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Water movement and stability of profiles in drained, clayey and swelling soils: at saturation, the structural stability determines the profile porosity

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Abstract

In clayey, swelling and more or less sodic soils, cultivation and seasonal climatic cycles induce variations in soil moisture which in turn cause variations in the soil structure. In particular, when the soil profile is saturated, some soils become impermeable because the soil porosity value does not remain sufficiently high throughout the drainage period to be effective for water movement. In the marshland soils of the French Atlantic coast, this ability is linked with the soil stability. We showed that soil profile stability and porosity are linked. First, we produced a classification of soil profiles ordered according to their degree of stability. Then, after describing the main features of the soil profile structure at saturation period, we proposed the concept of 'porosity profile'. This classification and concept were tested on farm fields by measuring two parameters: the water table in winter and the rooting depth of winter wheat. The values assumed by these parameters are indicators of field hydraulic and agronomic behaviour and more precisely of the depth of the soil layers where macroporosity allows water circulation and root colonisation. These results enabled us to validate the concept of 'porosity profile'.

Keywords: Macroporosity; Saline and sodic soils; Soil classification; Soil structure; Marshland soils; Water table; Root depth; Winter wheat

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1. Introduction

Certain marshland soils display similar characteristics: flat topography, a soil profile that is only slightly differentiated, high clay content and a swell/shrink potential, and more or less saline and sodic conditions (Van Hoorn, 1981; Salin, 1983; Rands, 1984; Moreno et al., 1995). In such situations the yearly recurrent cropping and climatic cycles induce soil moisture conditions which cause variations in the soil structure. In particular, when the soil profile is water saturated, the soil porosity value does not remain sufficiently high through-

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out the drainage period to allow water movement. In the marshland soils of the French Atlantic coast, this capacity is linked to the soil stability.

In this paper, we demonstrate the link between the stability of soil profiles and the hydraulic and agronomic behaviour of drained cultivated plots. To this end we produced a classification of profiles ordered according to their degree of stability. Then we described the main features of the soil profile structure at the saturation period and proposed the concept of 'profile porosity' which is defined by the thickness of the layers where macroporosity occurs.

The classification and concept were tested on farm fields by measuring two parameters: the water table level in winter and the root depth of winter wheat. The values assumed by these parameters are indicators of field behaviour and more precisely of the thickness of the layers in which macroporosity allows water circulation and root colonisation to occur. These results enabled us to validate the concept of 'porosity profile'.

2. Materials and methods

2.1. Experimental design and the stages in the study

We carried out two different series of studies. In the first we measured the structural stability of soil samples to produce a classification of standard profiles ordered by their degree of stability. The second series was designed to validate the soil profile classification by investigating field behaviour at the saturation period. The plots, cultivated with winter wheat, were selected on different farms so as to cover a wide spread of soil types, field drainage systems and farming systems. The first stage of the second series consisted of describing the main common features of the profile structure. The second stage consisted of observing and comparing the hydraulic and agronomic behaviour of the plots to prove that the depth of the macroporous layers provides an explanation for this behaviour.

2.2. Soil

The Western Marshlands (Marais de l'Ouest) in the central part of the French Atlantic coast extend over some 250 000 ha between the Vilaine river in the north and Gironde in the south. The soils are derived from recent marine and river sediments. As a result of similar conditions of sediment deposition in ancient bays and river estuaries (Chevallier et al., 1984; Ducloux, 1989), soil texture and clay mineralogy are the same, with 45 to 60% clay and more than 95% clay plus silt. Clay minerals consist of illite (50–60%), kaolinite and montmorillonite (20–25%). In 'dry' marshes where cultivation is possible, these characteristics remain roughly constant throughout the soil profile (Lafond and Verger, 1965; Morizet et al., 1970; Salin, 1983; Collas, 1985) the cation exchangeable capacity, measured at $\mathrm{pH} = 8.2$, is saturated and its value is high (25–30 cmol/kg). The soils however differ, mainly regarding age, natural drainage conditions and field drainage systems (Callot and Favrot, 1965; Wilbert, 1978; Salin, 1983; Ducloux, 1989). The climate is mild oceanic. The annual climatic balance is equilibrated: excess in winter (280 mm) balances out the summer deficit (250 mm). Owing to the very flat relief, with the land lying below the level of the highest tides, collective management of drainage is essential to control and drain the water out to the sea. As a result of soil age and water management, the soil profiles differ with respect to four chemical and physico-chemical characteristics, i.e. salinity and sodicity gradients and calcareous and organic matter content (Table 1). Therefore, both structural stability and permeability display significant spatial variability (Damour and Pons, 1987; Pons, 1997). In the French soil classification, these soils are referred to as salisols, salisodisols, sodisols and thalassosols (Baize and Girard, 1995), in FAO classification as fluvisols saliques and in Soil Taxonomy as Inceptisols Halaquepts or Mollisols Natralbolls or Natraquolls.

Consequently, although these soils possess many common features (origin, topography, clay content and swell-crack material), Collas (1985) and Pons (1985, 1988) recorded wide variation both in the drainage system effectiveness and in crop yields. Taking these soils into cultivation demands not only effective management of the main and collective drainage system as in the 'dry' marshes, but also requires field drainage. The main characteristics of the field drainage networks are spacing and depth (ZD) of the drains: 18 m spacing for open ditches at a depth of 0.40 to 0.50 m; 10–20 m spacing for pipe drains at a depth of 0.80 to 1.20 m.

2.3. Soils and plots

In the first series of studies, we took 111 samples from 42 soil profiles that represented a wide range of locations, deposition and cultivation ages. Soil samples were taken from 1980 to 1982, from profiles dug in saturated water conditions at the end of winter. The weakly differentiated profiles were characterised by three successive 0.30 m thick layers designated as H1, H2, H3. In the second series of studies, we observed soil structure, hydraulic and agronomic behaviour in winter of 40 plots differing in their physical conditions (year, drainage system, soil type) and crop management (farming systems). We selected winter wheat because this crop is subjected to excess water in winter and will therefore respond differently to varying degrees of excess.

2.4. Evaluation of structural stability

The relationship between soil stability and permeability has been demonstrated in a range of studies (Hénin et al., 1969; Loveday and Pyle, 1973; Collas et al., 1984). However, this relationship can be evidenced only on condition that the evaluation methods are adapted to the soil type. In the case of saline and sodic soils, the relation cannot be verified with a method based on evaluating the content of stable aggregates after several preliminary treatments (Hénin et al., 1969). Here, structural stability is better assessed by measuring the dispersion degree (Pons and Martineau, 1983; Pons, 1997) which also serves to identify the relations between soil stability and permeability (Quirk and Schofield, 1955; Shainberg et al., 1980, 1981). The Pons and Martineau test (1983), inspired from Emerson (1967), Loveday and Pyle (1973) and Greenland et al., (1975), is based on the dispersion intensity of soil aggregates when immersed in water and under mechanical stress. In a first stage, six 3–4 mm diameter aggregates, selected at random from the air-dried soil sample, were divided into two lots of three, and each lot dropped into 20 ml of distilled water in a clear, flat-bottomed, glass cup. After 10 min, dispersion of each lot is noted from 0 (no dispersion) to 4

Table 1
Main physio-chemical characteristics and structural stability of 'dry' marsh soils[a]

		CEC (cmol/kg)	ESP (%)	$CaCO_3$ (%)	Organic matter (%)	EC (dS)	*DI* (0–16)
Layer							
H1	M	30.0	7.0	5.4	3.0	1.4	5.5
0–0.30 m	SD	4.5	9.4	4.0	1.3	0.2	5.5
$N=31$							
H2	M	27.6	14.7	7.8	1.2	3.5	6.7
0.30–0.60 m	SD	3.4	13.0	4.4	0.4	0.8	6.2
$N=31$							
H3	M	25.8	30.4	7.1	0.8	6.8	11.0
0.60–0.90 m	SD	3.4	8.8	4.5	0.3	1.5	3.8
$N=16$							

[a] Structural stability is evaluated by *DI*, 'dispersion index'; *N*, number of samples; M, mean; SD, standard deviation.

(complete dispersion). In a second stage, the same procedure is done with a wet and remoulded sample: rough cubes of ≈ 4 mm side are formed and dropped into distilled water. After 2 h, dispersion is noted as before. The dispersion index (*DI*) is the general total of the dispersion note obtained by each lot of each stage. It varies from 0 (no dispersion) to 16 (maximum dispersion). If $DI \leq 6$, the soils are stable, if $DI \geq 10$, they are unstable, and if *DI* lies between 7 and 9, their stability is intermediate. Pons (1997) showed that DI is an indicator of soil structural stability.

2.5. Characteristics and observation of the soil structure

The plot profiles were investigated at the saturated period at the start of stem elongation. They were dug halfway between two drains. Observations were carried out down to rooting base and to 1 m depth at least. Soil structure was described following the methods of Hénin et al. (1969) and Gautronneau and Manichon (1987). When soils reach maximum swelling, hydraulic conductivity is strictly linked with macropore volume (Bouma and Wösten, 1979; Ahuja et al., 1984; Messing, 1989; Messing and Jarvis, 1990). The root diameter of winter wheat (Finney and Knight, 1973 cited in Cannell, 1977) is approximately the same as that of macroporosity which is defined by the minimum pore equivalent diameter value, i.e. $0.3–0.6 \times 10^{-3}$ m, depending on authors (Beven and Germann, 1982). Soil macroporosity is therefore a condition that favours root development in winter wheat. Investigating water movement through a saturated profile therefore means identifying the layers in which macroporosity and/ or roots occur.

In these soils, the exchangeable sodium content (ESP) and the soil solution salinity (EC) act on the hydratation capacity, the swelling degree and on the clay dispersion degree, and consequently on the structure of the soil profile. This accounts in part for the impermeability and morphology of the soil profiles (Tessier and Pedro, 1980; Halitim et al., 1984; Tessier, 1984; Guyot et al., 1984; Azib, 1989, Hallaire et al., 1996), and particularly for the lack of effectiveness of drainage systems and the poor behaviour of soils when drained and cultivated (Collas et al., 1984; Rands, 1984).

2.6. Observation of soil hydraulic and agronomic behaviour in winter

Soil hydraulic and agronomic behaviour was observed in 1981, 1982 and 1983. Water excess was evaluated by compiling the monthly weather balance (R-ET) at two periods. The first corresponds to re-wetting and the start of water excess (September–January), the second to water excess (saturation period from February to March). During the first period, the winter wheat reaches the start-of-tillering stage and during the second the start of stem elongation.

The water table depth in winter was taken as an indicator of the permeable layer base (Van Hoorn 1958; Trafford and Oliphant, 1977) or of drain depth. Damour et al. (1972) and Collas (1985) have shown that (a) in any marshland soil and any field drainage system, the water table shape is almost flat, and (b) the water table depth is not very sensitive to drain spacing. Consequently the water table was measured by placing piezometers at 1.20 m depth equidistantly of two neighbouring drains. The water table depth in winter was measured by calculating the mean of weekly piezometric values recorded during ≈ 10 weeks of the saturated period, i.e. mainly from mid-January to end of March.

Root density was evaluated on a vertical face of the profile (1.5 to 2 m width on the total rooting depth) at the start of stem elongation which is also the end of the saturated period (end of March), using the method applied by Meynard (1985). Root depth was assessed when root density was < 1 root $\times 10^{-2}$ m^2. This particular growth stage was chosen because the root system development shows that (a) the root dry matter and root depth are closely linked (Baldy, 1973; Welbank et al., 1974), and (b) the root dry weight/shoot dry weight ratio is maximum at the start of stem elongation (Gregory et al., 1978). The link between rooting depth and water table in winter was investigated in 30 of the 40 plots.

Table 2
The observed profile stability and profile classification[a]

			Type of soil profiles									
			1	2	3	4	5	6	7	8	9	10
			Stable						Intermediate			Unstable
Layer	Year	Drainage system										
H1: 0–0.30 m			S	S	S	S	S	S	I	I	I	U
H2: 0.30–0.60 m			S	S	S	I	I	U	I	I	U	U
H3: 0.60–0.90 m			S	I	U	I	U	U	I	U	U	U
Number of profiles = 42			11	13	1	0	1	1	0	2	5	8
Characteristics of the 40 plots cultivated with winter wheat												
	1981	Drain	3	3			1[b]	3		1		
		Ditches	1			1		1		1	3	1
	1982	Drain	1	1		1	2[b]				3	1
		Ditches				1				1	3	
	1983	Drain		1			2[b]				1	2
		Ditches								1		
Number of plots = 40			5	5	0	3	5	4	0	4	10	4

[a] The soil profile types are obtained by combining the three layers ordered by their degree of stability H1 ≧ H2 ≧ H3. Stability of soil layers: S, stable; I, Intermediate; U, unstable.

[b] Characteristics of the soil profile described in Fig. 1 and Fig. 4.

3. Results

3.1. Profile stability and classification

Table 2a presents the observed profile stability. It shows that the stability of soil layers varies greatly within and between the profiles. The first layer may be stable, intermediate or unstable, and in each profile, there is always a gradient of instability with depth: the stability of H1 ≥ H2 ≥ H3. This induced us to consider all the combinations of the three soil layers characterised by their structural stability (stable, intermediate, unstable) subjected to this gradient. We ended up with ten cases ordered according to their degree of instability and defined as 'profile types'. The types are characterised as stable (numbers 1–6), intermediate (numbers 7–9) and unstable (no. 10) when the first layer is respectively stable, intermediate or unstable. Consequently, the degree of stability of the profile may be defined by a single parameter, the depth of the unstable layer. On the basis of this result, the profile classification is defined as a succession of more or less thick layers ordered along a gradient of instability.

3.2. A porosity profile case: structure of a type 5 drained and cultivated soil

At the start of winter wheat stem elongation and therefore at the saturation period (Fig. 1), the water table depth is about 0.55 to 0.60 m. The plot is drained by pipes placed at 0.95 m depth. The plough layer (0–0.30 m) is stable; the substructure, consisting of more or less joined, different sized clods, leaves voids through which free water flows. The clods have a high internal porosity. The subsoil consists of two layers. The first, between 0.30 and 0.60 m, displays intermediate stability and a few thin cracks. The second, below 0.60 m, is unstable; it is massive, compact, with no cracks. A very thin layer of clay joins the prism faces and blocks the pores of former walls. Internal porosity in the subsoil structural elements is very low: it consists of rare and very fine pores of 0.2×10^{-3} m diameter. Macroporosity is therefore found only in the 0 to 0.55/0.60 m layers. So, when porosity decreases with profile depth, the profile porosity is defined by the thickness of the layers where macroporosity occurs.

3.3. Profile stability and water table depth in winter

Table 2 presents the main characteristics of the 40 plots cultivated with winter wheat. It shows the wide range of conditions concerning year, soil types and drainage system in which the plot hydraulic and agronomic behaviour was observed. Table 3 shows the high variability of water excess during the three years. For the period autumn–start of winter, the weather balance expresses the almost full variability observed over 19 years; for the winter period, values are lower than for a normal year.

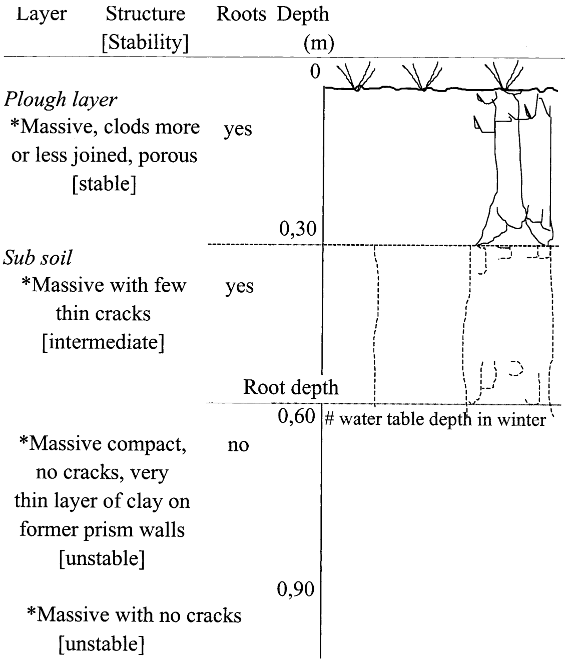

Fig. 1. Structure of soil profile type no. 5. The plot is planted to winter wheat and drained by pipe drains laid at 0.95 m depth. Observations made at the start of stem elongation (saturated period).

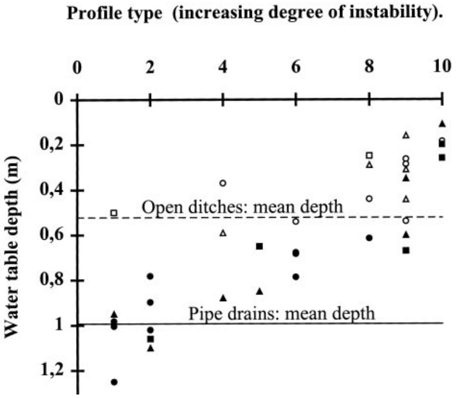

Fig. 2. Water table, soil profile type and field drainage system. Ditches (open), drains (filled); 1981 (circle), 1982 (triangle), 1983 (square).

Fig. 2 shows the relation between soil types and water table in winter: irrespective of the drainage system and year climate, the water table depth increases with profile stability until it reaches the drain level. For drain pipes (mean depth: 1 m), the water table depth varies significantly (from 1.20 to 0.10 m). With a high degree of profile stability (soil types numbers 1, 2 and 4), the water table depth is linked to drain depth, and the unstable layer occurs below 0.60 m. At the other extreme, when the soil profile is unstable (soil type no. 10), the water table moves inside the unstable plough layer. In this case, the depth of the profile's impermeable layer (0–0.30 m) and not the drain depth determines the water table depth. In-between these two situations, the depth of the unstable layer of soil types numbers 5–9 lies between 0. 30 and 0.60 m and that of the water table is about 0.40 and 0.70 m. In open ditches, the drains lie at about 0.50 m depth. In this case, the water table depth is linked to the soil type, but the depth of the open ditches restricts water table variation.

In brief, the mean water table depth during the saturated period results from the interaction of soil types and drainage system and reflects the drainage efficiency; it characterises the hydraulic behaviour of drained plots. It enables us to classify the different drainage systems and soil types independent of yearly weather effects. It is indicative of the depth of the unstable soil profile layers lying above the drains. These unstable layers form the impermeable layers of the soil profile.

3.4. Depth of roots at the start of elongation and depth of the water table

Fig. 3 shows the close link between water table depth in winter and rooting depth at the start of

Table 3
Weather balance (rainfall − evapotranspiration) in mm during the period of water excess[a]

Climatic period	Soil water content	Growth stage	Year			Average of 19 years
			1981	1982	1983	
(1) Autumn-start of winter (01/09 to 31/01)	Rewetting, start of water excess	Germination and emergence, start of tillering	213	359	435	243
(2) Winter (01/02 to 31/03)	Water excess	Tillering, start of stem elongation	37	49	36	65

[a] Weather periods correspond to different soil water contents and growth stages of winter wheat.

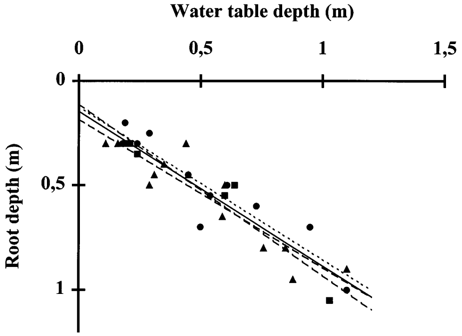

Fig. 3. Root depth at start of stem elongation and water table depth in winter (m). 1981 (circle), 1982 (triangle), 1983 (square). Regression: 1981 (point) $R^2 = 0.85$; 1982 (point and dash) $R^2 = 0.84$; 1983 (dash) $R = 0.92$; 3 years (continuous line) $R^2 = 0.85$.

stem elongation. The coefficients of determination and the regression equation parameters are almost identical in the three years (Table 4). This close proportionality shows that the field drainage system and soil type account for the rooting depth at the end of winter irrespective of the year's weather characteristics. This confirms that macroporosity and root growth were also closely linked. On the other hand, there are no roots in the unstable layers of the profile during the saturation period.

3.5. The porosity profile and its indicators

3.5.1. Profile stability and drainage efficiency

The depth of the unstable layer (ZI) determines the degree of profile stability. The unstable layers form the impermeable zone of the profile at saturation. The layers having no macroporosity are unfavourable for early development of winter wheat roots. We synthesised these results by using the notion of 'porosity profile' at saturation (Fig.

Table 4
Regression coefficient (R^2) and regression equation between root depth at the start of stem elongation (y) and water table depth (x)

	1981	1982	1983	Total period
R^2	0.85	0.84	0.92	0.85
y	$0.71x+11$	$0.71x+18$	$0.82x+11$	$0.73x+15$
Total plots	11	13	6	30

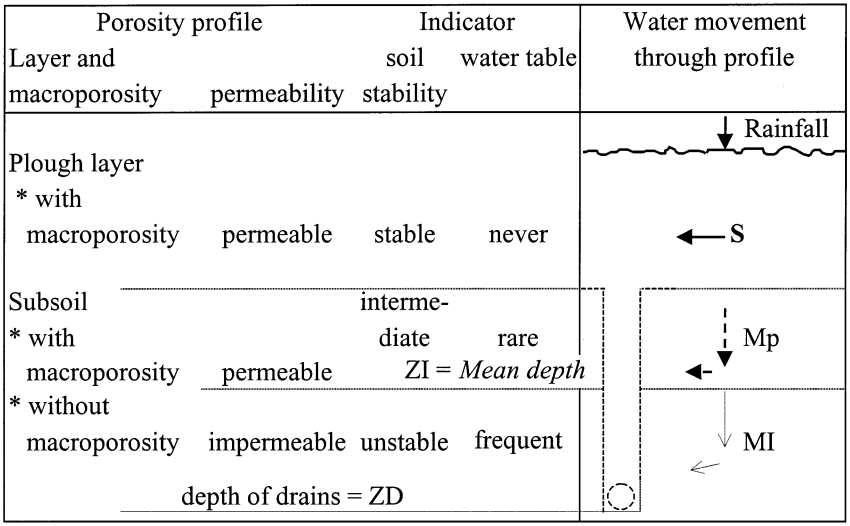

Fig. 4. Porosity profile: characteristics, porosity indicators and water movement. ZI, depth of unstable layers; water movement through the plough layer (S), permeable (Mp) and impermeable (MI) subsoil layers (Concaret et al., 1976).

4). The porosity profile may be described by a single parameter, the depth of the ZI. This layer separates the first permeable layers from the underlying impermeable layers. The former consist of the yearly ploughed layers (in the case of Fig. 4, the first layer is stable) and the stable or intermediate sub-soil layers; the latter of the unstable profile layers. The thickness of these layers depends on depth of ploughing for the ploughed layer and soil type for the subsoil layers. If the drain depth (ZD) is known, water movement in the profile can be predicted. If $ZI < ZD$, the water flow through the permeable cultivated (S) and subsoil (Mp) layers is fast, and slow through the impermeable subsoil layers (MI). With $ZI > ZD$, only the fast water flow through S and Mp occurs.

The permeability of the profile layers can thus be diagnosed either from its causes (structural stability of soil layers) or its effects (drained plot behaviour: water table depth in winter and depth of wheat rooting at the end of winter according to the drainage system depth, structural characteristics of the profile layers). But the water table depth in winter is the indicator which, is most convenient and easiest to obtain for diagnosing the porosity profile on the condition that the drain depth is known.

3.5.2. Structure and root system at saturation

At saturation, the profile porosity is minimal. The porosity of the soil layers decreases due to clay swelling, with cracks closing up to a greater or lesser degree. Macroporosity is partially preserved if the soil stability is high or intermediate. This is the case in Fig. 1 and Fig. 4 where macroporosity partly persists inside and between the clods in the stable plough layer. In cases of high or intermediate stability of the subsoil layers (0.30–0.60 m) a network of a few functional cracks survives, enabling water flow. On the other hand, if the subsoil layer is unstable ($>$ 0.60 m), macroporosity disappears during the saturated period; the layer structure is massive, compact with no cracks or live roots. This particular structure enables us to assess the depth of the unstable layer. The rooting depth of wheat is restricted by the soil hydromorphy, a result of interaction between drain depth and depth of the unstable layer.

4. Conclusion

In swelling, more or less sodic clay soils, there is a close relation between soil stability and profile porosity at the saturation stage. The drainage system efficiency and rooting depth of winter wheat are indicators of the hydraulic and agronomic behaviour of the plots. This means that the soil stability factor has a far greater effect on plot behaviour than other environmental factors such as weather variation and cultivation methods.

At saturation profile swelling is maximum: the cracks in the unstable layers close up and the layers become impermeable. On the other hand, in the soil layers with strong and intermediate stability, there remains a sufficient degree of macroporosity to allow for water movement and the early development of the wheat root system. The ‘porosity profile’ enables us to differentiate between macro and microporosity or more simply between the permeable and impermeable layers at the saturation period. If the pores are the locus of soil-water exchanges, the distinction between macro and microporosity inside a soil profile enables us to identify two water circulation regimes, one fast, the other slow, and therefore to predict drainage water quality.

At saturation, the porosity profile is characterised by a single parameter, i.e. the depth of the ZI. The unstable layers can be detected by their particular, massive and compact structure. The value of ZI may be evaluated either by its causes or by its effects. The soil structural stability is the indicator of causes, while the indicators of effects are the water table depth in winter, a result of interaction between soil type and drainage system, and the rooting depth of the winter crop at the end of winter. This hypothesis needs confirming with winter crops other than wheat.

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