period of 16 minutes.

If the infiltration rate of a soil is too low, ponding can be prevented by loosening of the soil, replacing the soil by a better one or covering the soil with a top layer with a high infiltration rate and storage capacity. In the Netherlands covering the soil with a sandy top layer is a common measure in sports field construction. The main objective is to make the surface more suitable for playing and to protect the underlying soil against deterioration of structure by compaction. To this purpose a thickness of the sandy top layer of about 5 to maximally 10 cm is sufficient as it corresponds with the depth influenced by compaction caused by playing (see Sections 2.6.2 and 4.3.4). At low infiltration rates of the subsoil the top layer serves at the same time as a temporary storage for a precipitation surplus. The thickness of the top layer necessary to store a certain surplus can be derived from the soil water characteristic of the top layer material.

To illustrate this Top layers 4 and 5 of Table 14 were chosen. Both have rather high saturated hydraulic conductivities but differ with regard to their soil water characteristics (see Fig. 40). It is assumed that the pore volume corresponding with the ψ-interval between -20 and -80 cm is available to temporarily store the precipitation surplus. The limit of $\psi = -80$ cm was chosen because during the wet part of the playing season the top layer does not drain below this limit. In view of the soil strength, the top layers involved should not be wetted above a ψ-value of -20 cm (Table 16). Within the range $-20 > \psi > -80$ cm Top layers 4 and 5 can store 2.26 respectively 1.48 cm water per 10 cm depth. In drier periods a larger part of the pore volume will be available.

Fig. 46 shows for the Top layers 4 and 5 the thickness required to prevent ponding on smooth horizontal fields more frequently than once per 1, 2 and 5 years (entire year curves) at various rates of infiltration of the subsoil. Below an infiltration rate of the subsoil of $5\ \mathrm{cm \cdot d^{-1}}$ the thickness of the top layer required rapidly increases. Also the allowable frequency of ponding chosen highly influences the thickness required. Assuming that Top layers 4 respectively 5 overlie the 3 subsoils mentioned in Table 15, the thickness of the top layer required to prevent ponding more frequently than once per 1, 2 and 5 years is derived from Fig. 46. The results are given in Table 18. Taking into account actual infiltration measurements in the field, showing an initial infiltration rate decreasing rapidly down to a constant rate corresponding with the saturated hydraulic conductivity, the infiltration rate of the subsoils was set equal to their k_0-values. Depending on the storage capacity of the top layer and the allowable frequency of ponding, on a poor permeable soil a considerable thickness of the top layer additional to the 5 to 10 cm minimally required may be necessary to prevent ponding (see also De Jong, 1979).

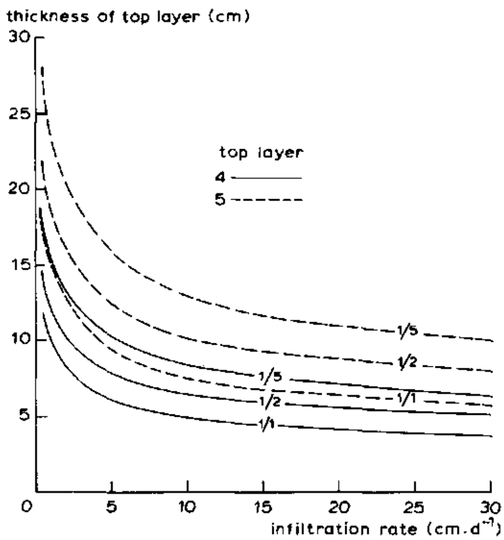


Fig. 46. Thickness of the to be added Top layers 4 and 5 (see Table 14) required to prevent ponding more frequently than once per 1, 2 and 5 years, versus the infiltration rate of the subsoil.

Table 18. Thickness (cm) of Top layers 4 and 5 required to prevent ponding more frequently than once per 1, 2 respectively 5 years when overlying a humous medium sand, sandy clay loam and silty clay loam.

Subsoil	Humous medium sand			Sandy clay loam			Silty clay loam		
i (cm·d^{-1})	16.4			2.78			0.65		
Once per .. years	1	2	5	1	2	5	1	2	5
Top layer 4	4.3	5.9	7.5	7.3	9.2	11.8	11.1	13.3	17.0
Top layer 5	6.7	9.1	11.6	11.3	14.3	18.2	17.2	20.7	26.3

5.4.2 Soil water conditions in the top layer

5.4.2.1 Influence of hydraulic conductivity of top layer and subsoil

The soil water pressure heads existing under steady-state flow conditions in the top layer depend on precipitation, evaporation, hydraulic conductivity of top layer and subsoil, drain depth and drain intensity. The final significance of these factors for the pressure head in the top layer is shown by pressure head profiles. These can be calculated from Darcy's equation for unsaturated vertical water flow.

The calculation of the ψ-distributions starts at the phreatic level, where $\psi = 0$. When a parallel drain system is present the highest point of this level is located midway between the drains. Its height above drain level (see Fig. 47) can be calculated according to Ernst (1956) from:

$$h_m - h_0 = \Delta h_{vert} + \Delta h_{hor} + \Delta h_{rad} \qquad (33)$$

where

h_m = hydraulic head at the phreatic level midway between the drains (m)
h_0 = hydraulic head at the open water level in the drains (m)
Δh_{vert} = hydraulic head for vertical flow (m)
Δh_{hor} = hydraulic head for horizontal flow (m)
Δh_{rad} = hydraulic head for radial flow (m)

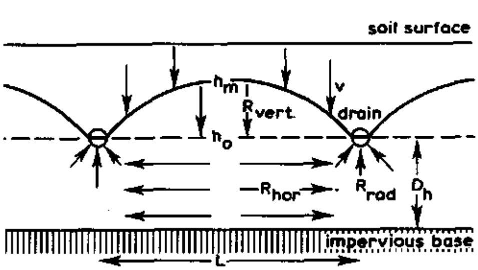


Fig. 47. Steady-state groundwater flow to parallel drains, separated into vertical, horizontal and radial flow (see text).

Eq. (33) can be written as:

$$h_m - h_0 = -vR_{vert} - v(R_{hor} + R_{rad}) \quad (34)$$

where

v = stationary flux (negative downwards) ($m \cdot d^{-1}$)
R_{vert} = resistance to vertical flow (d)
R_{hor} = resistance to horizontal flow (d)
R_{rad} = resistance to radial flow (d)

The resistance to vertical flow is:

$$R_{vert} = \frac{h_m - h_0}{k_0} \quad (35)$$

For the resistances for horizontal plus radial flow can be written (Hooghoudt, 1940; Ernst, 1956):

$$(R_{hor} + R_{rad}) = \frac{L^2}{8k_0 d} \quad (36)$$

where

L = spacing between parallel drains (m)
d = thickness of the so-called equivalent layer (m)

In Fig. 47 the thickness of the layer available for horizontal flow, D_h, thus is replaced by an imaginary layer of smaller thickness, d, in order to also include the radial flow in the equation for horizontal flow, Eq. (36). This d-value can be calculated (see Ernst, 1962) with $d/D_h = L/(L + 8k_0 D_h R_{rad})$.

Substitution of Eq. (35) and Eq. (36) into Eq. (34) leads to:

$$h_m - h_0 = -v\left(\frac{h_m - h_0}{k_0}\right) - v\frac{L^2}{8k_0 d} \quad (37)$$

In Eq. (37) $8k_0 d/L^2 = A$ represents the so-called drain intensity (d^{-1}). Writing for $h_m - h_0 = m_0$ Eq. (37) reduces to:

$$m_0 = -\frac{v}{A\left(1 + \frac{v}{k_0}\right)} \quad (38)$$

Once the height of the phreatic surface above drain level has been defined with Eq. (38) the ψ-distribution in the unsaturated zone from the phreatic level upwards can be calculated with Darcy's equation which reads after combining Eq. (6) with Eq. (23):

$$v = -k_0 e^{\alpha\psi}\left(\frac{d\psi}{dz}+1\right) \tag{39}$$

Integration of Eq. (39) between the boundaries $z = z_1$ and $z = z_2$ and $\psi = \psi_1$ and $\psi = \psi_2$:

$$\int_{z_1}^{z_2} dz = \int_{\psi_1}^{\psi_2} \frac{-\frac{1}{\alpha}\, d(v + k_0 e^{\alpha\psi})}{v + k_0 e^{\alpha\psi}} \tag{40}$$

yields

$$z_2 - z_1 = -\frac{1}{\alpha}\left[\ln\left(v + k_0 e^{\alpha\psi_2}\right) - \ln\left(v + k_0 e^{\alpha\psi_1}\right)\right] \tag{41}$$

or written explicitly for ψ_2:

$$\psi_2 = \frac{1}{\alpha}\ln\left[\frac{v}{k_0}\left(e^{\alpha(z_1 - z_2)} - 1\right) + e^{\alpha(\psi_1 + z_1 - z_2)}\right] \tag{42}$$

When the hydraulic conductivity constants k_0 and α are known, ψ-distributions are easily to calculate from Eq. (42) for homogeneous as well as layered soils. Fig. 48 gives a number of such ψ-profiles. The soil profiles exist of 3 severely compacted top layers (Top layer 6, 9 and 11 of Table 14) each of 10 cm thickness, overlying 3 subsoils having strongly different hydraulic conductivities (see Table 15). For each situation a drain depth of 100 cm was taken and a drain intensity

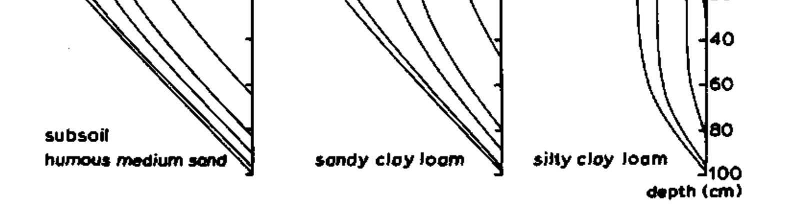


Fig. 48. Soil water pressure head distributions in profiles consisting of the 10 cm thick Top layers 6, 9 and 11 (see Table 14) overlying 3 different subsoils (see Table 15) at 5 downward fluxes: 1, $v = -1.0$; 2, $v = -0.5$; 3, $v = -0.3$; 4, $v = -0.1$ and 5, $v = -0.05\ \text{cm}\cdot\text{d}^{-1}$. Drain depth 100 cm, drain intensity $A = 0.030\ \text{d}^{-1}$.

$A = 0.030\ d^{-1}$, i.e. a drain discharge rate of $1.5\ cm \cdot d^{-1}$ at a groundwater table depth of 50 cm below the surface. This standard is commonly applied in the design of subsurface drainage for sports fields in the Netherlands.

A larger downward flux gives a higher (wetter) ψ at the interface of top layer and subsoil because of higher groundwater table depths and steeper slopes of the subsoil ψ-distribution curves. The lower the hydraulic conductivity of the subsoil and the higher the flux, the higher the phreatic surface, the steeper the slope of the subsoil ψ-distribution curve and the higher the ψ at the interface between top layer and subsoil.

The presence of a top layer acts favourably on the ψ at the soil surface when its hydraulic conductivity is better than that of the subsoil. The pressure head at the surface of the top layer on the silty clay loam is about 8 cm lower (drier) than at the interface. At higher hydraulic conductivities of the subsoil and higher fluxes, compacted top layers cause wetter conditions at the surface than occur at the interface. A summary of pressure heads at the surface found from the ψ-profiles of Fig. 48 is given in Table 19. The effect of the top layer on ψ at the surface is small when compared with the effect of the subsoil. The differences in ψ as a result of differences in subsoil are very obvious, while those resulting from differences in top layer are practically negligible. The significance of the ψ-values found at the top layer surface can be evaluated with the aid of the ψ-limits given in Table 16. To prevent reduction of the soil strength below the value required for adequate playing conditions the pressure head in Top layer 6 must not exceed −20 cm. For Top layers 9 and 11, which are more humous, the ψ-limit is −30 cm. On the humous medium sand subsoil these limits were not exceeded at the given downward fluxes. Top layers 9 and 11 did fall short at a flux of $1\ cm \cdot d^{-1}$, when overlying the sandy clay loam. On the silty clay loam subsoil these top layers did already become too wet at a flux of about $0.1\ cm \cdot d^{-1}$ and the more poor Top layer 6 at about $0.3\ cm \cdot d^{-1}$. Ponding occurred on this subsoil for all three top layers at a flux of $1\ cm \cdot d^{-1}$. Table 19 indicates that more poor sandy top layers, having a limit at higher (wetter) ψ-values, are to be preferred on less permeable subsoils.

Table 19. Pressure heads (ψ) at the surface of 3 compacted top layers (6, 9 and 11, see Table 14) with a thickness of 10 cm overlying 3 different subsoils (see Table 15) at 5 fluxes. Drain depth 100 cm and drain intensity $A = 0.030\ d^{-1}$.

Fluxes	Humous medium sand			Sandy clay loam			Silty clay loam		
($cm \cdot d^{-1}$)	6	9	11	6	9	11	6	9	11
1.0	−42	−40	−35	−24	−21	−18		ponding	
0.5	−57	−59	−55	−44	−43	−40	−11	−10	−9
0.3	−66	−70	−69	−55	−56	−54	−19	−18	−16
0.1	−82	−86	−85	−75	−78	−77	−32	−32	−31
0.05	−89	−92	−92	−85	−87	−86	−41	−40	−40

5.4.2.2 Influence of subsurface drainage

Apart from type of top layer and subsoil, drain depth and drain intensity determine the soil water conditions in the top layer. Fig. 49 gives ψ-profiles in a soil consisting of Top layer 11 with a thickness of 10 cm overlying the sandy clay loam soil. The ψ-profiles are calculated at 2 downward fluxes, drain depths of 80, 100 and 120 cm and drain intensities of 0.030 and 0.015 d^{-1}. The first drain intensity applies to sports fields and the second to arable land.

At the low flux, doubling of the drain intensity from 0.015 to 0.030 d^{-1} decreased ψ at the surface with only 2 cm at all drain depths. At the flux of 0.5 $cm \cdot d^{-1}$ it decreased ψ at the surface with 10, 7 and 5 cm at drain depths of 80, 100 and 120 cm respectively. The effect of drain intensity is more pronounced at shallow drain depths.

An increase in drain depth is more effective to obtain drier top layer conditions than an increase in drain intensity. At the flux of 0.1 $cm \cdot d^{-1}$ an increase in drain depth from 80 to 100 respectively 120 cm below the surface, lowered the ψ at the surface with 11 respectively 20 cm for both drain intensities. At the higher flux the same increases in drain depth decreased ψ with 10 and 16 cm at an $A = 0.015\ d^{-1}$ and with 6 and 9 cm at an $A = 0.030\ d^{-1}$.

In the Netherlands a drain depth of 80 to 100 cm and a drain intensity of 0.030 d^{-1} are common for sports fields. Greater drain depths appear to be more preferable at low fluxes, but also at higher ones although less pronounced. The usually applied drain intensity of 0.030 d^{-1} has only sense at shallow drain depths.

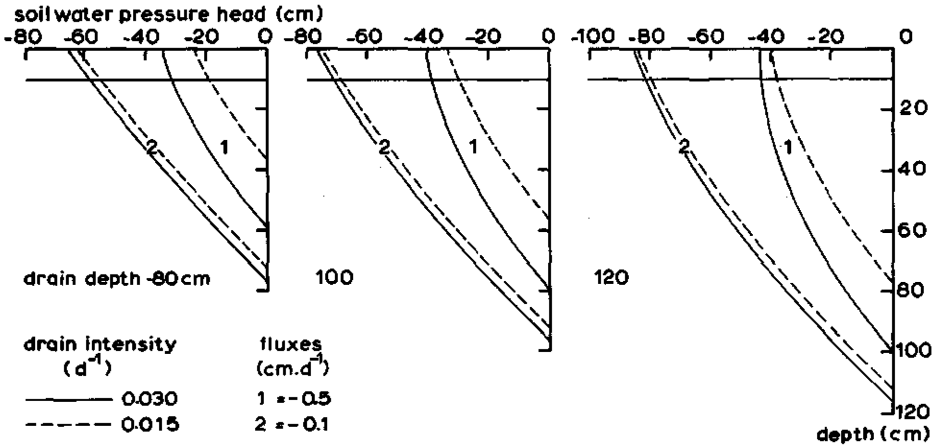


Fig. 49. Soil water pressure head distributions in profiles consisting of the 10 cm thick Top layer 11 (see Table 14) overlying the sandy clay loam subsoil (see Table 15) at 3 drain depths, 2 drain intensities and 2 downward fluxes.

5.5 Non-steady-state approach of soil water conditions

Generally the flow of water in soils occurs under non-steady-state conditions. Flux, water content and pressure head vary not only with depth but also with time. The equation of continuity reads:

$$\frac{\partial \theta}{\partial t} = -\frac{\partial v}{\partial z} \tag{43}$$

where

θ = volumetric water content ($cm^3 \cdot cm^{-3}$)

t = time (day)

Combination with Eq. (6) gives for one-dimensional vertical flow

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} k(\psi) \left(\frac{\partial \psi}{\partial z} + 1\right) \tag{44}$$

Eq. (44) is a partial differential equation which is non-linear because of the dependency of k and ψ on θ. The equation is mostly solved in a numerical way (e.g. Van Keulen & Van Beek, 1971; Wind & Van Doorne, 1975; Feddes et al., 1978; Vauclin et al., 1979). Analog models also have been used to solve the problem of non-steady unsaturated flow (Wind, 1972, 1979; Wind & Mazee, 1979). To study the effects mentioned in Section 5.1 on a non-stationary basis the electronic analog developed by Wind & Mazee (1979) was used.

5.5.1 Electronic analog used

The analog of Wind & Mazee (1979) to simulate transient soil water flow is based on the similarity between the integrated flow equation of Darcy and Ohm's law. The flux is represented by electric current, unsaturated hydraulic conductivity by electric potential and water content by condensator load. The model consists of a number of boxes, i.e. 'layers', containing a conductive and a capacitive part, which are mutually connected by resistors. The topmost box representing the soil surface simulates infiltration, evaporation, ponding and run-off. Ten other boxes represent soil layers, which can have a thickness of 10 or 20 cm. Another box simulates drainage which can be set at any desired depth up to 190 cm. Drain intensity and saturated conductivity are adjustable. Because the pressure head ψ as such is not present in the analog, the $k(\psi)$ and $\psi(\theta)$-relationships of the various soil layers are combined to a $k(\theta)$-relationship. Such a $k(\theta)$-relationship input is represented by three straight line segments of which the slope, $dk/d\theta$, maximum and breakpoints are set with thumbwheel switches on each box.

The output of the model includes the water content and conductivity of each layer, surface runoff and drain outflow. If desired, the depth of the groundwater table can be calculated from the drain outflow.

The scales of the model are adjustable. With regard to the time scale, the shortest model time is 2.31×10^{-5} day, i.e. 1 day is equivalent with 2 seconds in the model. As heavy rains of short duration may cause ponding or conditions too wet for playing, variations in rainfall intensity within a day are important. Therefore precipitation has been put into the model on an hour-basis. This implies that the time scale had to be lengthened to 11.11×10^{-4} day which means that 1 day took 9.6 seconds model time.

5.5.2 Precipitation sequence applied

For the investigation of the influence of different top layers, subsoils, subsurface drainage and a sandy drainage layer on the soil water conditions in the top layer, precipitation amounts at one-hour intervals were available from 1971 onwards. Finally the two-month period September through October 1974 was selected for the following reasons:

- the period coincides with the wet part of the playing season;
- the two months were very wet with 142 and 140 mm against an average precipitation of 71 and 60 mm (Anonymous, 1971);
- the period contained a number of hourly rainfall intensities that were rather high for autumn and winter;
- some rather dry periods occurred between the wet periods.

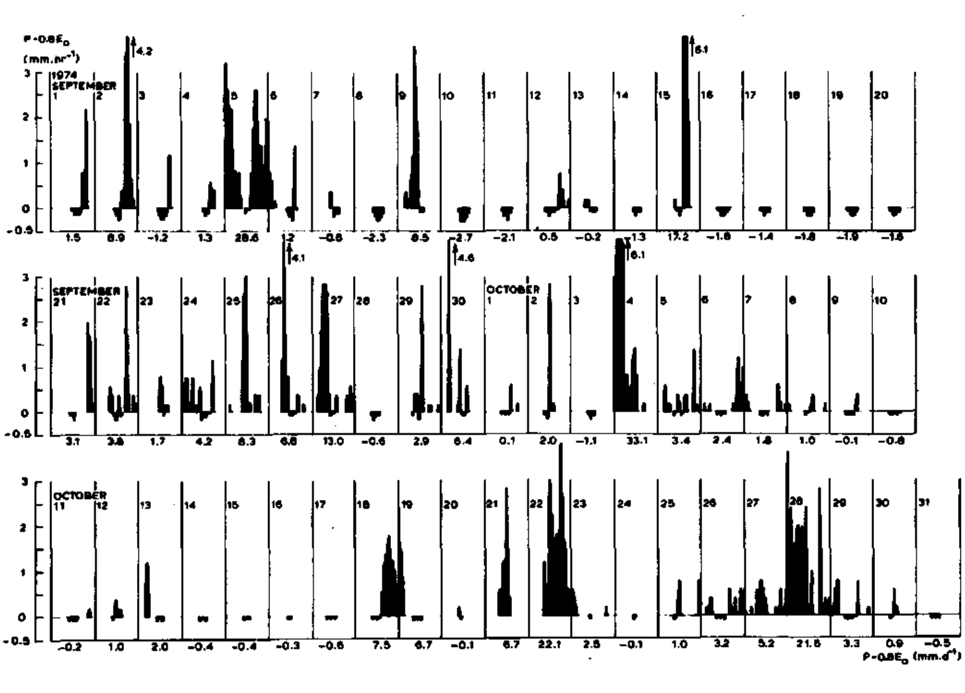


Fig. 50. Hourly precipitation surplus ($P - 0.8E_0$) over the months September and October 1974 at De Bilt, Netherlands, used as input for the electronic analog.

Table 20. Frequency with which one-hourly amounts of precipitation in September through October 1974 were exceeded as compared with the same period in an average year in the period 1931–1960.

Precipitation in 1-hour (mm)	Frequency of occurrence	
	1974	1931–1960
≥1	88	45
≥2	43	17
≥3	19	7
≥4	8	3
≥5	5	2
≥7	2	0.7

Precipitation was put into the model in $mm \cdot h^{-1}$ as a precipitation surplus (Fig. 50), being the difference between precipitation and 0.8 times open water evaporation, $(P-0.8E_o)$. Table 20 shows how often various amounts of precipitation in a one-hour period were exceeded in September through October 1974, as compared with 30-year averages derived from frequency distributions of KNMI (1966b).

5.5.3 Soil water conditions in the top layer

5.5.3.1 Influence of hydrological characteristics of top layer and subsoil

Because soil water conditions in the top layer depend not only on their own hydrological properties but also on the type of subsoil, the influence of differences in top layer have to be studied in combination with different subsoils. To that purpose the top layers mentioned in Section 5.2.1 were studied in combination with the subsoils mentioned in Section 5.2.2.

In the electronic analog the upper layer represented a 10 cm thick sandy top layer overlying a subsoil with a depth of 100 cm. According to sports fields drainage practice in the Netherlands the drain depth and drain intensity (A) were taken to be 100 cm and $0.030\ d^{-1}$ respectively. These figures imply a drain discharge of $1.5\ cm \cdot d^{-1}$ at a groundwater table depth of 50 cm below the surface.

An example of the simulated course of soil water conditions in a top layer in relation to rainfall conditions is given in Fig. 51. The cases simulated apply to Top layers 7, 8 and 9 of Table 14, i.e. sand with 6.6% organic matter compacted to three different densities, overlying the humous medium sand subsoil of Table 15. For purposes of illustration only part of the simulated 61-day period is presented (14 September to 9 October 1974). The period contains a rather dry spell interrupted by a heavy shower of 17.2 mm of rain on 15 September, followed by a wet period. The soil water content of the more compacted Top layers 8 and 9 moves closer towards the point of saturation than the of Top layer 7. The higher

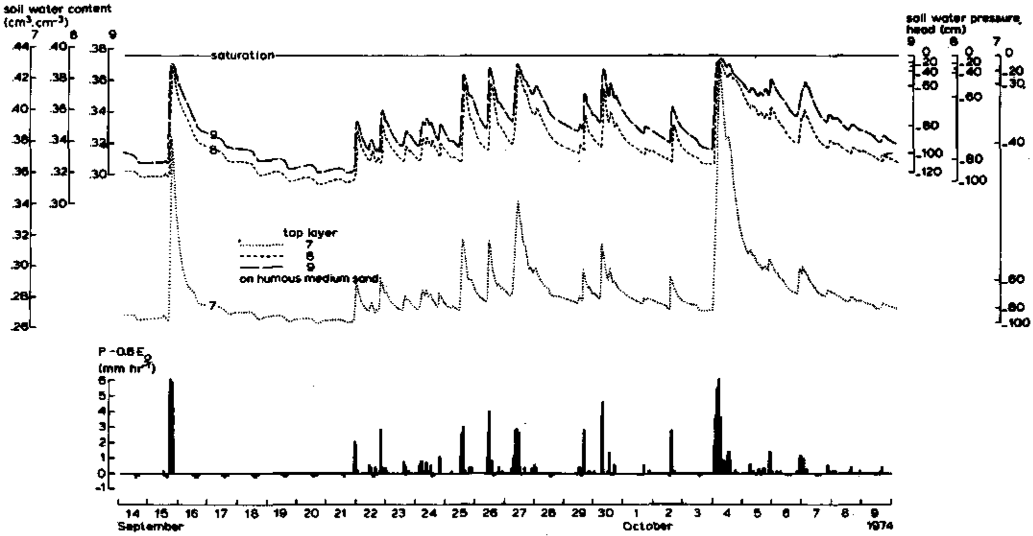


Fig. 51. Simulated course over part of September and October 1974, based on precipitation data at De Bilt, Netherlands, of soil water content and soil water pressure head at 5 cm depth in 3 differently compacted top layers (see Table 14) overlying the humous medium sand subsoil (see Table 15). Drain depth 100 cm, drain intensity $A = 0.030\ d^{-1}$.

the degree of compaction the narrower the range of fluctuations of the soil water content during the wet season. The range of fluctuations of the pressure head is about the same for the three top layers. Ponding ($\psi > 0$) did not occur. The limit for sufficient soil strength ($\psi = -30$ cm) was exceeded once in Top layer 7 during a short period on 4 October, a day with 33.1 mm of rain. In Top layer 8 the limit was exceeded twice, on 15 September as well as on 4 October. In the most compacted Top layer 9 the ψ-limit was also exceeded on 27 September, a day with 13 mm of rain.

The more compacted the top layer, the slower the decrease in soil water content and pressure head in dry periods and the longer the period during which a particular pressure head value is exceeded. Fig. 51 shows for the more compacted top layers that a heavy shower in a rather dry period, such as occurred on 15 September, caused hardly wetter soil conditions than less intense rains in a wet period, such as occurred on 25, 26, 27 and 30 September.

The influence of different subsoils on the soil water conditions in the top layer is illustrated in Fig. 52. When Top layer 6 of Table 14, a severely compacted sand with 4.3% organic matter, overlies the silty clay loam of Table 15 the limit of $\psi = -20$ cm required for a soil strength sufficient for intensive playing was frequently exceeded (12 times) and for a summed duration of 7 days. Ponding or fully saturated conditions ($\psi = 0$) of Top layer 6 occurred ten times. When this top layer was placed on the sandy clay loam, the pressure head limit was only exceeded twice with a summed duration of 1.1 days. On the humous medium sand subsoil the soil strength of Top layer 6 was always sufficient for adequate playing conditions in the period considered. Fig. 52 also shows that the lower the

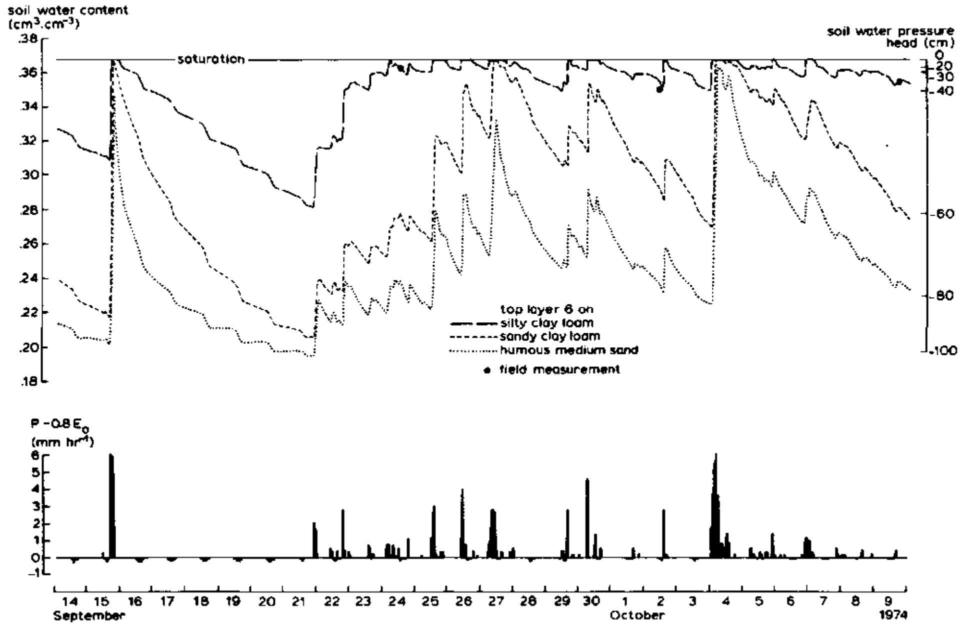


Fig. 52. Simulated course over part of September and October 1974, based on precipitation data at De Bilt, Netherlands, of soil water content and soil water pressure head at 5 cm depth in Top layer 6 (see Table 14) overlying 3 different subsoils (see Table 15). Drain depth 100 cm, drain intensity $A = 0.030\ d^{-1}$.

hydraulic conductivity of the subsoil, the closer the topsoil is to saturation and the smaller the fluctuations of soil water content and pressure head in the top layer. Fig. 52 also gives in situ measurements of ψ at three different dates. The simulated ψ-values compare well with the measured data.

Table 21 summarizes the summed number of days and times over the 61-day period considered on which the 11 top layers of Table 14 were judged to be to soft for playing according to the pressure head limits defined in Section 5.3.

Apart from the less compacted Top layers 1 and 10, it appears that the sandy top layers with an organic matter content up to 4.3% overlying humous medium sand were always playable in spite of the rather high compaction degrees of Top layers 2, 5 and 6. At higher organic matter contents both duration and frequency of unplayable situations increase a little. In the case of Top layer 11, having the lowest conductivity and storage capacity, the summed duration of unplayable conditions is 1 day split into six occasions. Ponding, i.e. $\psi > 0$, did not occur on the humous medium sand subsoil.

A too small degree of compaction, i.e. a $\rho' < 0.45$, as applies for the top layers 1 and 10, means that lower (drier) ψ-limits are required to obtain an adequate soil strength. However, the lower the pressure head required, the longer and the more frequently it will be exceeded in wet periods. So always a certain compaction is required to prevent the occurrence of insufficient soil strength resulting from too wet soil conditions.

Table 21. Summed duration and frequency of occasions on which soil water pressure head (ψ) limits for adequate playing conditions during the period September through October 1974 were exceeded for 28 combinations of top layer (see Table 14) and subsoil (see Table 15). Drain depth 100 cm, drain intensity $A = 0.030\ d^{-1}$.

Top layer				Subsoil					
				humous medium sand		sandy clay loam		silty clay loam	
	org. m. content (%)	ρ′	ψ-limits (cm)	duration (day)	frequency	duration (day)	frequency	duration (day)	frequency
1	0.4	0.10	−40	4.3	6	8.9	7		
2	0.4	0.59	0	0	0	0.2	1		
3	2.3	0.47	0	0	0	0	0		
4	4.3	0.45	−20	0	0	0.9	3	4.4	7
5	4.3	0.61	−20	0	0	1.7	7	12.2	23
6	4.3	0.72	−20	0	0	3.8	9	20.6	20
7	6.6	0.46	−30	0.2	1	2.2	7	12.3	11
8	6.6	0.60	−30	0.4	6	4.3	16	24.1	25
9	6.6	0.80	−30	0.7	4	5.6	17	27.7	26
10	8.6	0.29	−60	11.2	13	30.4	15		
11	8.6	0.73	−30	1.0	6	6.5	27		

When the 11 top layers overlie the sandy clay loam subsoil with less favourable hydrological properties, both duration and frequency of unplayable situations increase. Moreover, ponding occurs the more frequently, the higher the organic matter content and degree of compaction. If the top layer is very poor and is sufficiently compacted (Top layers 2 and 3 of Table 21) playing conditions will seldomly fail on the sandy clay loam subsoil. Comparing the top layers with higher organic matter contents (Top layer 4 through 11) the summed duration of inadequate playing conditions shows a gradual increase with higher organic matter contents while the frequencies increase more stepwise. The frequencies for Top layers 4, 5, 6 and 7 are much lower than for Top layers 8, 9 and 11. This is due to differences in storage capacity (see Table 13).

Excessively wet soil conditions and therefore much more unfavourable playing conditions can be met when having a silty clay loam as subsoil. For the conditions simulated, long durations of too wet pressure heads or ponding occurred regularly, even for those top layers that have a favourable hydraulic conductivity and soil water characteristic. A simulation experiment was also performed without a sandy top layer. In that situation the silty clay loam showed a still larger number of days with pressure heads > -20 and > -30 cm in the upper 5 cm (22.2 and 32.8 days respectively).

On a poor permeable subsoil a sandy top layer can improve the soil water conditions at the surface, and the more the larger the storage capacity. An increase in storage capacity can be obtained by increasing the top layer thickness. Such an increase in top layer thickness considerably reduces the duration and frequency of unplayable conditions (Table 22). If the thickness of Top layer 4, the most favourable of the three given in Table 22, is increased to 20 cm unplayable conditions are reduced from a summed duration of 4.4 down to 1.7 days. A

Table 22. Summed duration and frequency of occasions on which the soil water pressure head limits for adequate playing conditions were exceeded in September through October 1974, at thicknesses of 10 and 20 cm of Top layers 4, 5 and 6 (see Table 14), when overlying the silty clay loam subsoil (see Table 15). Drain depth 100 cm, drain intensity $A = 0.030\ d^{-1}$.

	Top layer					
	4		5		6	
Thickness (cm)	10	20	10	20	10	20
Duration (day)	4.4	1.7	12.2	7.0	20.6	9.5
Frequency	7	5	23	14	20	16

poorer sandy top layer sufficiently compacted such as Top layers 2 and 3 of Table 21 will be even more favourable because they have still sufficient soil strength at a ψ-limit of 0 cm. The different results obtained by the three top layers in Table 22 can be explained by their differences in soil water characteristic (see Fig. 40). Apart from top layer thickness, the soil water characteristic of the sand used on subsoils with low conductivities is of great significance. This implies that when on such subsoils a medium sand is used as top layer, its thickness may be smaller (see also De Jong, 1979).

5.5.3.2 Influence of subsurface drainage

Another measure to control the water conditions in the top layer is subsurface drainage. However, quantitative information on effects of drain depth and drain intensity on the soil water status of top layers overlying different soils is hardly available.

On sports fields in the Netherlands, subsurface drainage is judged to be necessary on soils where the groundwater table regularly rises above 50 cm below the surface. Drain depths usually vary between 70 and 100 cm below the surface. In the here presented model approach three drain depths were chosen: 75, 100 and 120 cm below the surface. To study the influence of drain spacing, each drain depth was combined with three different drain intensities A (see Section 5.4.2.1):

$$A = -\frac{v}{m_0} \tag{45}$$

where

v = the drain discharge rate $(cm \cdot d^{-1})$

Accounting for the for sports fields highest permissible groundwater table depth of 50 cm below the surface, A was adjusted in the model on basis of the values of v and m_0 given in Table 23. In the Netherlands a discharge rate of $1.5\ cm \cdot d^{-1}$ is usually applied in drainage design for sports fields, while $0.75\ cm \cdot d^{-1}$ approaches the criterion for arable land. The discharge of $15\ cm \cdot d^{-1}$, an unrealistically high

Table 23. Values of drain discharge rate (v) and height of the water table midway between the drains (m_0) as adjusted on the electronic analog to obtain different drain intensities A at the 3 drain depths chosen.

Drain depth (cm-surface)	0.5A		A		10A	
	v ($cm \cdot d^{-1}$)	m_0 (cm)	v ($cm \cdot d^{-1}$)	m_0 (cm)	v ($cm \cdot d^{-1}$)	m_0 (cm)
75	0.75	25	1.5	25	15	25
100	0.75	50	1.5	50	15	50
120	0.75	70	1.5	70	15	70

value, was taken to see whether the rather large discharge rate of $1.5\ cm \cdot d^{-1}$ in some cases is still too small. Lower respectively higher drain intensities imply wider respectively narrower drain spacings.

The soil profiles applied in the model consisted of two differently compacted top layers, Numbers 10 and 11 (see Table 14) each of 10 cm thickness overlying either the better permeable humous medium sand or the less permeable sandy clay loam (see Table 15).

An illustration of the influence of drain depth on the soil water conditions in the top layer is given in Fig. 53. The figure shows that at greater drain depths the

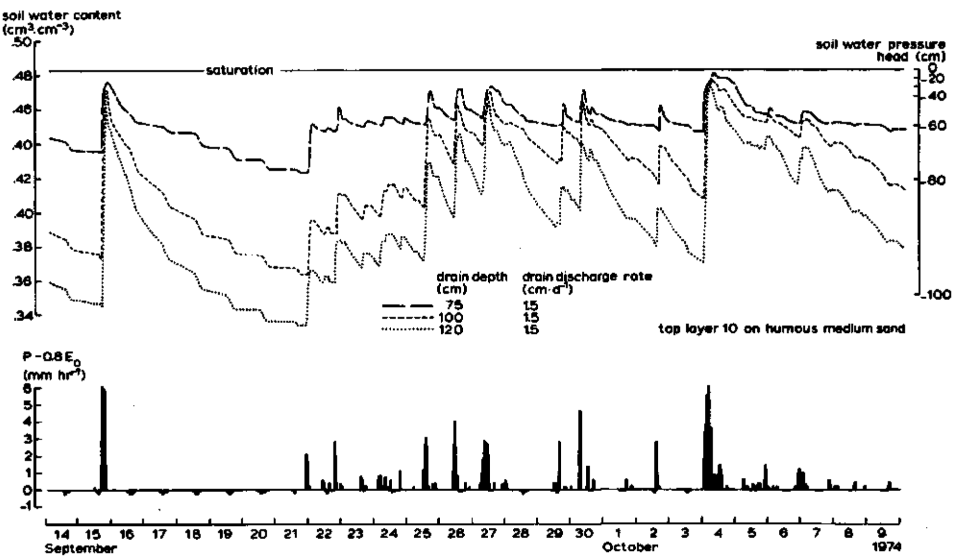


Fig. 53. Simulated course over part of September and October 1974, based on precipitation data at De Bilt, Netherlands, of soil water content and soil water pressure head at 5 cm depth in Top layer 10 (see Table 14) overlying the humous medium sand subsoil (see Table 15) at drain depths of 75, 100 and 120 cm respectively and a drain discharge rate of $1.5\ cm \cdot d^{-1}$.

top layer dries more rapidly. The average soil water content, θ, and pressure head, ψ, are much lower at the greater drain depths but when heavy rains occur the differences in θ and ψ between shallowly and deeply drained soils are rather small.

According to Section 5.3 the soil strength of the less compacted Top layer 10 is insufficient for intensive playing at ψ-values > -60 cm. At a drain depth of 75 cm this limit is continuously exceeded in wet periods. By using greater drain depths playing conditions of this top layer can considerably be improved.

At a drain depth of 100 cm the influence of an increased drain discharge rate mainly is observed after a rain shower when the soil is drying (Fig. 54). Increasing the drain discharge rate has a small effect with heavy rains. Doubling the drain discharge rate from 0.75 to 1.5 $cm \cdot d^{-1}$ gives an improvement of the same order as increasing it tenfold from 1.5 to 15 $cm \cdot d^{-1}$.

Fig. 55 summarizes the effects of drain depth and drain intensity (see also Table 23) on the sum of the number of days with soil conditions being too wet for intensive playing on Top layers 10 and 11 in the period September through October 1974. The ψ-limits at which the soil strength is insufficient for intensive playing are -60 and -30 cm for Top layers 10 and 11 respectively (see Section 5.3). The effect of drain depth and drain intensity appears to depend strongly on the applied top layer as well as on the type of subsoil. The summed duration of unplayable conditions for the severely compacted Top layer 11 is much less than for Top layer 10 for all corresponding drain depths and drain intensities on both the humous medium sand and the sandy clay loam subsoil. In consequence of the

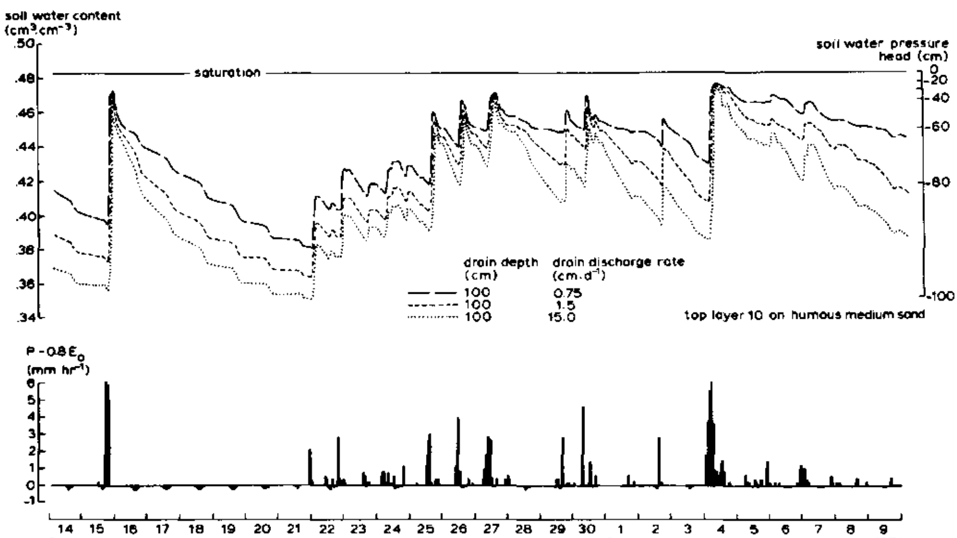


Fig. 54. Simulated course over part of September and October 1974, based on precipitation data at De Bilt, Netherlands, of soil water content and soil water pressure head at 5 cm depth in Top layer 10 (see Table 14) overlying the humous medium sand subsoil (see Table 15) at a drain depth of 100 cm and drain discharge rates of 0.5, 1 and 10 times the standard of 1.5 $cm \cdot d^{-1}$.

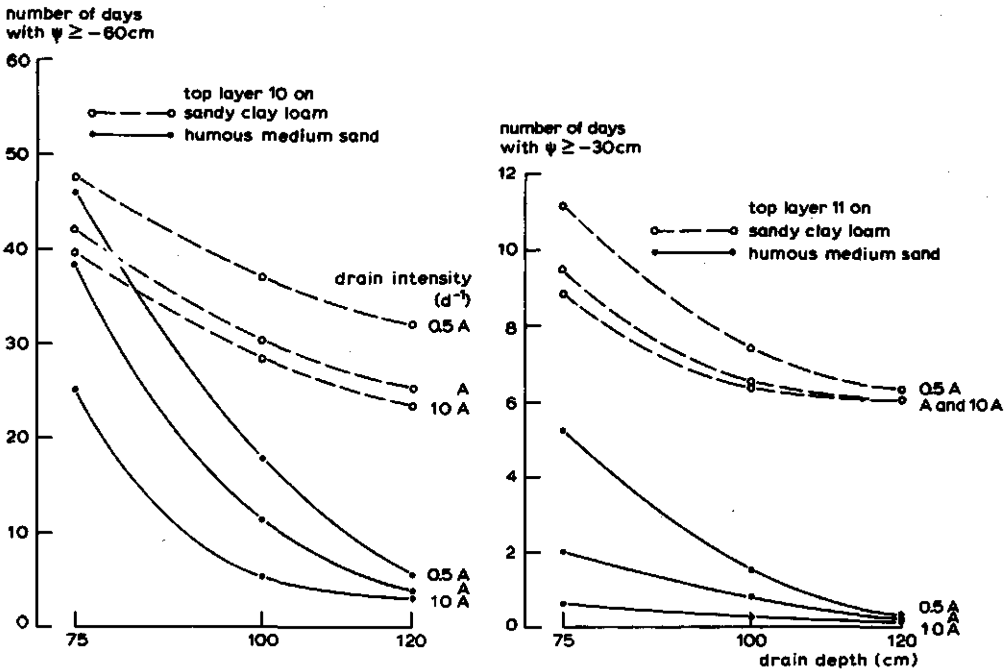


Fig. 55. Summed number of days on which the soil water pressure head limits for intensive playing, $\psi = -60$ and $\psi = -30$ cm, were exceeded during September through October 1974 in Top layers 10 and 11 (see Table 14) overlying the sandy clay loam respectively the humous medium sand subsoil (see Table 15), versus drain depths of 75, 100 and 120 cm at drain intensities of 0.5, 1.0 and 10 times the standard A (see Table 23).

higher compaction degree, Top layer 11 has a sufficient soil strength at higher pressure heads. The higher (wetter) the ψ-limit is, the less lastingly and the less often it will be exceeded. When a top layer having too small a degree of compaction (Top layer 10) overlies a permeable subsoil, a deep subsurface drainage can improve the playing conditions considerably. The reduction in unplayable days is much smaller when this top layer overlies a less permeable subsoil. The latter which needs tube drainage the most, reacts the least to it. In addition to subsurface drainage it therefore is advantageous to compact the top layer on such soils to higher densities (going for example from Top layer 10 to Top layer 11) or to cover them with a poor sandy top layer, bringing in this way the ψ-limit to a higher (wetter) value.

The right hand side of Fig. 55 clearly shows that an increase in drain depth is almost always much more effective to reduce the number of unplayable days than an increase in drain intensity. A drain depth of 120 cm below the surface combined with a low drain intensity is much more favourable than a drain depth of 75 cm combined with a high drain intensity. Increasing the drain intensity from 0.5A to A is much more effective than increasing it from A to 10A. High drain intensities are only of importance at shallow drain depths. A drain discharge rate of $1.5\,cm \cdot d^{-1}$ at a groundwater table depth of 50 cm below the surface (i.e. drain intensity A, usual on sports fields), is only appropriate when drain depths deeper than 100 cm below the surface cannot be realized.

5.5.3.3 Influence of a sandy drainage layer

In practice it is often proposed to insert a sandy layer between subsoil and top layer or root zone (Daniel, 1969; Daniel et al., 1974; Deutscher Normenausschuss, 1974; Moesch, 1975). The sand layer must function as a drainage layer (see also Fig. 2), ensuring temporary storage of water when heavy rains occur, as well as enabling lateral water movement to drain tubes installed at the interface of drainage layer and subsoil. Sometimes the contribution of the subsoil to discharge or supply water is completely eliminated by inserting a plastic barrier between sandy drainage layer and subsoil. Then the drain tubes are used for water discharge as well as sub-irrigation (Daniel et al., 1974; Moesch, 1975).

Because of the high construction costs the thickness of drainage layer and top layer must be limited. The consequence of this limitation is a shallow drain depth and high groundwater tables that go with high (wet) pressure heads in the top layer. To prevent in this situation top layer conditions being too wet, the consequence of applying sand as drainage layer material have been investigated with the electronic analog, especially:

- the type of sand used as drainage layer;
- the best combination of various types of top layers and drainage layers.

Because the suitability for drainage layer construction strongly depends on the storage capacity of the sand, three sands were chosen having widely different storage capacities (Fig. 56). The soil water characteristic of Sand 1 represents a coarse (600–1000 μm) sand without humus mentioned by Rijtema (1969), Sand 2 is a fine sand without humus (Top layer 1 of Table 14) and Sand 3 is the humous medium sand, earlier used as subsoil (see Table 15). The soil water characteristic of Sand 1 differs from the other two by a very high storage capacity in the very

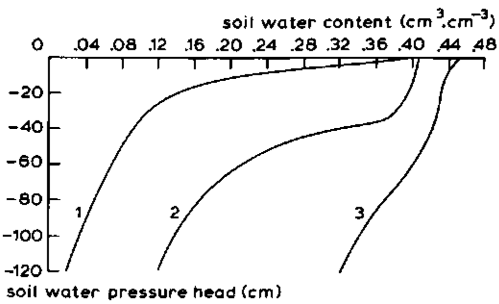


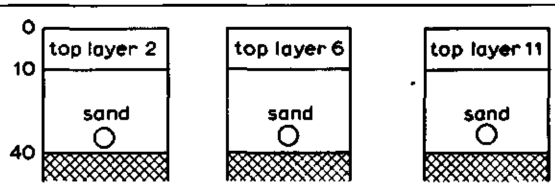
Fig. 56. Soil water characteristics of 3 drainage layer materials: a coarse sand (1) and a fine sand (2), both without humus, and a humous medium sand (3) all having the same hydraulic conductivity $k = 16.4e^{0.045\psi}$.

wet range. Over the range $-30 < \psi < 0$ the soil water content changes by about $0.29\ cm^3 \cdot cm^{-3}$. This implies that supply or discharge of great quantities of water are accompanied by small changes in ψ. The soil water characteristic of Sand 2 shows a strong increase in storage capacity at ψ-values smaller than -35 cm. The characteristic of Sand 3 shows a gradual but rather small change in water content over the ψ-range illustrated. The difference in storage capacity between the curves of Sand 2 and Sand 3 begins at ψ-values < -35 cm. Unlike Sands 1 and 2, Sand 3 can supply a considerable amount of water to the grass roots.

To investigate the influence of differences in storage capacity of the sands used, the hydraulic conductivity of the humous medium sand subsoil (Sand 3) of Table 15 was taken to apply also for the other two sands. The hydraulic conductivity characteristics are $k_0 = 16.4\ cm \cdot d^{-1}$ and $\alpha = 0.045\ cm^{-1}$. This combination earlier proved to be sufficiently high under the weather conditions considered (see Table 21).

According to Table 16 the poorer the top layer the higher (wetter) the ψ-limit can be before soil strength becomes unsatisfactory for adequate playing conditions. Therefore in the model Top layers 2, 6 and 11 of Table 14, having ψ-limits of 0, -20 and -30 cm respectively were placed on a 30 cm thick drainage layer composed of one of the three sands from Fig. 56. The thickness of the top layers

Table 24. Summed duration in days and frequency (between brackets) of occasions on which the pressure head (ψ) limits of Top layers 2, 6 and 11 (see Table 14) overlying 30 cm thick drainage layers composed of one the 3 sands of Fig. 56 were exceeded during September through October 1974.



Drain depth (cm-surface)		35		35		35	
Drain discharge rate ($cm \cdot d^{-1}$)		15	15	15	15	15	15
Groundwater table depth (cm-surface)		20	30	20	30	20	30
Type of sand	ψ-limits (cm)	Duration (frequency)					
1	0	0 (0)	0 (0)				
	−20			0.4(4)	0 (0)		
	−30					29.4(7)	22.4(11)
2	0	1.9(8)	0.4(5)				
	−20			4.7(14)	3.0(14)		
	−30					9.0(19)	7.6(18)
3	0	1.8(8)	0.3(3)				
	−20			5.0(14)	2.7(13)		
	−30					12.1(19)	10.4(18)

was 10 cm. The depth of the drain tubes in the drainage layer was 35 cm below the surface. For each top layer–drainage layer combination two different drain intensities were taken: a drain discharge of $1.5\,cm \cdot d^{-1}$ at groundwater table depths of 20 i.c. 30 cm below the surface. This leads to drain spacings that are in the proportion of 3 to 1. Table 24 shows the summed duration and frequency of inadequate playing conditions. The simulation relates to the 61-day period September through October 1974. From the table the following conclusions can be drawn:

– The best combination is a sandy top layer sufficiently compacted, having an organic matter content not higher than about 4% (Top layers 2 and 6), overlying a coarse sandy drainage layer (Sand 1); top layers with higher organic matter contents do not suit on such shallowly drained constructions.
– When the drainage layer consists of finer sands (Sands 2 and 3) a sandy top layer practically without humus (Top layer 2) is to be preferred,.
– For the combinations poor top layer over coarse textured drainage layer, wider drain spacings are allowed than for the poor top layer – finer textured drainage layer combinations. The effect of increasing drain intensities, i.e. narrower drain spacings, decreases with increasing organic matter content of the top layer.

The differences shown in Table 24 can be explained from the differences in ψ-limit between the top layers involved (see Table 16) and the differences in storage capacity between the 3 types of sand used as drainage layer material (see Fig. 56). The coarse sand has a large storage capacity over the range $-30 < \psi < 0$ cm. At the applied drain depth of 35 cm below the surface, ψ in the overlying top layer fluctuated therefore over long periods within the narrow range between -20 and -30 cm in spite of precipitation or evaporation (see Fig. 57). It is also the high storage capacity of the coarse textured drainage layer that prevents fully saturated conditions. Therefore the ψ-limit of 0 cm, Top layer 2, was never exceeded and the ψ-limit of -20 cm of Top layer 6 only seldomly, in contrast to the ψ-limit of -30 cm of Top layer 11. When the drainage layer has a smaller storage capacity (Sands 2 and 3) ψ in the top layer fluctuated within a wider range. The lower (wetter) ψ-limits of Top layers 2 and 6 then were exceeded over longer periods and more frequently.

Unfortunately, a construction which is best from the point of view of preventing soil conditions being too wet, i.e. a poor sandy top layer on a coarse textured drainage layer, is the most drought-susceptible. Additional water supply in summer will be necessary, either by sprinkler irrigation or by sub-irrigation via the drain tubes (Daniel et al., 1974; Moesch, (1975). Sub-irrigation has the disadvantage that the permanently rather high water content of the top layer will influence the composition of the sward in an undesirable way. Moreover, the breakdown of organic matter (clippings, roots) will be very slow in such a poor and wet top layer, giving thatch formation and so making the turf susceptible to damage by playing.

These disadvantages, together with the high construction costs make application of a drainage layer only advisable when the subsoil is nearly impermeable. This

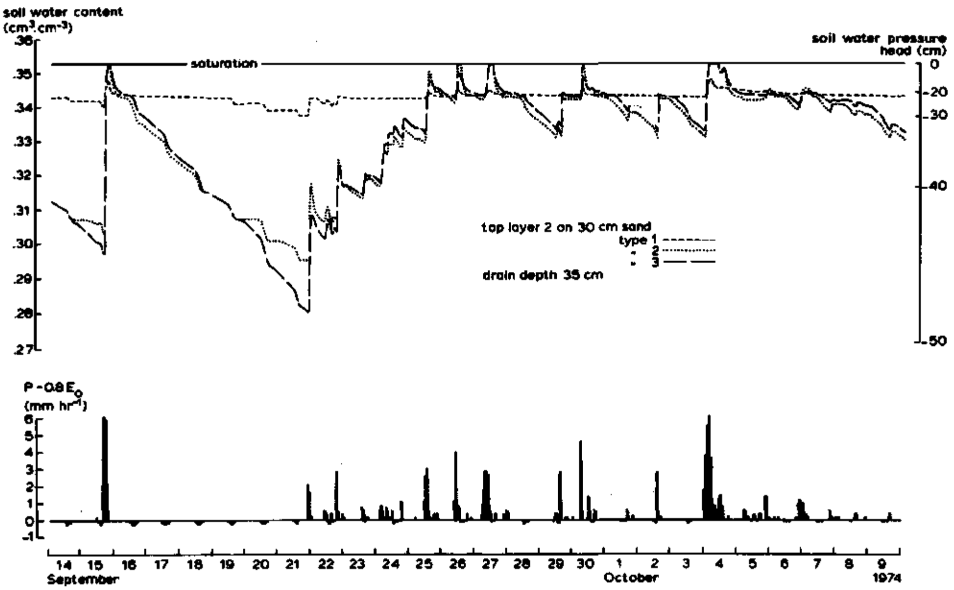


Fig. 57. Simulated course over part of September and October 1974, based on precipitation data at De Bilt, Netherlands, of soil water content and soil water pressure head at 5 cm depth in top layer 2 overlying a 30 cm thick drainage layer consisting of a coarse sand (1), a fine sand (2), both without humus, and a humous medium sand (3) (see also Fig. 56). Drain depth 35 cm, drain discharge rate $1.5\ cm \cdot d^{-1}$ at a highest admissible groundwater table depth of 20 cm below the surface.

the more so as it appears from Table 22 that a construction without a drainage layer, consisting of a just sufficiently compacted 20 cm thick sandy top layer with 4.3% organic matter content (Top layer 4) on a poorly permeable silty clay loam, proved to be an entirely acceptable solution. The poorer sandy Top layers 2 and 3, with pressure head limits closer to saturation, would give even better results. Top layers 2 and 3 will give results of the same order as achieved by means of the best coarse textured drainage layer construction.

6 Conclusions and recommendations

From the investigations described above a better understanding of soil properties and processes influencing playing conditions of grass sports fields could be obtained. Moreover, some useful directions for their construction and maintenance could be derived. The following main conclusions and recommendations can be formulated.

6.1 Required top layer strength, densities and pressure heads

- Playing conditions depend on the bearing capacity of the top layer. The latter depends on top layer composition, bulk density and soil water conditions and on the reinforcing action of the underground parts of the grass.
- Penetration resistance as measured with a cone is a simple and reproducible measure to judge playing conditions.
- Deformation of the top layer does not occur on intensively played parts of a sports field when the penetration resistance, measured with a cone having a base of 1 cm^2 and a top angle of 60°, amounts to at least 1.4 MPa. For less intensively played parts a penetration resistance of at least 1.0 MPa is required.
- Because of differences in the organic matter content of sandy top layers it is not possible to formulate a uniform standard of their bulk density satisfying the required soil strength. However, the penetration resistance is almost always sufficiently high for adequate playing conditions when the top layer is compacted to a relative density (ρ') of 0.45 or more.
- This ρ'-value corresponds for sand with organic matter contents of 1, 2, 3, 4, 5, 6, 7 and 8% with bulk densities of 1.65, 1.61, 1.56, 1.52, 1.47, 1.44, 1.41 and 1.38 $g \cdot cm^{-3}$ respectively.
- To maintain the bulk density at these appropriate levels regular playing and, in periods with a low playing frequency, compaction by rolling will be suitable maintenance measures.
- If the relative density (i.e. degree of compaction) amounts to 0.45 or more, soil strength can still be insufficient because the soil conditions are too wet. From relationships between penetration resistance and soil water pressure head for different bulk densities, pressure head (ψ) limits were derived at which the soil strength becomes insufficient for adequate playing conditions. For sands with 0 to 2%, 3%, 4% and 5 to 8% organic matter and compacted to a relative density of 0.45 or higher these limits are $\psi = 0$, -10, -20 and -30 cm respectively. The limits indicate that poor sandy top layers can be wetter than top layers containing more organic matter, before the soil strength falls below the required value of 1.4 MPa.

– The decrease in soil strength because of an increase in pressure head above these limits, is strongest and most detrimental on midfields, where the highest penetration resistance and most intensive playing are found.
– Top layers insufficiently compacted, i.e. having a relative density liberally below 0.45, have a ψ-limit for adequate soil strength at lower (drier) values (ψ in the order of -40 to -60 cm) than the more compacted ones. However, the lower the ψ-limit, the more lastingly and frequently this limit will be exceeded during wet periods.

6.2 Top layer composition, compactability and soil strength

– With respect to top layer composition and compactability it was found that the higher the organic matter and clay content, the greater the increase in bulk density with increasing compaction level, especially under wet soil conditions. This behaviour implies that differences in bulk density of the top layer between lightly and heavily played parts will be greater the higher the organic matter and clay content.
– In practice a reduction of bulk density of the top layer, induced by root growth and loosening activities of soil organisms, is often observed especially during non-playing periods. Because this decrease in bulk density reduces the soil strength more at higher organic matter and clay contents, more intensive efforts will then be required to maintain the high bulk density necessary for adequate playing conditions. Therefore on infrequently played fields a sandy top layer with an organic matter content in the order of 4% and a clay content of less than 5% suits best.
– At corresponding compaction conditions medium sand top layers obtain a higher bulk density than fine sand ones (also when both types are enriched with clay).
– With regard to the influence of composition and compaction on top layer soil strength it was evident that organic matter contributes considerably to the soil strength of sand, but only after compaction to relatively high bulk densities (see the limits given before). So compaction by regular playing, if necessary supplemented by rolling, is a very effective measure to maintain the playing conditions of humous sandy top layers.
– Within the $-80 < \psi < 0$ cm range of pressure heads, prevailing during the main part of the playing season, clay particles hardly contribute to the soil strength of poor sandy top layers, this in contrast to organic matter.
–Under drier soil conditions occurring, however, mainly outside the playing season, a top layer consisting of a sand-clay mixture has considerably more soil strength and stability than a poor sandy top layer.
– Because under wet conditions clay-sand mixtures have a high compactability and the presence of clay hardly contributes to soil strength and reduces the hydraulic conductivity, it is advisable to keep the clay content of top layers of sports fields used in winter at a low value. Thereby keeping in mind standards of maximally 5% of particles $<2\ \mu m$ and 10% $<20\ \mu m$.
– On clayey soils with earthworm activity it is not easy to keep the sandy top layer

that low in clay content. The best way is top-dressing with poor sand from the start of the playing season and during the playing season if necessary followed by regularly repeated sand dressings in thin layers of 1 to 2 mm combined with rolling. Then, regular playing gives a homogeneous sandy top layer low in clay content.

– With respect to soil strength fine sand is to be preferred above medium sand for construction of top layers on clayey soils. To prevent ponding a medium sand top layer is to be preferred because then its thickness may be smaller.

6.3 Grass viability and soil reinforcement by roots

– It was found that the rather high bulk densities required for sufficient top layer strength can temporarily be detrimental to soil aeration. The general impression gained from this study does not suggest a seriously injurious effect of deficient soil aeration on grass viability. Moreover it appeared that direct injury to the sward by playing, widely overshadows the indirect consequences of playing such as an increased mechanical resistance for root growth and a reduced soil aeration.

– Turf cultivation aiming at improving water permeability and gas exchange between soil and atmosphere (aerification) is performed on a rather large scale in the Netherlands. The compacting influence resulting from playing extends to a depth of 5 to maximally 10 cm, thus turf cultivation when performed should be carried out to these depths. In connection with the preceding paragraph it may be questioned, however, to what extent such measures have sense regarding the small influence of soil aeration.

– The reduction of the sward density during autumn and winter depends on playing frequency as well as intensity. This reduction can go to 0.8 to 0.9 on intensively played parts. A strong decrease in sward density needs not always to be detrimental for playing conditions because of the remaining reinforcement of the top layer by the root mass concentrated for up to 90% in the upper 5 cm. In spite of continued playing a strong recovery of the sward is normally observed in spring, it can be stimulated by sod seeding and watering.

– Grass roots contribute considerably to top layer soil strength. This contribution was found to vary in the order of 0.8 to 1.6 MPa. Short term variations in soil strength result from changes in soil water pressure head and bulk density.

– The reinforcing action of grass roots is more essential for top layers with low (about 0 to 3%) than with higher organic matter contents.

– Unstable poor sandy top layers without grass have little soil strength both in a loose and a dense state. But because of their low compressibility these sands reinforced by grass roots show high penetration resistances and hardly deform. Such top layers have the restriction, however, that the playing frequency must be kept at such a level that too large a reduction of root intensity is prevented. Especially under dry conditions they are very susceptible to damage by frequent playing.

– Sandy top layers with a higher (>3%) organic matter content have in a loose state little soil strength in spite of the presence of grass roots. A prerequisite for adequate soil strength then is compaction to a higher bulk density (see the pertinent values mentioned earlier). In that case the soil itself gains considerable strength and depends less on the reinforcing function of grass roots. Therefore this type of top layers allows a higher playing frequency than the poorer ones.

6.4 Top layer–subsoil–drainage combinations

– From the point of soil strength, top layers which have higher organic matter contents (up to 8%) and are adequately compacted are to be preferred. However, the higher the organic matter content and compaction degree the lower the hydraulic conductivity and the smaller the storage capacity of the top layer and the greater the probability of too wet soil conditions.

– Soil water conditions of the top layer depend not only on its hydrological properties. They are also affected by factors as thickness of the top layer, type of subsoil, subsurface drainage or type of sports field construction such as the introduction of a sandy drainage layer between top layer and subsoil. Once the influence of these factors is quantified, it is possible to indicate how they can best be combined under different conditions.

– From simulations with different combinations of top layer and subsoil it appeared that the soil water conditions of the top layer are highly influenced by the hydrological properties of the subsoil. The better the hydraulic conductivity of the subsoil the lower (drier) the pressure heads in the top layer and reversely.

– On poor-permeable soils (e.g. fine clayey soils) a poor sandy top layer (0 to maximally 4% organic matter) suits best. On medium-permeable soils (e.g. loamy soils) an organic matter content up to about 6% is allowable. On well-permeable soils (e.g. sandy soils) an organic matter content of the top layer up to about 8% can be permitted. Of course this all under the condition that the bulk density satisfies the lower limits given earlier.

– Top layers with too low a compaction level ($\rho' < 0.45$) will have regularly unplayable conditions in winter, even when they are overlying permeable well-drained subsoils. Rolling and, if possible, compaction by regular playing will improve the playing conditions.

– The compacting influence of playing extends to a depth of maximally 10 cm. Therefore generally a top layer of 10 cm sand is adequate. Greater thicknesses (e.g. up to 20 cm) may be required, however, on subsoils with poor permeability.

– The main effect of tube drainage is to shorten the duration of wet soil conditions. Differences in soil water conditions between poorly and well-drained soils are the largest during the drying stage.

– The effect of subsurface drainage on the playing conditions depends strongly on the applied top layer and type of subsoil. Too little compacted top layers are more drainage demanding than top layers adequately compacted. The soil water conditions of a too little compacted top layer overlying a permeable subsoil can considerably be improved by deep subsurface drainage. Additional top layer compaction gives a still better result.

– Subsoils with poor permeability, which need subsurface drainage the most, react the least to it. Therefore in addition to tube drainage, less permeable soils if used for sports fields need poor sandy top layers having for adequate soil strength a ψ-limit close to saturation.

- Generally great drain depths combined with a low discharge rate (i.e. wide drain spacings) are much more effective to control the soil water conditions in the top layer than shallow drain depths combined with a high discharge rate (i.e. narrow drain spacings).
- The drain discharge rate of 1.5 cm $\cdot$ d^{-1} at a groundwater table depth of 50 cm below the surface, as usually applied as the standard for tube drainage design for sports fields in the Netherlands, is only appropriate at drain depths shallower than roughly 100 cm below the surface.
- With respect to sports field constructions with a tube-drained sandy drainage layer between top layer and subsoil it appeared that the best construction is a sandy top layer compacted to a relative bulk density of 0.45 and having an organic matter content of maximally 4%, overlying a coarse sandy drainage layer. Top layers with higher organic matter contents do not suit on such shallowly drained constructions.
- When the drainage layer consists of finer sands a sandy top layer practically without humus is to be preferred.
- For the combinations of a poor top layer over a coarse textured drainage layer, wider drain spacings are allowed than for the poor top layer – finer textured drainage layer combinations.
- Application of a drainage layer has disadvantages as high construction costs and susceptibility for drought. When, as is usual with such constructions, subirrigation through the drain tubes is applied, the water content of the top layer in summer will be high. This may lead to an undesirable development of the sward composition and to a strong thatch formation. Therefore this construction is only to be considered on nearly impermeable subsoils.

Table 25. Conspectus of the suitability of top layer – subsoil combinations for adequate playing conditions and grass viability on sports fields in a temperate humid climate. The top layer must consist of sand with a clay content <5%. The drainage of the subsoil must conform with the requirement that the given ψ-limit of the top layer is only infrequently exceeded (see Table 21). + = appropriate; – = not recommended.

Top layer with			Conductivity of subsoil		
org. m content (%)	bulk density (g $\cdot$ cm^{-3})	ψ-limit (cm)	low (e.g. clayey soils)	medium (e.g. loamy soils)	high (e.g. sandy soils)
1	≥1.65	0	+	–	– – –
2	≥1.61	0	+	–	– –
3	≥1.56	–10	+ + +	+	–
4	≥1.52	–20	+ +	+ + +	+ +
5	≥1.47	–30	–	+ + +	+ + +
6	≥1.44	–30	– –	+	+ + +
7	≥1.41	–30	– – –	–	+ +
8	≥1.38	–30	– – –	– – –	+

Summarizing a number of conclusions and recommendations mentioned before, Table 25 gives a conspectus of the suitability of top layer-subsoil combinations for grass sports fields.

Summary

This study deals with the playing conditions of grass sports fields. Because they are mainly controlled by the soil strength of the top layer, a soil physical–soil mechanical–hydrological research was carried out. The investigation is divided into an inventorizing part based on field data, an analysing part based on laboratory measurements and an analysing as well as generalizing part based on model research.

The field investigations were performed over several years on seven grass soccer fields differing in top layer, subsoil and drainage. It proved that the playing conditions of the top layer can be characterized by means of the penetration resistance of a cone. This resistance depends on soil composition, soil bulk density, soil water conditions and the reinforcing action of grass roots. Limits for the density as well as the pressure head were established at which soil strength becomes insufficient for adequate playing conditions.

Compactability and strength of sands usually applied in sports field construction were comprehensively examined in the laboratory. The influence on these properties of bulk density, soil water content, soil water pressure head, organic matter content, clay content and coarseness of sand could be established, as also the contribution of grass roots to top layer soil strength.

The incompatibility between top layer compaction required for adequate playing of the turf and viability of grass was examined. To this purpose the course of sward density and root distribution were determined on intensively as well as extensively played parts of four grass sport fields. In addition soil aeration was measured during two playing seasons strongly differing in precipitation, on four regularly played fields in terms of oxygen diffusion rate and oxygen concentration in the soil gas phase. Measured rates and concentrations were compared with values mentioned in literature as limiting for grass growth.

The extent to which an increase in bulk density and organic matter content of the top layer is permitted with respect to top layer water conditions was investigated. Effects of top layer thickness, type of subsoil and subsurface drainage, by means of drain tubes or a tube drained sandy layer between top layer and subsoil, were included in the investigations. Soil hydrological properties of differently composed and compacted top layers as well as of various subsoils were determined. To establish the soil water conditions of the top layer, decisive for the extend of shortcoming of its hydrological properties, a steady-state approach respectively a non-steady-state approach of soil water flow has been applied.

Taking steady-state conditions, an estimate of duration, frequency and depth of ponding has been made from amount-duration-frequency precipitation curves. From ponding depths that should appear on the original soil and soil water

characteristics of the top layer sand to be used, the top layer thickness necessary to prevent ponding was derived. To illustrate the effects of top layer, subsoil and subsurface drainage on soil water conditions in both top layer and subsoil, pressure head profiles have been calculated. To study the effects under non-steady-state conditions an electronic analog was used. This analog simulates the variation with time of the pressure head in the top layer as a combined effect of precipitation, hydrological characteristics of top layer and subsoil and the properties of the drainage system. With the aid of the density and pressure head limits obtained from field and laboratory measurements, duration and frequency of inadequate playing conditions could be derived from the simulated course of the pressure head.

For the main results of this study, together with conclusions and recommendations for construction and maintenance of grass sports fields, the reader is referred to the statements which constitute Chapter 6.

Samenvatting, conclusies en aanbevelingen

Het onderzoek

Met de toename van het aantal beoefenaren van veldsporten is de behoefte aan grassportvelden sterk toegenomen. Vanwege de groeiende vraag, het toenemende ruimtebeslag en de hoge aanleg- en onderhoudskosten is het de moeite waard aandacht te besteden aan de bespeelbaarheid van sportvelden. In de literatuur worden vele, vaak nogal uiteenlopende, normen voor de aanleg van sportvelden gegeven. Nagenoeg alle hebben betrekking op de verzadigde doorlatenheid en de korrelgrootteverdeling van de toplaag (Hoofdstuk 1). Soms wordt nog aanvullende informatie gegeven over grenswaarden voor het totale poriënvolume, het met lucht gevulde poriënvolume en de vochthoudendheid van de toplaag. Vele van de gegeven normen houden nauwelijks rekening met frequentie, intensiteit en plaats (klimaat, bodem) van het gebruik. Bovendien zijn ze slechts een indirecte maat voor de eigenschappen die de bespeelbaarheid bepalen en ze zijn veelal nauwelijks gecontroleerd op de overdraagbaarheid naar veldomstandigheden.

Deze studie beoogt bij te dragen aan de kennis van die eigenschappen en processen in toplaag en ondergrond die de bespeelbaarheid van sportvelden op meer directe wijze bepalen. Er werd gekozen voor een bodemfysische–grondmechanische–hydrologische benadering van de bespeelbaarheid, waarbij de mechanische sterkte van de toplaag centraal stond. Het onderzoek betrof voetbalvelden en bestond uit een inventariserend deel uitgevoerd in het veld, een analyserend deel berustend op laboratoriumwaarnemingen en een modelonderzoek dat behalve een analyserend ook een generaliserend karakter had.

Gedurende enkele speelseizoenen werd onderzoek verricht op een zevental sportvelden met een zandige toplaag. De grondsoorten waarop de sportvelden lagen en de ontwatering verschilden (Hoofdstuk 2). Grenswaarden van de indringingsweerstand, waarbij de toplaag te zwak wordt voor bespeling, konden worden vastgesteld. Ook voor de volumedichtheid van en de drukhoogte van het bodemvocht in de toplaag werden grenswaarden gevonden waarbij de mechanische sterkte te gering wordt voor een goede bespeelbaarheid.

Om inzicht te krijgen in verbeteringsmogelijkheden van de bespeelbaarheid door de volumedichtheid en vochtomstandigheden in de toplaag te beïnvloeden werd een uitvoerig onderzoek in het laboratorium verricht naar de verdichtbaarheid en de mechanische sterkte van zanden die als toplaag worden gebruikt (Hoofdstuk 3). Het effect van volumedichtheid, vochtgehalte en drukhoogte van het bodemvocht, organische-stof- en lutumgehalte en grofheid van het zand op deze eigenschappen kon worden vastgesteld. Tevens werd een indruk verkregen van de bijdrage van de graswortels aan de mechanische sterkte van de toplaag.

Omdat toplaagverdichting strijdig kan zijn met de groeimogelijkheden van het gras werd de bedekkingsgraad en de bewortelingsintensiteit vastgelegd zowel op intensief als extensief bespeelde plekken van een viertal sportvelden (Hoofdstuk 4). Op dezelfde velden werden gedurende twee speelseizoenen, die in natheid verschilden, zuurstofdiffusie- en zuurstofgehaltemetingen verricht. De gemeten waarden werden vergeleken met waarden die in de literatuur als limiterend voor grasgroei worden opgegeven.

Onderzocht werd in hoeverre vergroting van de volumedichtheid en verhoging van het organische-stofgehalte van de toplaag ter verbetering van de bespeelbaarheid toelaatbaar zijn met het oog op de vochtomstandigheden. Hierbij werd tevens aandacht besteed aan de invloed van de dikte van de toplaag, de ondergrond en de drainage door middel van buizen of door het aanbrengen van een zandlaag tussen toplaag en ondergrond, op de vochtomstandigheden in de toplaag (Hoofdstuk 5). Hiertoe werden eerst de vochkarakteristiek en het capillair geleidingsvermogen van verschillend samengestelde en verdichte toplagen en van verschillende grondsoorten bepaald. Om te kunnen beoordelen wanneer deze eigenschappen onvoldoende zijn, moeten de vochtomstandigheden die als gevolg van deze eigenschappen voorkomen, worden bepaald. Hiervoor zijn een stationaire en een niet-stationaire benadering van de stroming van water in de grond toegepast. Onder aannemen van stationaire stromingsomstandigheden werd met behulp van regenduurlijnen een schatting gemaakt van de duur en frequentie van plasvorming en de diepte van de plassen. De dikte van de toplaag nodig om plasvorming te voorkomen werd afgeleid uit de diepte van de plas en de vochtkarakteristiek van het te gebruiken zand. Daarnaast werd het beloop met de diepte van de druk van het bodemvocht berekend om de invloed te bepalen van toplaag, ondergrond en drainage op de vochtomstandigheden in de toplaag. Dezelfde invloeden werden ook bestudeerd voor niet-stationaire stromingsomstandigheden. Hierbij werd een elektrisch analogon gebruikt. Dit simuleert het verloop van de drukhoogte van het bodemvocht in de toplaag in afhankelijkheid van de neerslag, de hydrologische eigenschappen van toplaag en ondergrond, en de drainage. Uit het gesimuleerde verloop van de druk van het bodemvocht werden de duur en de frequentie van onbespeelbare situaties afgeleid met behulp van via veld- en laboratoriumonderzoek gevonden kritische waarden voor volumedichtheid en drukhoogte van het bodemvocht.

Conclusies en aanbevelingen

Het onderzoek verschafte inzicht in de eigenschappen en processen die de bespeelbaarheid van grassportvelden beïnvloeden. Een aantal nuttige richtlijnen voor aanleg en onderhoud konden worden afgeleid. Dit leidde tot de volgende conclusies en aanbevelingen (Hoofdstuk 6).

Vereiste mechanische sterkte, dichtheden en vochttoestand

– De bespeelbaarheid hangt af van de draagkracht van de toplaag. De draagkracht wordt bepaald door samenstelling, volumedichtheid, vochtomstandigheden en de

wapening door graswortels.
- De indringingsweerstand gemeten met een conus is een eenvoudige en reproduceerbare maat voor de bespeelbaarheid.
- Wanneer de indringingsweerstand, gemeten met een conus met een basis van 1 cm^2 en een tophoek van 60°, tenminste 1,4 MPa bedraagt, wordt de toplaag op intensief bespeelde delen van een sportveld niet vervormd. Op minder intensief bespeelde delen moet de indringingsweerstand tenminste 1,0 MPa zijn.
- Wegens de verschillen in organische-stofgehalte van zandige toplagen is het niet mogelijk een uniforme grenswaarde voor de volumedichtheid waarbij de mechanische sterkte voldoende is te formuleren. De indringingsweerstand is echter veelal voldoende hoog voor een goede bespeelbaarheid wanneer de toplaag verdicht is tot een relatieve dichtheid (i.e. mate van verdichting) van 0,45 of hoger.
- Deze waarde van de relatieve dichtheid komt bij zand met organische-stofgehalten van 1, 2, 3, 4, 5, 6, 7 en 8% overeen met volumedichtheden van respectievelijk 1,65; 1,61; 1,56; 1,52; 1,47; 1,44; 1,41 en 1,38 $g \cdot cm^{-3}$.
- Om deze volumedichtheden te kunnen handhaven zijn regelmatige bespeling en, in perioden met een lage bespelingsfrequentie, verdichting door rollen passende onderhoudsmaatregelen.
- Indien de relatieve dichtheid 0,45 of meer is, kan door te natte vochtomstandigheden de mechanische sterkte nog onvoldoende zijn. Uit verbanden tussen indringingsweerstand en drukhoogte van het bodemvocht bij verschillende volumedichtheden konden grenswaarden voor de drukhoogte (ψ) waarbij de mechanische sterkte van de toplaag te gering wordt voor een goede bespeelbaarheid worden afgeleid. Voor zanden met 0 tot 2%, 3%, 4% en 5 tot 8% organische stof en verdicht tot een relatieve dichtheid van 0,45 of hoger, zijn de grenswaarden respectievelijk $\psi = 0$, -10, -20 en -30 cm. Deze grenswaarden laten zien dat schrale toplagen natter mogen zijn dan toplagen met een hoger organisch stofgehalte voordat de indringingsweerstand zakt beneden de vereiste waarde van 1,4 MPa.
- Is de toplaag onvoldoende verdicht, dat wil zeggen duidelijk beneden een relatieve dichtheid van 0,45, dan moet voor voldoende mechanische sterkte de ψ-grenswaarde lager (droger) zijn dan voor een meer verdichte toplaag: $\psi < -40$ tot -60 cm. Naarmate de ψ-grenswaarde lager is zal hij echter in natte perioden langduriger en vaker worden overschreden.

Samenstelling, verdichtbaarheid en mechanische sterkte

- Met betrekking tot de samenstelling en verdichtbaarheid van de toplaag werd gevonden dat bij toenemende belasting de volumedichtheid sterker toeneemt naarmate het organische-stof- en lutumgehalte hoger zijn; dit vooral onder natte omstandigheden. Dit betekent dat verschillen in volumedichtheid van de toplaag tussen extensief en intensief bespeelde plekken groter zullen zijn naarmate het organische-stof- en lutumgehalte hoger zijn.
- In perioden waarin niet of weinig wordt gespeeld, wordt dikwijls waargenomen dat, als gevolg van wortelgroei en regenwormactiviteiten, de volumedichtheid van

de toplaag afneemt. De afneming van de mechanische sterkte die hiervan het gevolg is, is groter bij hogere organische-stof- en lutumgehalten van de toplaag. Hierdoor vragen deze velden qua onderhoud meer inspanning om de voor een goede bespeelbaarheid vereiste volumedichtheid te handhaven. Het is dan ook beter om velden die weinig worden bespeeld te voorzien van een toplaag met een organische-stofgehalte van ongeveer 4% en een lutumgehalte beneden 5%.

- Onder gelijke verdichtingsomstandigheden verkrijgt matig grof zand een hogere volumedichtheid dan matig fijn zand; ook wanneer klei wordt bijgemengd.
- Met betrekking tot de invloed van samenstelling en verdichting op de mechanische sterkte van de toplaag bleek zeer duidelijk dat organische stof een belangrijke bijdrage levert aan de mechanische sterkte van zand, echter alleen na verdichting tot relatief hoge volumedichtheden (zie de eerder gegeven grenswaarden). Dus verdichting door regelmatige bespeling, indien nodig aangevuld met rollen, is een zeer effectieve maatregel om de bespeelbaarheid van meer humeuze toplagen op peil te houden.
- In het traject van drukhoogten van het bodemvocht van $-80 < \psi < 0$ cm, hetgeen geldt voor het grootste deel van het speelseizoen, dragen kleideeltjes (lutum) nauwelijks bij aan de mechanische sterkte van schraal zandige toplagen. Dit in tegenstelling tot organische stof.
- Onder drogere omstandigheden, die echter voornamelijk buiten het competitieseizoen vallen, heeft een zandige toplaag met kleibijmenging meer mechanische sterkte en stabiliteit dan een schrale toplaag.
- Omdat onder natte omstandigheden schrale toplagen met kleibijmenging sterk verdicht worden en de kleideeltjes nauwelijks bijdragen aan de mechanische sterkte en bovendien de doorlatendheid doen afnemen, moet worden geadviseerd het kleigehalte van toplagen van vooral in de winter gebruikte sportvelden laag te houden. Hierbij kan worden gedacht aan een norm van maximaal 5% van de deeltjes $<2\ \mu m$ en 10% van die $<20\ \mu m$.
- Op kleigronden met regenwormactiviteit is het niet eenvoudig een dergelijk laag kleigehalte te handhaven. In plaats van de gebruikelijke toediening van 0,5 tot 1 cm zand in het voorjaar kan het best vanaf het begin van het speelseizoen zodebezanding worden toegepast, indien nodig doorlopend tijdens het speelseizoen, in hoeveelheden van 1 tot 2 mm per keer, gecombineerd met rollen. Bij regelmatige bespeling wordt aldus een homogene toplaag met een laag lutumgehalte behouden.
- Met het oog op de mechanische sterkte is matig fijn zand als toplaag op kleigronden te verkiezen boven matig grof zand. Om plasvorming te voorkomen verdient matig grof zand de voorkeur, omdat dan de toplaag minder dik behoeft te zijn.

Groeimogelijkheden voor gras en wapening door wortels

- Met betrekking tot de groeimogelijkheden voor gras bleek dat bij de vrij hoge volumedichtheden die vereist zijn voor een voldoende mechanische sterkte van de toplaag, tijdelijk sterk verlaagde zuurstofconcentraties in de bodem kunnen voorkomen. Uit het onderzoek werd de indruk verkregen dat deze verminderde aeratie niet erg schadelijk is voor de grasgroei. Bovendien bleek dat de door bespeling direct aan de grasmat toegebrachte schade de indirecte gevolgen van bespeling, zoals een verminderde bodemaeratie, verre overtreft.

– Onderhoudsmaatregelen gericht op verbetering van de water- en luchtdoorlatendheid van de toplaag (bodembeluchting) worden in Nederland op grote schaal toegepast. Omdat de invloed van verdichting als gevolg van bespeling zich uitstrekt tot een diepte van 5 tot maximaal 10 cm, moet eventuele bodembeluchting in elk geval tot deze diepte gaan. Met betrekking tot beïnvloeding van de bodemaeratie kan men zich, gezien het in de vorige paragraaf gestelde, echter afvragen in hoeverre deze maatregelen zin hebben.

– De bedekkingsgraad van het gras gedurende de herfst en winter hangt af van de bespelingsfrequentie en -intensiteit. Op intensief bespeelde delen kan deze teruggaan van 1,0 tot circa 0,2. Een dergelijke afneming van de bedekkingsgraad hoeft niet altijd schadelijk te zijn voor de bespeelbaarheid wegens de blijvende wapening van de toplaag door de wortelmassa die voor 90% in de bovenste 5 cm is geconcentreerd. Ondanks bespeling wordt in het voorjaar een sterk herstel van de zodedichtheid waargenomen, dat gestimuleerd kan worden met doorzaaien en water geven.

– De zode levert een grote bijdrage aan de mechanische sterkte van de toplaag. Deze bijdrage ligt in de orde van 0,8 tot 1,6 MPa. Veranderingen in mechanische sterkte die zich op korte termijn voordoen zijn een gevolg van veranderingen in druk van het bodemvocht en in volumedichtheid.

– Vastlegging van de toplaag door graswortels is van meer betekenis voor toplagen met relatief lage (circa 0 tot 3%) dan met hogere organische-stofgehalten.

– Niet-stabiel schraal zand heeft zowel in losse als in verdichte toestand een geringe mechanische sterkte. Maar omdat dit type zand weinig samendrukbaar is, heeft het, eenmaal door graswortels vastgelegd, een hoge indringingsweerstand en wordt dan nauwelijks meer vervormd. Schrale toplagen hebben echter de beperking dat de bespelingsfrequentie zodanig moet zijn dat een te sterke achteruitgang van de bewortelingsintensiteit wordt voorkomen. Vooral onder droge omstandigheden zijn deze toplagen bij frequente bespeling erg gevoelig voor schade.

– Zandige toplagen met hogere (>3%) organische-stofgehalten hebben, ondanks de beworteling van het gras, in losse toestand een te geringe mechanische sterkte. Door verdichting tot hogere volumedichtheden (zie de eerder gegeven grenswaarden) wint de toplaag aanzienlijk aan sterkte en is voor zijn stevigheid dan minder afhankelijk van de vastlegging door de wortels. Op deze toplagen kan daarom een hogere bespelingsfrequentie worden toegestaan dan op schrale toplagen.

Toplaag-ondergrond-drainage combinaties

– Uit het oogpunt van mechanische sterkte moet de voorkeur worden gegeven aan toplagen met relatief hoge organische-stofgehalten, mits voldoende verdicht. Naarmate het organische-stofgehalte en de volumedichtheid toenemen zullen echter de doorlatendheid en het bergend vermogen van de toplaag afnemen en wordt de kans op te natte bodemomstandigheden groter.

– De vochtomstandigheden in de toplaag hangen niet alleen af van hydrologische eigenschappen van deze laag. Zij worden ook beïnvloed door andere factoren, zoals de dikte van de toplaag, het type ondergrond en de drainage. Ook het aanbrengen van een zandlaag tussen toplaag en ondergrond, bedoeld om de afvoer van water te vergemakkelijken, is van invloed.

– Uit simulaties van verschillende combinaties van toplaag en ondergrond bleek dat de vochtomstandigheden in de toplaag in hoge mate worden beinvloed door de hydrologische eigenschappen van de ondergrond. Naarmate het capillair geleidingsvermogen van de ondergrond hoger is, is de drukhoogte van het bodemvocht in de toplaag lager (droger) en andersom.

– Op slecht doorlatende gronden (zoals zwaardere kleigronden) past een schrale toplaag (maximaal 4% organische stof) het best, op matig doorlatende gronden (zoals zavels en lemige gronden) zijn organische-stofgehalten in de toplaag tot ongeveer 6% toelaatbaar. Zand toplagen op goed doorlatende gronden (zoals zandgronden) mogen een organische-stofgehalte hebben tot ongeveer 8%. Dit alles uiteraard onder de voorwaarde dat de volumedichtheden voldoen aan de eerder gegeven grenswaarden.

– Toplagen die onvoldoende verdicht zijn (relatieve dichtheid lager dan 0,45) zullen in de winter regelmatig onbespeelbaar zijn, ook als ze liggen op goed doorlatende en goed gedraineerde ondergronden. Rollen, en indien mogelijk regelmatig bespelen, kunnen de bespeelbaarheid verbeteren.

– Verdichting als gevolg van bespeling gaat tot een diepte van maximaal 10 cm. In het algemeen is een dikte van de toplaag van 10 cm dan ook voldoende. Op ondergronden met geringe doorlatendheid zijn dikten tot 20 cm aan te bevelen.

– Het belangrijkste effect van drainage is het verkorten van de tijdsduur van natte bodemomstandigheden. Verschillen in vochttoestand van de toplaag tussen slecht en goed gedraineerde gronden zijn het grootst tijdens het droger worden van de grond na regen.

– Het effect van drainage op de bespeelbaarheid hangt sterk af van de aanwezige toplaag en ondergrond. Voor een goede bespeelbaarheid hebben losse toplagen meer behoefte aan drainage dan toplagen die voldoende zijn verdicht. Liggen te gering verdichte toplagen op een goed doorlatende ondergrond dan kan met behulp van drainage de bespeelbaarheid aanzienlijk worden verbeterd. Een aanvullende toplaagverdichting geeft een nog gunstiger resultaat.

– Ondergronden met een geringe doorlatendheid, die in feite het meest drainage behoeven, reageren het minst op drainagemaatregelen. Het is daarom noodzakelijk om slecht doorlatende gronden, indien gebruikt voor sportvelden, behalve van drainage tevens te voorzien van een schrale toplaag waarvan de ψ-grenswaarde voor voldoende bespeelbaarheid dicht bij verzadiging ligt.

– In het algemeen is een grote draindiepte gecombineerd met een lage afvoernorm (i.e. grote drainafstand) veel effectiever voor beheersing van de vochtomstandigheden in de toplaag dan een geringe draindiepte gecombineerd met een hoge afvoernorm (i.e. kleine drainafstanden).

– De afvoernorm van 1,5 cm $\cdot$ d^{-1} bij een grondwaterstand van 50 cm beneden maaiveld, zoals in Nederland wordt toegepast bij de drainage van sportvelden, is niet zinvol bij draindiepten van meer dan circa 100 cm beneden maaiveld. Bij een draindiepte van 120 cm kan worden volstaan met een afvoernorm van 0,7 cm $\cdot$ d^{-1}.

- Een drainagemethode die nogal eens in het buitenland wordt toegepast bestaat uit het tussen toplaag en ondergrond aanbrengen van een zandlaag (drainagelaag) voorzien van drainbuizen. Uit dit onderzoek bleek dat de beste combinatie bestaat uit een voldoend verdichte zandige toplaag met maximaal 4% organische stof liggend op een drainagelaag van grof zand. Toplagen met hogere organische-stofgehalten (circa 5 tot 8%) passen beslist niet op een dergelijk ondiep gedraineerd profiel.
- Indien de drainagelaag uit fijner zand bestaat verdient een toplaag vrijwel zonder humus de voorkeur.
- Bij toepassing van een drainagelaag van grof zand kunnen ruimere drainafstanden worden toegepast dan wanneer de drainagelaag uit fijn zand bestaat.
- Het toepassen van een drainagelaag heeft bezwaren zoals dure aanleg en droogtegevoeligheid. Indien, zoals gebruikelijk bij deze constructie, infiltratie via de drains wordt toegepast zal het vochtgehalte van de toplaag ook in de zomer hoog zijn, hetgeen tot een ongewenste ontwikkeling van de samenstelling van de grasmat en tot een sterke viltvorming kan leiden. Daarom komt een dergelijke aanlegmethode slechts in aanmerking op zeer slecht doorlatende ondergronden.

Op basis van de voorafgaande conclusies en aanbevelingen geeft tabel 26 een globaal overzicht van de geschiktheid van toplaag–ondergrond combinaties voor grassportvelden in een gematigd humide klimaat.

Tabel 26. Geschiktheid van toplaag – ondergrond combinaties voor grassportvelden in een gematigd humide klimaat. De toplaag dient te bestaan uit zand met een kleigehalte <5%. De drainage moet zodanig zijn dat de vermelde ψ-grenswaarden zo weinig mogelijk worden overschreden (zie Tabel 21). + = geschikt; – = niet aan te bevelen.

Toplaag met			Doorlatendheid ondergrond		
organisch stofgehalte (%)	volume-dichtheid ($g \cdot cm^{-3}$)	ψ-grens-waarde (cm)	gering (bv. klei-gronden)	matig (bv. zavel- en lemige gronden)	goed (bv. zand-gronden)
1	≥1.65	0	+	–	– – –
2	≥1.61	0	+	–	– –
3	≥1.56	−10	+ + +	+	–
4	≥1.52	−20	+ +	+ + +	+ +
5	≥1.47	−30	–	+ + +	+ + +
6	≥1.44	−30	– –	+	+ + +
7	≥1.41	−30	– – –	–	+ +
8	≥1.38	−30	– – –	– – –	+

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