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Tillage of soils in relation to their bi-modal pore size distributions

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ABSTRACT

The optimum water content for tillage has been defined as the water content at which production of small aggregates is greatest and production of large aggregates or clods is least.

Recent work on the optimum water content for tillage and on the soil structures produced by tillage has been based on the water retention characteristics of soils (plotted as gravimetric water content against the natural logarithm of the pore water suction in hPa). It was assumed that the van Genuchten water retention equation, which has a unique inflection point, provides an adequate fit to the water retention data. When this equation has been fitted to experimental data, it has been found that the optimum water content for tillage is given by the water content at the inflection point of the fitted curve, and that the size distribution of clods and aggregates produced by tillage is related simply to the slope, *S*, of the curve at the inflection point. Although this procedure is useful for prediction purposes, it does not explain why the inflection point is the optimum water content for tillage.

A more detailed examination of water retention data has shown that most soils have pore size distributions that are bi-modal. That is, there are two distinct peaks of pore size corresponding with the textural and structural pore spaces that usually occur in the range of water suctions used in traditional water retention studies (10–15,000 hPa).

In this paper, results of tillage experiments are re-examined in terms of the bi-modal pore size distribution of soils. It is shown that the optimum water content for tillage occurs when the matrix porosity is saturated, but the structural porosity is drained (i.e. is air-filled). The mechanism of crumbling of soil during tillage is discussed in terms of the expansion, elongation and joining-up of pre-existing, air-filled micro-cracks. These comprise the air-filled portion of the structural porosity. It is concluded that taking account of the bi-modal nature of the soil pore size distribution leads to an improved understanding of the physical basis of tillage.

1. Introduction

Tillage at a certain water content produces the smallest amount of clods and large aggregates and the largest amount of small aggregates. This water content is called the optimum water content for tillage, w_{opt}. The optimum water content for tillage was found to be equal to the water content at the inflection point of the water retention curve as fitted with the van Genuchten (1980) equation (Dexter and Bird, 2001; Dexter et al., 2005).

Some other work on the optimum water content for tillage has used the plastic (or lower Atterberg) limit, *PL*, of the soil. For example, Ojeniyi and Dexter (1979) found with an Australian soil that tillage at a water content of $w = 0.9\,PL$ was optimum. This result was then incorporated into a more general model for soil tillage (Dexter, 1979). Mueller et al. (2003) also concluded that tillage at a water content $w = 0.9\,PL$ was optimum. Arvidsson and Bölenius (2006) found with a Swedish soil that tillage at $w = 0.76\,PL$ produced a greater proportion of small aggregates than tillage at $w = 0.91\,PL$. Keller et al. (2007) did tillage experiments in the field on four different Swedish soils. In relation to *PL*, they showed that $w = 0.7\,PL$ gave the best prediction of the optimum water content for tillage. However, they also tested the predictions of w_{opt} obtained from water retention studies (i.e. Dexter and Bird, 2001; Dexter and Birkás, 2004). They showed that the water content at the inflection point of the water retention curve provides a better estimate of the optimum water content for tillage, w_{opt}, than any proportion of the lower plastic limit, *PL*.

However, knowledge of the optimum water content for tillage does not give information about the size distribution of aggregates or clods produced by tillage.

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The size distribution of clods and aggregates produced by tillage can be estimated from S-theory which is based on the concept of the structural state of the soil as quantified by water retention data (Dexter, 2004a,b,c; Dexter and Czyż, 2007). The value of S is given by the slope of the water retention curve at its inflection point (as observed when pore water suction, h, is plotted on a logarithmic scale):

$$S = \frac{dw}{d(\ln(h))} \quad (1)$$

where w is the gravimetric water content in kg kg^{-1} and h is the suction of the pore water in hPa. S can be considered as an index of soil physical quality (Dexter, 2004a,b,c; Dexter and Czyż, 2007). At the inflection point, the water content is w_i and the matric water potential is h_i.

Values of S can be used to give information about the size distribution of aggregates or clods produced by tillage as shown by Dexter and Birkás (2004) and Keller et al. (2007). The results from five Hungarian soils with clay contents in the range 350–600 g kg^{-1} showed that the production of clods (>50 mm) was negatively correlated with S and was zero for values of $S > 0.036$ (Dexter and Birkás, 2004). The results from the four Swedish soils with clay contents in the range 220–540 g kg^{-1} studied by Keller et al. (2007) are summarized in Fig. 1. With neither the Hungarian nor the Swedish soils did the ranking order of the values of S coincide with the ranking order of the clay contents.

The three lines in Fig. 1 correspond to the mass proportions, P, of clods > 50 mm, aggregates > 10 mm and aggregates > 5 mm, produced during tillage, respectively. The three lines are given by

$$P \geq x = 1 - \frac{S}{S_x}, \quad \text{for } S < S_x \quad (2)$$

where the values of S_x are given by $S_x = 0.041$, $S_x = 0.087$ and $S_x = 0.153$, for values of x = 50 mm, 10 mm and 5 mm, respectively. The values of S_x for x = 50 mm obtained for the Hungarian soils ($S_x = 0.036$) and the Swedish soils ($S_x = 0.041$) are very close even though these soils have completely different genetic origins, have different contents of clay and organic matter and have experienced different management practices. These results support the view that given values of S have the same physical meaning in all soils.

The proportions of clods larger than 50 mm was considered because these are not useful agronomically. The production of clods >50 mm during tillage can be considered to be an indication of poor soil physical quality.

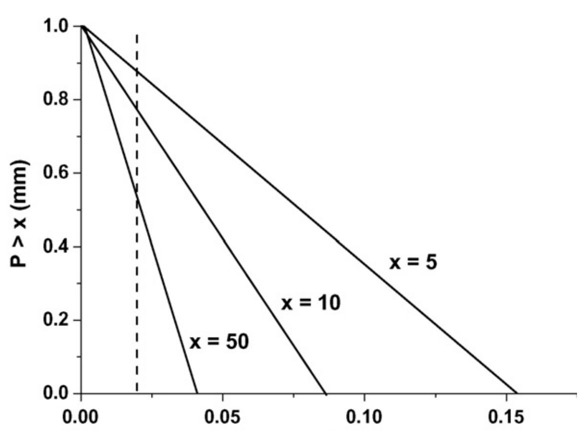

Fig. 1. Proportions of aggregates or clods produced by tillage of soils with different values of S. For example, tillage of a soil with a given value of S is predicted to produce mass proportions of clods or aggregates given by the values of y at which the vertical line (shown as a broken line) intersects the lines for >50, 10 and >5 mm, respectively. Soils with different physical quality will have vertical lines that intersect the x-axis at the appropriate value of S (figure after Keller et al., 2007).

On the basis of practical experience with a wide range of soils in the field, Dexter (2004a,b,c) and Dexter and Czyż (2007) have put different values of S into descriptive categories to facilitate comparisons of the physical quality of soils. These categories are

$S \geq 0.050$	very good
$0.050 > S \geq 0.035$	good
$0.035 > S \geq 0.020$	poor
$0.020 > S$	very poor

We can see from the above values that the initiation of the production of clods >50 mm during tillage corresponds closely to the boundary between "good" and "poor" soil physical quality as given by the value of $S = 0.035$.

Soils with larger values of S produce smaller aggregates when tilled and may be tilled with satisfactory results over a wider range of water contents (Dexter et al., 2005). Factors that cause soil degradation, such as compaction and reductions of organic matter content, reduce the value of S and hence have the consequence of coarser soil structures being produced by tillage. However, the mechanisms responsible for this have not been clear.

The purpose of this paper is to re-examine the results of the tillage experiments reported by Dexter and Birkás (2004) and Keller et al. (2007) using a more-accurate water-retention function that takes separate account of both the matrix and structural porosities of soil (Dexter et al., 2008a). This equation for bi-modal pore size distributions takes a double-exponential form. Combinations of the tillage and the water-retention data are then used to provide a better physical basis for understanding the observed behaviour of soil during tillage.

2. Materials and methods

2.1. Soils and experiments

In this paper, we combine two types of previously measured experimental data:

(1) data from tillage experiments done on 9 soils in the field in Hungary and Sweden (Dexter and Birkás, 2004; Keller et al., 2007);
(2) data from water-retention measurements on 84 French and Polish soils.

We then assume that some findings from (2) are applicable to the soils used in the tillage experiments in (1). This then enables us to draw new conclusions about how soil structure and water content affect the results of tillage.

We took this approach because the water retention data for the soils used in the tillage experiments did not allow fitting of the more accurate, bi-modal, double-exponential water retention equation which has five adjustable parameters (Dexter et al., 2008a). As a rule-of-thumb, there should be measurements for at least twice as many suctions as there are adjustable parameters. It was not realistic to repeat the tillage experiments (which involved the sieving by hand of many tonnes of tilled soil) and the associated water retention experiments at an increased number of suctions. Therefore, we decided to use our existing data sets in the most efficient way possible.

2.2. Soil water retention data

We have used two sources of water-retention data for this work. The databases are in alphabetical order as follows: