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Drainage criteria for soil workability

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Summary

Early workability of the soil after rain is of great economic significance in modern farming. The role of drainage in this respect is well recognized but has so far not been explicity translated into drainage requirements and design criteria.

In this paper drainage requirements for workability are formulated on the basis of the soil moisture content at the lower plastic limit. It is investigated how the latter value relates to field capacity. Currently used drainage design criteria are analysed with respect to soil workability requirements; it is concluded that there is little technical and even less economic scope for improving soil workability by adopting stricter criteria, leading to narrower drain spacings. However, a convincing case can be made for increasing the drain depth in medium and heavy textured soils beyond the commonly applied depth at present of about 100 cm, under prevailing conditions in the Netherlands.

The effects of soil management on soil workability are also briefly discussed.

Introduction

More harm is often done in modern farming by the interference of excess water with the timely or proper execution of essential farm operations than by the direct adverse effects of excess water on plant growth. Delays due to wet, non-workable field conditions can result, directly or indirectly, in considerable yield losses or cost increases. Under the tight calendar of modern farming a delay in one operation may have serious repercussions on subsequent operations. When the operation is not delayed but executed under unsuitable soil moisture conditions, the effectiveness of the operation is often low and serious damage may be done to the soil, affecting future crops (Anon., 1970).

The role of drainage in controlling soil moisture conditions for soil workability is well recognized (Reeve & Fausy, 1976), but so far is not explicitly taken into

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account in drainage design. It is the purpose of this paper to analyse whether currently used drainage design criteria, which were developed mostly on the basis of crop growth requirements, also meet the workability requirements.

Soil consistency and soil workability

The strength of the cohesive and adhesive forces acting within the soil largely determines the behaviour of the soil when tilled or when machinery moves over the soil. There are various kinds of cohesive and adhesive forces acting within the soil. In a moist soil, however, the most important ones are those excercised by the water film bonds between the soil particles. The current strength of these bonds manifests itself in the state of consistency of the soil. When the soil moisture content is low, there are few water film bonds to hold the soil particles together and the soil consistency is friable. As the moisture content increases, more and more bonds establish and the soil consistency turns plastic. As the films also become thicker, eventually a point is reached where the surface tension forces become too weak for the bonds to hold the particles together and the soil consistency becomes viscous. The moisture content at which the soil consistency changes from friable to plastic, is referred to as the lower plastic limit (LPL); the upper plastic limit (UPL) marks the dividing point between the plastic and the viscous state of consistency.

The best soil consistency state for working the soil is the friable state (Kohnke, 1968; Baver et al., 1972; Archer, 1975). When the soil is worked at a moisture content at or above LPL, it is liable to smearing and puddling while, moreover, the operation itself is ineffective as the cohesive forces are too strong for the soil to crumble.

Adhesive forces also are stronger than below LPL, resulting in higher draft requirements. Traffic over the land is likely to result in harmful soil compaction when the soil moisture content is near or slightly above LPL.

So generally field operations should not be executed at a soil moisture content at or above LPL. The task of drainage is to help quickly dry the soil after rain to below LPL, so that field operations can be resumed. The depth to which the soil has to be dried varies somewhat per operation (tillage depth, compaction load, etc.). Considering the pressure distribution in the soil under wheel loading (Söhne, 1955) and tillage depths, a dried depth of 20-30 cm should be adequate for most farm work.

Relation between the lower plastic limit and field capacity

As drainage of excess water from the soil decreases sharply when the soil moisture content has fallen to field capacity (FC) [1], it is of special interest to know how LPL and FC relate. The LPL value refers to a moisture condition of a moulded soil; the FC value to that of a structured field soil. When the FC value is larger than the

[1] In this case field capacity has been set at pF 2.0.

LPL value, the field soil still contains, when drainage has virtually stopped, enough water to make the soil plastic when moulded, for example by machinery. So drainage alone will not dry such a soil enough to make it workable; evaporative drying of the soil is required in addition.

Data presented in Table 1 and Fig. 1 refer to well structured topsoil samples of an alluvial soil, containing some 3 % organic matter. The predominant clay mineral is kaolinite.

The amount of water required to make a soil plastic depends primarily on the specific surface area: the greater this area, the more water film bonds establish, and the more water is required. The LPL values thus increase in line with a percentage of fines in the soil (Fig. 1). The FC value, taken as the moisture content at pF 2.0, also increases with the content of fines in the soil, but also depends on the soil structure as is apparent from the differences in moisture content at pF 2.0 determined on core samples and on crushed soil. In the latter soil the influence of the macro-porosity has been eliminated.

Due to the interaction of soil structure no consistent relation between the FC value and the LPL value of a particular soil is to be expected. The effect of structure is least for light textures and here as a rule field moisture content at pF 2.0 will be approximately equal to or slightly less than at LPL. The available data suggest that for normally well structured, medium and heavy textured soils with a good macro-porosity, the field moisture content at pF 2.0 should be about equal to that at LPL. For poorly structured soils of this texture, however, the FC values may be much higher than the LPL values.

In view of the nature of consistency, consistency limits are characterised by the soil moisture content rather than by the soil moisture tension. The soil workability

Table 1. Moisture content in % by weight at different pF values and at lower and upper plastic limits for soils of different texture.

Texture	BD *	Core samples				Crushed soil		LPL *	UPL *
	(g/ml)	pF 0.0	pF 0.4	pF 1.0	pF 2.0 (=FC)*	pF 2.0	pF 4.2		
Loamy sand	1.47	29.9	26.8	25.6	10.9	10.7	4.4	14.5	20.8
Sandy loam	1.40	32.6	29.6	28.8	22.8	30.4	11.8	21.9	27.6
Loam	1.39	34.0	32.0	31.0	27.0	35.8	15.3	26.2	33.2
Clay loam/clay	1.38	34.1	32.8	32.0	29.6	42.6	20.7	31.1	40.9
Very fine sandy Loam	1.23	43.9	40.1	38.9	32.4	42.4	10.8	28.6	35.3
Silt loam	1.26	41.0	39.5	38.3	33.2	46.1	17.2	32.9	40.6
Silty clay loam/ Silty clay	1.25	42.0	40.2	39.1	36.3	49.2	24.9	38.2	52.0

* BD = bulk density; LPL = lower plastic limit; UPL = upper plastic limit; FC = field capacity.

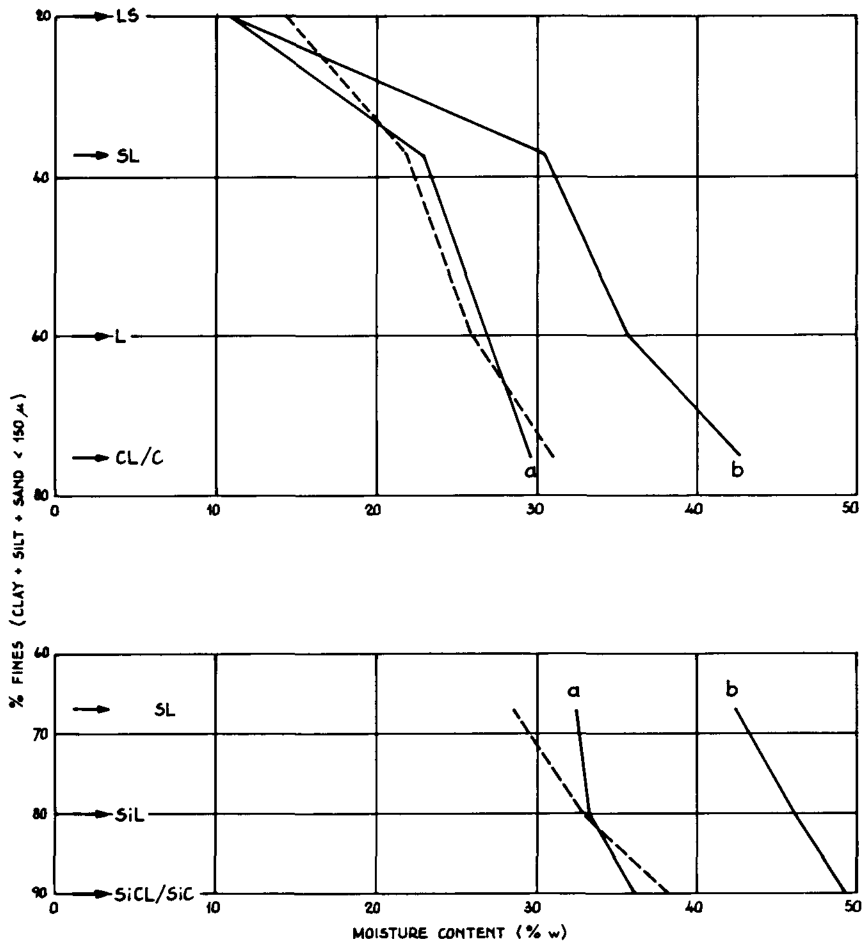

Fig. 1. Moisture content at pF 2.0 and at lower plastic limit for soils of different texture and structure.
——— pF 2.0; a = core sample, b = crushed soil; ---- lower plastic limit.

is best assessed by relating the field soil moisture content to the LPL value. The critical moisture content may be indicated by its corresponding pF value but the latter value has otherwise no diagnostic significance.

Drainage design criteria

In the Netherlands, a commonly applied criterium for water-table control by parallel tube drains is the requirement that the drainage capacity be adequate to control the water-table midway between two drains at 0.5 m below he soil surface under a steady state discharge of 7 mm/day. Enforcing this criterium, the required

Table 2. Fall of water-table.

t (days)	h_t (m)	Water-table below soil surface (m)
1	0.75	0.25
2	0.51	0.49
3	0.34	0.66
4	0.22	0.78
5	0.14	0.86

drain spacing has been calculated by the Hooghoudt formula for the situation as depicted in Fig. 2A.

$$L^2 = \frac{8Kdm_0 + 4\ Km_0^2}{q}, \text{ in which}$$

L = drain spacing
K = hydraulic conductivity
d = depth to impermeable layer (equivalent)
m_0 = available head.

The result is L = 30 m. For this spacing the rate of fall of the water-table, starting with a water-table at the soil surface, has been calculated by means of the Glover-Dumm non-steady drainage formula:

$$h_t/h_0 = 1.16\, e^{-\alpha t},\ \alpha = \pi^2\, KD/\mu L^2, \text{ in which:}$$

h = water-table above the drainage base; at t = o, h = h_0 and at t = t, h = h_t.
μ = drainable pore space
KD = transmissivity of the aquifer
L = drain spacing.

The results are given in Table 2.

The steady state soil moisture profiles corresponding with the water-table at t = 2 days and t = 4 days, as sketched in Fig. 2B, show the rate of restoration of the aeration of the rootzone (for the loam soil from Table 1). An air porosity of 5 % in the upper root zone appears to be adequate for good growth of most crops. This condition will be reached at t= 4-5 days. The moisture content in the top layer is then still well above LPL and the soil is not yet workable.

The above analysis, of course, does not take into account the evaporative drying of the soil. The effect of evaporation losses on the soil moisture profile has been schematically indicated in Fig. 2B. During the first days, part of the evaporative enerby will be spent on water on the foliage or on the soil surface, while water evaporated from in the soil is extracted from a very shallow surface layer only. Evaporative drying provides only a minor contribution to a quick restoration of the root zone aeration, which mostly depends on drainage. It contributes, however, greatly towards making the soil quickly workable after rain.

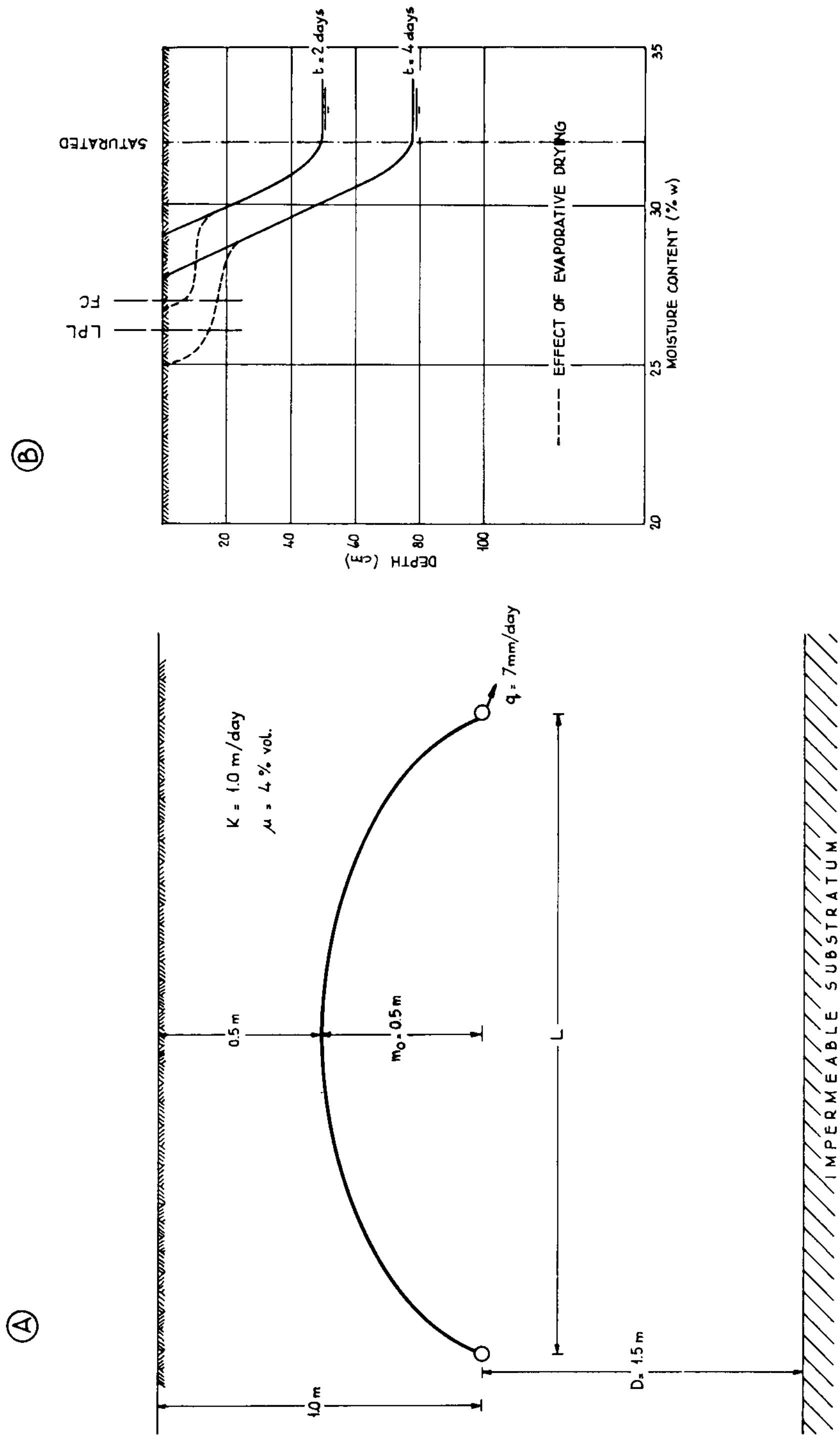

Fig. 2. Soil drainage by water-table control. A: a commonly used steady state design criterion. B: Sketch of the soil moisture profiles under a falling water-table, and the effect of evaporative drying.

Discussion

In view of the relations between LPL and FC as discussed earlier, the moisture in the top 20-30-cm layer typically must fall well below FC to render the soil workable. To achieve this by drainage alone takes a long time as the drying effect of drainage becomes insignificant when FC is approached. Increasing the drainage capacity by using a narrower drain spacing accelerates the early drainage flow but the same slowing down of the drying process will occur in the later stages. The small gain in time in reaching workable conditions is unlikely to outweigh the higher costs. Only evaporative drying can help to reduce the length of the final drying stage, or to reach the 'below LPL' end point at all. The latter certainly holds true for all soils with a LPL value $<<$ FC value as is the case for most poorly structured medium and heavy textured soils. So the conclusion must be that there is little technical and even less economic scope for improving early soil workability by adopting stricter drainage design criteria, resulting in narrower spacings, than currently used.

Wind (1976) studied the influence of drainage on soil workability in the spring in the Netherlands by simulating soil moisture conditions in the top layer during that period using non-steady unsaturated flow models and 23 years of historical rainfall and evaporation data. Results could be checked against available field observations on workability. The number of workable days was found to be hardly influenced by the drain spacing. Drain depth, however, greatly afected workability, the explanation being that under deep drainage the soil drains more thoroughly in between two rainy periods, so more of the next rain can be stored in the soil below LPL and less has to drain/evaporate to reach again workable conditions. In the above study it was found that on average there are 6.2 workable days in March-April when the drain depth is 40 cm, 12.5 days when 100 cm, 15.4 days when 150 cm and 17.1 days when 200 cm. So deep drainage allows earlier spring planting, resulting in better yields. At the other hand, deep drainage makes light textured soils more drought sensitive, and the currently commonly applied drain depth of approx. 100 cm appears to be about correct for a sandy loam soil under the prevailing conditions in the Netherlands (Wind, 1976; van Wyk & Feddes, 1976).

While drought damage may be unimportant for heavier textured soils, benefits due to better workability at drain depths of more than 100 cm should be weighed against the higher costs of deeper drainage. For the Netherlands a 1.5-3 % yield increase (relative to maximum yields) is to be expected from an increase in drain depth from 100 cm to 150 cm (Wind, 1976). Considering the effect on the number of workable days, the yield increase resulting from a drain depth increase from 150 cm to 200 cm may be expected to be in the order of 1-2 %. Field drainage costs normally will decrease when the drain depth increases from 100 cm up to 200 cm as the higher costs of deeper installation of the field drains are more than compensated for by the savings resulting from the wider spacings that can be used. The effect on total costs varies, depending on the costs of providing a corresponding deep disposal/outlet system. When the latter does not involve great technical difficulties, the benefits of deeper drainage arising from better soil workability may normally be expected to outweigh the higher costs for drain depths up to 200 cm, on soils with a good moisture holding capacity producing high value crops. Drain depths more than 200 cm seem to improve workability very little, while drainage costs often increase sharply. Of course, the above applies to the Netherlands; depending on the improvement of soil workability resulting from deeper drainage, and its economic significance in relation to drainage costs, quite different conclusions may apply elsewhere.

Other than by deep drainage, there would appear to be opportunities also for improving early soil workability after rain by good soil management. This because of the influence of soil management on the relation between LPL and FC. Any measure which either increases the LPL value more than the FC value, or decreases the FC value more than the LPL value, thus bringing LPL closer to or even above FC, would in principle improve the soil workability. Fig. 1 suggests one such measure to be increasing the macro-porosity of the medium and heavy textured soils, allowing more water to drain freely and leaving less in the soil at FC. This would especially benefit poorly structured soils which have been subjected to smearing, puddling, compaction etc., as such soils hold much more water at FC than a well structured soil (Koenings, 1961). Often such a poor structure is a result of untimely working of the soil, and a vicious circle is likely to develop with the present poor workability condition of the soil leading to more untimely farm operations. Exposure of the soil to frost or to intensive drying, addition of organic matter, etc. are the well-known remedies for such a situation.

It is also well-known that the LPL value increases with the organic matter content of the soil (Baver et al., 1972). Boekel (1963) claims that with an increasing soil organic matter content, soils become better workable as the LPL value increases more than the FC value, but this does not seem to hold true for all soils (Archer, 1975). Obviously, the effect of an increase of the organic matter content of the soil on the FC value depends on the current state of the soil structure, and especially on the current macro-porosity. When the latter is low the FC value of heavy soil may well decrease rather than increase by raising the soil organic matter content.

Finally, it is conceivable that also the aggregate stability has an influence on workability. A soil may have the necessary moisture content to become plastic when moulded, but a high aggregate stability may resist moulding of the soil and no harm would be done by working such a soil at a moisture content above LPL.

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