Int. Agrophysics, 2003, 17, 105–110

INTERNATIONAL
Agrophysics
www.ipan.lublin.pl/int-agrophysics

Soil water, solute storage and drainage in a deeply loosened, heavy-clay soil of southern Romania

C. Paltineanu

Fruit Research Institute, 0312 Pitesti-Maracineni, Romania

Received November 12, 2002; accepted January 28, 2003

A b s t r a c t. One year after draining and extensively loosening heavy-clay soils, irrigation water was sprinkled over it daily for 10 h for a 3-day period, using a 10 mm h^{-1} rate, perpendicularly over plastic drains. Five days after the initial application of water another 140 mm of water was applied, and on the 7th day, an 80 mm solution containing complex chemical (NPK) nutrients was also spread over the soil plots. The deep loosening tracks modified the soil's hydraulic properties by decreasing bulk density and increasing soil porosity, water permeability and, implicitly, soil water flux. Solute penetration also showed a preferential character. Under the moist conditions of the heavy-clay soil studied, these tracks were very active soil macropores that had a role similar to that which cracks have on dry soils. Soil water volume and flux as well as drain discharge decreased curve-linearly with time following field saturation over several days of internal drainage. The pipe drainage system combined with deep loosening was an efficient, yet expensive measure in the land reclamation of these heavy-clay soils. When discussing priorities for the hydroimprovement measures needed to control soil water, it could be said that the priority is to prevent excess rainfall in these soils during spring, while secondly it is important to irrigate them during summer time.

K e y w o r d s: leaching, internal drainage, soil water flux

INTRODUCTION

Heavy-clay soils containing 45–60% clay are representative of the southern and western parts of Romania. Most of them develop intense swell-shrink processes and are naturally compacted soils. Such soils show surface-gleyed characteristics, their matrix possessing a very low hydraulic conductivity. For these reasons they need to be deeply loosened. In Romania, studies were published concerning the deep loosening effects on soil porosity and drainage in heavy-clay soils (Nicolae, 1969; Stanga, 1978; Colibas *et al.*, 1981; etc.).

Fertilizers are very useful in agriculture to increase yield. The fate of fertilizers in soil or water also depends on how the soil's hydraulic properties affect the environment. Over recent decades, many studies have been published on water or solute movement within swell-shrink soils (May and Trafford, 1979; Loveday and Cooper, 1984; Harris *et al.*, 1984; Jarvis and Leeds Harrison, 1987; Kamphorst, 1988; Bouma and Booltink, 1990; Bronswijk, 1991; Stagnitti *et al.*, 1998; Montas, 1998; Paltineanu, 1998). Some scientists used either colored, or chemically uncolored solutes, or fertilizers as tracers in soils. Other papers dealt with this convective-dispersive process in some heavy-clay soils similar to those described in this paper (Powlson *et al.*, 1992; Goss *et al.*, 1993, etc.). But neither of these authors showed in detail, the influence of the horizontal distance from the soil of deep loosening tracks.

The purpose of this paper is to bring more evidence on the specific mechanism of water and solute movement and storage which depends on the horizontal distance from deep loosening tracks through the moist heavy-clay soil of southern Romania, provided with a drainage system and under the application of a sprinkler solute.

MATERIALS AND METHODS

This experiment was performed in the vadose zone with its heavy-clay soil showing intensive swell-shrink processes. The plots investigated were located in the Gavanu-Burdea Plain, southern Romania. The clay (particles <0.002 mm) content ranged between 45.0–55.5% g g^{-1}, whereas the pH varied between 6.0 in the topsoil and 7.5 at a 1.5 m depth in the subsoil. A specific feature of these soils

Corresponding author's e-mail: icpp_mar@geostar.ro

was represented by the very low values of saturated hydraulic conductivity, namely 0.1–0.2 mm h^{-1} as determined by the standard method in this country (Canarache, 1990).

The trial design consisted of three, 30 m^2 experimental plots (A, B, C), each of them located over a plastic drainage pipe placed at the bottom (0.9 m depth) of a permeable backfill. Drains were spaced 11 m apart and water was collected in a nearby canal heading toward a natural valley. One year prior to the experiment, the drainage system had been built to control the temporary excess soil water during heavy storms. The micro-plots investigated were spaced 1.43 m apart between two deeply loosened tracks. Deep loosening was carried out down to 60–65 cm perpendicularly over the drainage pipes, resulting in two parallel, deeply loosened soil tracks passing through the central part of the micro-plots, bordered by 0.1 m high frameworks. The vegetation-free surface of the plot was then manually leveled in order to minimize runoff.

Water was applied over the three plots via perforated pipes at about a 10 mm h^{-1} rate during a 3 day period. The daily application of water attained 100 mm. The onset of drainage was noticed and drain flow values through the three drains were collected. Five days from the start of the application of water when the soil was wet, an additional 140 mm of water was applied at a rate according to the basic infiltration rate (about 6 mm h^{-1}) in order to create a moisture content nearly equal to field saturation. After a week totaling 440 mm of water application, an 80 mm NPK solution was spread over the plots, again at the basic soil infiltration rate. The solute-suspension used here contained some complex chemical nutrients (N_{16}, P_{16}, K_{16}) and had a very high (3%) concentration. The N was both as NH_4 (9.8%) and NO_3 (6.2%), while P was as P_2O_5 (9.4% dissolved in water, the rest as suspension) and K as K_2O (12% dissolved in water), and Cl^- (about 10%). The chemicals used in the experiment altered the viscosity, the solid-liquid contact angle and the surface tension of the water applied, and also prompted ionic changes and the formation of heavy-soluble compounds as well. However, because of their agricultural importance, it was appropriate to use these fertilizer-derived chemicals as tracers. Water and solute amounts applied together during the experiment reached about 520 mm and were similar in size to the mean annual precipitation recorded in this region.

After applying all the solute, drainage flow occurred at a maximum rate as determined by the hydraulic conditions of the deeply-loosening, soil-drain-canal system. Drain flow values were measured under both field saturation and non-saturation conditions after the application of solute until the drain flow decreased to zero. The plots were then covered with polyethylene sheets in order to prevent the further evaporation of soil water and enable any variation in the soil's moisture content to be due to internal drainage only.

Soil water flux values were calculated using instantaneous soil moisture content profiles. 1, 3 and 7 days following the cessation of the application of solute, 100 cm^3 soil core samples were taken from a certain spatial arrangement as follows: plot A was first sampled by digging (after 1 day) followed by plot B (after 3 days) and plot C (after 7 days). To emphasize the spatial variability of the soil parameters studied, 4 vertical sampling sections were designed (a, b, c, d, equally spaced 1 m apart, with 'a' starting near the drain pipes) and were taken at each experimental plot. At the same time, the influence of the deep loosening tracks on the same soil parameters was also investigated. Thus, within each vertical sampling section, 6 soil samples equally spaced between the loosening tracks were taken at the horizontal distance d =7.5, 33.0, and 58.5, respectively, for each soil depth studied. A d of 300 cm was also used as a control. The undisturbed soil samples were taken from each vertical sampling section at a 10 cm vertical step down to a depth of 80 cm.

In the laboratory, the soil moisture content (θ) was gravimetrically measured and the bulk density (BD) was calculated by dividing the dry soil mass by its volume. The soil's electro-conductivity, as identified by the soluble-salts content (SSC), was determined using the current Romanian method (the conductometric method) as described by Borlan and Hera (1973).

The number of soil-core replicates for each parameter was different: 24 for BD and 8 for θ and SSC. Data obtained from the experiment was then processed through the analysis of variance.

RESULTS AND DISCUSSION

Bulk density

The deep loosening of the heavy-clay soil investigated changed the BD distribution over the soil profile, and most probably other related soil physical properties, too. Figure 1 depicts the BD variation for the three situations presented, which depends on the horizontal distance (d) from the deep loosening tracks. Just near (d=7.5 cm) the deep loosening tracks, BD decreased significantly in comparison to the control situation down to a depth of 60 cm. Over this depth, BD generally ranged between 1.36 and 1.32 Mg m^{-3}. Except for the topsoil, where BD presented low values, in the other two situations (d=33.0 and 58.5 cm) BD decreased slightly (between 1.36 and 1.47 Mg m^{-3}) when compared with the control treatment. Even where deep loosening had been performed down to 60–65 cm, there was a slight change in the BD variation even at a depth of 70 cm, due probably to the mechanical effect on the soil of the tractor used for the work.

Total porosity

As with the bulk density, the soil's total porosity manifested a similar trend in the profile distribution over the

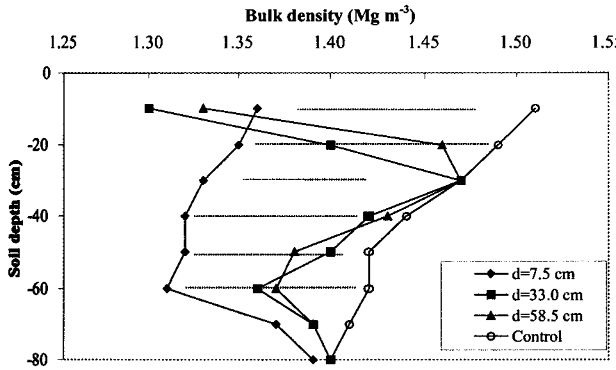

Fig. 1. Bulk density versus the horizontal distance (*d*) from the deep loosening tracks, Gavanu-Burdea Plain, Romania (horizontal lines are 5% LSD).

soil horizons (Fig. 2). Deep loosening also created significant differences in total porosity as related to *d*, down to a depth of 0.6 m. Significant differences occurred not only between the control and the other treatments but also between the *d*=7.5 cm treatment and the other two deeply loosened treatments within various depths.

Soil moisture content

θ-variation under internal drainage conditions from the field saturation (satiation state, Hillel, 1980) to the relatively steady-state conditions was also influenced by *d* (Fig. 3). A comparison was done between the three *d*-values and the control (*d*=300 cm) within the three situations studied. Water storage in the soil was enhanced by the decrease in BD, and implicitly the increase in soil porosity. The higher θ values occurred just near the soil's deep, loosening tracks (at *d*=7.5 cm). For the same depth, θ decreased significantly ($P < 0.05$)

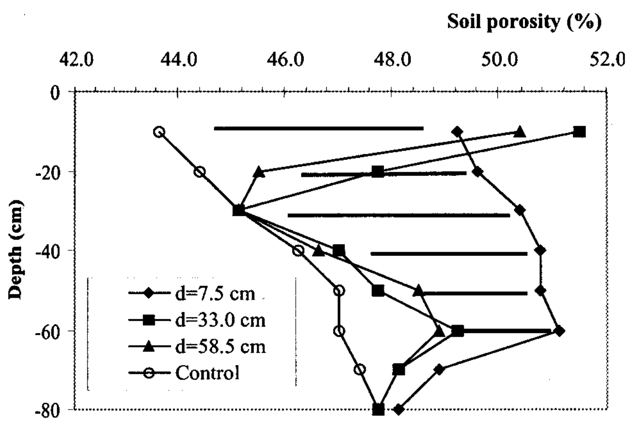

Fig. 2. Soil total porosity versus the horizontal distance (*d*) from the deep loosening tracks, Gavanu-Burdea Plain, Romania (horizontal lines are 5% LSD).

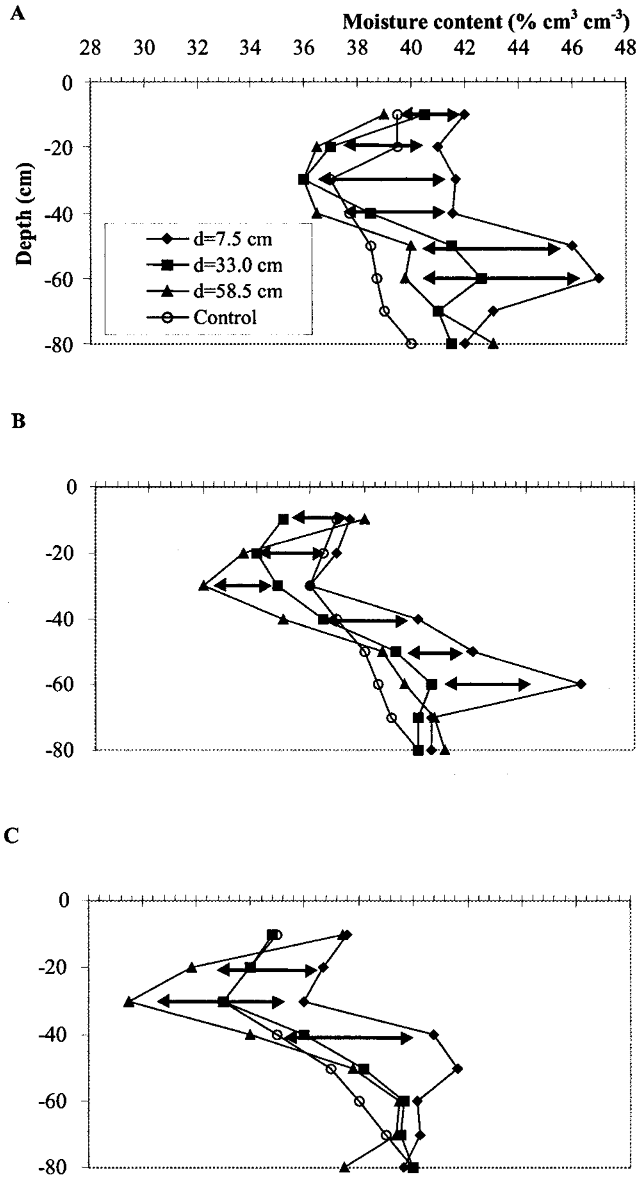

Fig. 3. Soil moisture content versus the horizontal distance (*d*) from the deep loosening tracks 1 day (plot A), 3 days (plot B) and 7 days (plot C) following the application of solute (horizontal arrows are 5% LSD).

while *d* increased for all three plots (A, B and C). Visual observation revealed the existence of very thin water films in and near the deep loosening tracks, especially when digging the first soil plot (A), though this was less evident at plot B. These findings show the important role of freeing up heavy-clay soils by various means (deep loosening, deep plowing, drainage by moles, etc.) in order to increase soil water and air permeability. However, no correlation was noticed between the horizontal distances from the soil sampling sections and the permeable backfill over the drainage pipe. The spatial distribution of θ showed no trend in comparison to this field parameter.

These results are consistent with other authors' findings in similarly textured soils. Thus, in the UK, Cannell *et al.* (1984) found that permeable backfills over drains influenced drainage conditions laterally only by about 4–6 m, while Jarvis and Leeds-Harrison (1987a and b) showed that mole drainage depended critically on the presence of fissures in the soil surface. Other investigators working in the UK held similar opinions, e.g., Trafford and Masey (1975) found that both experimental results and hydraulic conductivity data suggested that heavy-clay soils needed small distances between drains for efficient soil water control. However, such recommendations are not feasible from the economical point of view. May and Trafford (1979) and Trafford and Oliphant (1977) found that pipe drain spacing had a weak effect in draining heavy-clay soils and emphasized the special role of freeing up the soil to accomplish this. Armstrong (1978) held the same view, reporting that mole drainage was the preferred treatment for heavy-clay soils manifesting temporary water-logging. Drainage pipes represented the principal method of collecting and transporting excess soil water, while breaking up or freeing up the soil was the most effective drainage method (Trafford and Rycroft, 1973).

Dynamics of soil water volume and flux

The drained soil-water volume and flux from the field saturation under internal drainage following deep loosening had a somewhat similar pattern for both the deeply loosened soil and soil under natural conditions (Fig. 4). Soil water drained volume curves were fitted using logarithmic time-series regression equations computed through the least squared method, while soil water flux curves were drawn as derivatives of the first ones. Topsoil horizons (0–20 and 20–40 m depth) manifested the highest (about 58%) leaching of the total drain flow occurring during the 7 days of this experiment. The ensuing soil horizons: 40–60 and 60–80 m depth showed a smaller weight in drain flow (data not shown). As opposed to the natural situation of such soils, where the B horizon begins below a depth of 40 cm and internal drainage is very poor (Paltineanu *et al.*, 1991; Paltineanu, 1998), the drainage flow from the entire soil horizons freed up through deep loosening in this experiment was much higher (Fig. 4).

Thus, deep loosening modified the hydraulic conditions of the heavy-clay and high-compacted B horizon by increasing soil permeability for water and air. There is a strong correlation between the saturated hydraulic conductivity (K_s) and bulk density (inverse) as well as between K_s and total porosity (direct) within these soils (Paltineanu, 1998).

Zimmer and Lesaffre (1989) measured the isotopic natural composition of precipitation, soil water and drainage, during the same winter. Similarly, they found a small-sized soil depth (about 0.4 m) of water infiltration in the wet, undisturbed heavy-clay soil studied, and a much higher infiltration in the disturbed soil.

The internally drained water volume had its maximum values during the first day. Thus, the 0–0.8 m soil horizon had a total drainage volume of 67 mm of water, and a water flux of about 10 mm day^{-1} at the end of that day (Fig. 4A). These variables decreased abruptly over the following days. Anyway, the drain discharge (drain flow rate) values decreased to zero after two days of continuous drainage (Fig. 4 B). Drain discharge was always much lower than the soil water flux because it was one of its components, even if the drain tube collected soil water from the permeable backfill

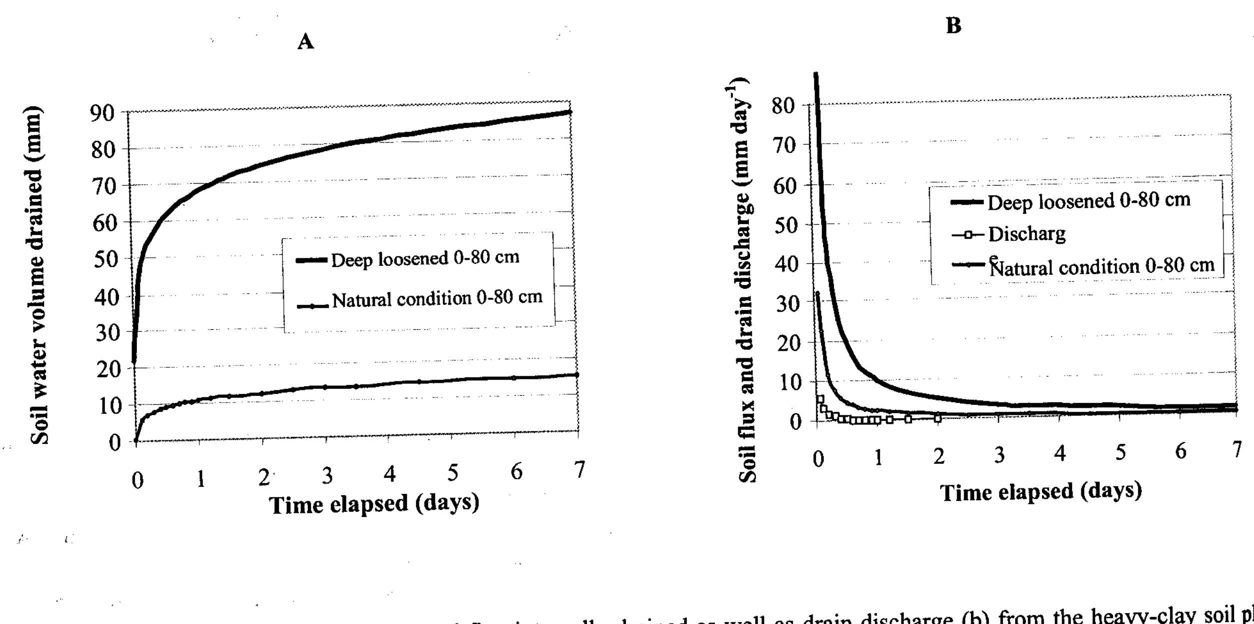

Fig. 4. Dynamics of soil water volume (a) and flux internally drained as well as drain discharge (b) from the heavy-clay soil plo investigated; start of drain flow was at field saturation (fitted curves).

intersected by deep loosening tracks. This could be explained by the fact that drain discharge existed only at high θ values when soil water could flow more easily to concentrate in drains, while soil water flux could exist most of the time both vertically and laterally within the soil plot. For the following two days there was an internal drainage volume of about 10–12 mm while the soil flux reached approximately 3.5–4.0 mm day^{-1}. The volume of water internally drained continued to decrease with time towards the end of the experiment, whereas the flux also decreased, reaching ca. 1.5–2.0 mm day^{-1} over the same period of time.

As seen from the above presentation, the maximum period of excess soil water evacuation through both drainage pipes and the soil itself from the field saturation state was about 2–3 days under the conditions of year 1 following the drainage system and the deep loosening process. This period could be changed (increased) by the evolution of deep loosening efficacy during the next years.

Dynamics of traceable solution penetration in soil

SSC solute penetrated the soil similarly to θ as they were closely related (Fig. 5). However, there was a delay in SSC penetration in soil versus water infiltration. Water already applied prior to the application of solute will probably have induced a relative leaching of SSC in soils.

SSC distribution in soil one day after the application of solute is depicted in Fig. 5A. Except for the upper part of the topsoil (0.0–0.1 m depth), SSC was stored as a function of d in the horizontal planes of each depth studied within the major part of the soil depth affected by deep loosening. SSC reached maximum values just near the deep loosening tracks, and decreased significantly ($P < 0.05$) with d for each soil depth. The solute penetration front reached around 40–45 cm in the soil matrix after the first day of drainage, and almost 60 cm near the deep loosening tracks. From a 45 cm depth downwards, SSC manifested higher values within the control treatment in comparison to situations 1, 2 and 3, due to soil leaching prior to the application of solute and, possibly, due to the initial spatial variability of SSC in soils and its trend to be slower when compared with soil water infiltration.

SSC distribution in the soil three days after the application of solute is depicted in Fig. 5B. SSC changed over time due to the effect of solute redistribution vertically under internal drainage. The solute front penetrated deeper downwards in soils. At the same time, there was a decrease in SSC in topsoil horizons as well as an increase in it deeper in the soils when compared to the control treatment. Also, the difference in SSC attributed to d (significant at two soil depths) decreased due to the more even situation.

The SSC front penetrated vertically deeper seven days following the application of solute (Fig. 5C), a trend noticed during the earlier stage (B) which developed more intensely. SSC continued to decrease in the upper horizons as internal drainage continued and SSC accumulated deeper in the soil. There were differences still in SSC attributed to d (significant at some soil depths). For predominantly convective leaching, the process studied reached almost steady-state conditions, indicating equilibrium between drainage and solute storage in the soil. Other physico-chemical processes could become more intense from that point onwards.

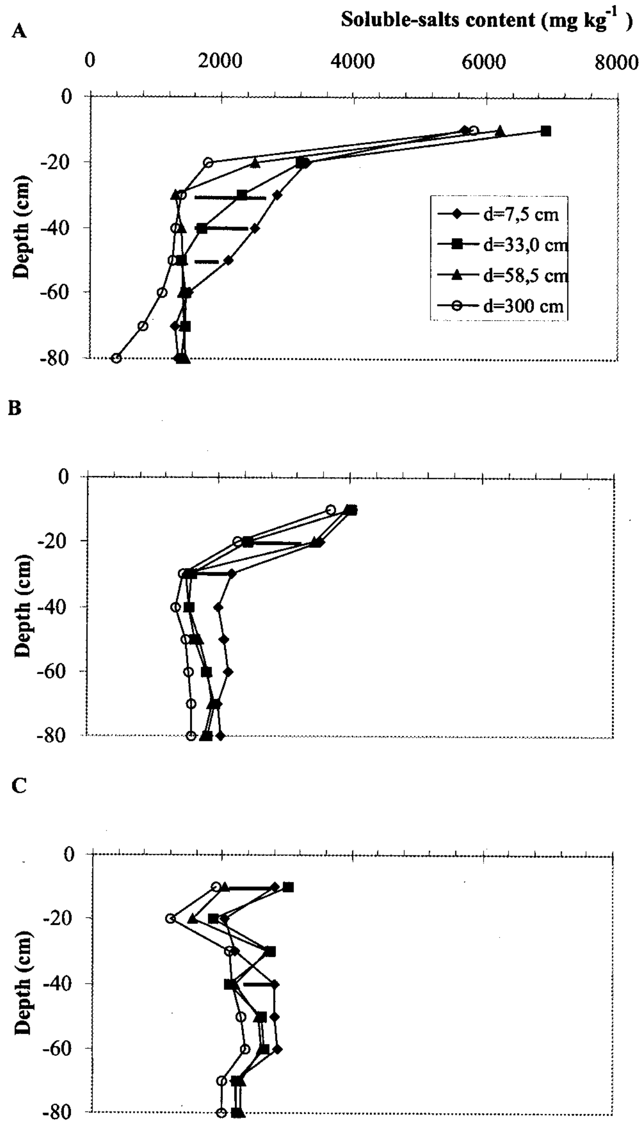

Fig. 5. The content of soluble-salts in the soil versus the horizontal distance (d) from the deep loosening tracks 1 day (plot A), 3 days (plot B) and 7 days (plot C) following the application of solute (horizontal lines are 5% LSD).

Deep loosening tracks essentially enhanced solute penetration in soils, especially during the first stages of leaching, both horizontally and vertically, until it reached steady-state conditions. Solute penetration was not homogeneous. It appeared to be preferential through and near the deep loosening tracks.

CONCLUSIONS

1. The method by which water and solute is transported in a heavy-clay soil provided with pipe drainage systems and affected by having been deeply loosened was essentially different from that of the natural, unchanged situation of soils described in various papers.

2. The deep loosening tracks modified the soil's hydraulic properties by decreasing bulk density and increasing soil porosity, water permeability and, implicitly, soil water flux. Solute penetration also showed a preferential character. Under the moist conditions of the heavy-clay soil studied, these tracks were very active soil macropores that had a role similar to that which cracks have on dry soils.

3. Soil water volume and flux as well as drain discharge decreased curve-linearly with time following field saturation over several days of internal drainage.

4. The pipe drainage system combined with deep loosening was an efficient, yet expensive measure in the land reclamation of these heavy-clay soils. When discussing priorities for the hydro-improvement measures needed to control soil water, it could be said that the priority is to prevent excess rainfall in these soils during spring, while secondly it is important to irrigate them during summer time.

REFERENCES

Armstrong A.C., 1978. The effect of drainage treatments on cereal yields: results from experiments on clay lands. J. Agric. Sci., 91, 229–235.

Borlan Z. and Hera Cr., 1973. Methods of characterizing soil fertility in order to be used in a reasonable nutrient application (in Romanian). Ed. Ceres, Bucharest, 487.

Bouma J. and Booltink H.W., 1990. Using soil porosity to analyses to improve characterization of water movement in heavy-clay soils. Trans. 14th Int. Congress of Soil Sci., Com., 1, Kyoto.

Bronswijk J.J.B., 1991. Magnitude, modelling and significance of swelling and shrinkage processes in clay-soils. Ph.D Thesis, Landbouwuniversieit Wageningen.

Cannell R.Q., Goss M.J., Harris G.L., Jarvis M.G., Douglas J.T., Howse K.R., and Le Grice S., 1984. A study of mole drainage with simplified cultivation for autumn-sown crops on a clay soil. J. Agric. Sci., 102, 539–559.

Colibas I., Colibas M., and Stanga N., 1981. Effect of deep loosening on some soil-amelioration indexes under the conditions of luvic, surface-gleyed, agrillo-iluvial soils of Campia Crisurilor (in Romanian). Publication SNRSS, Brasov, 19A, 85–91.

Goss M.J., Howse K.R., Lane P.W., Christian D.G., and Harris G.L., 1993. Losses of nitrate-N in water draining from autumn-sown crops established by direct drilling or mouldboard ploughing. J. Soil Sci., 44, 35–48.

Harris G.L., Goss M.J., Dowdell R.J., Howse K.R., and Morgan P., 1984. A study of mole drainage with simplified cultivation for autumn-sown crops on a clay soil. J. Agric. Sci., 102, 561–581.

Hillel D., 1980. Applications of Soil Physics. USA, Academic Press.

Jarvis N.J. and Leeds Harrison P.B., 1987a. Modeling water movement in drained clay soil. I. Description of the model, sample output and sensitivity analysis. J. Soil Sci., 487–498.

Jarvis N.J. and Leeds Harrison P.B., 1987b. Modeling water movement in drained clay soil. II. Application of the model in Evesham Series clay-soil. J. Soil Sci., 499–509.

Kamphorst A., 1988. Water and salt transport in the irrigated cracking clay-soils of the Kachhi Plains, Pakistan, Part I. Soil Technology, 1, 271–281.

Loveday J. and Cooper J.M., 1984. Hydraulic conductivity and structure of three Australian irrigated clays. Proc. ISSS Symp. on water and solute movement in heavy-clay soils. Publ. 37, Wageningen.

May J. and Trafford B.D., 1979. The analysis of the hydrological data from a drainage experiment on clay land. LDS, FDEU, MAFF, UK, Technical Bulletin, 77/1, 17.

Montas H., 1998. Solute transport during infiltration in soils with preferential flow pathways: a physico-geometric theory. CD: Symp. 05, Scientific registration 1043. 16th World Congress of Soil Science, Montpellier, France, 20–26 August.

Nicolae C., 1969. Deep loosening of the luvic, surface-gleyed soils of Albota, district Arges (in Romanian). Stiinta solului, Bucharest, 7, 42–49.

Paltineanu Cr., 1998. Water and soulte movement in swell-shrink soils with application in irrigation, drainage and the environment (in Romanian). Agris Editor, Bucharest, 178.

Paltineanu Cr., Paltineanu I.C., Paltineanu R.N., and Avrigeanu G.H., 1991. Dynamics of internal drainage in heavy-clay soils (in Romanian). Publication ASAS, Buletin Informativ, 20, Bucharest, 35–46.

Powlson D.S., Hart P.B.S., Poulton P.R., Johnston A.E., and Jenkinson D.S., 1992. Influence of soil type, crop management and weather on the recovery of 15N-labelled fertilizer applied to winter wheat in spring. J. Agr. Sci., 118, 83–100.

Stagnitti F., Li L., Allinson G., Sherwood J., Ueoka M., Lockington D., Philips I., and Turoczy N., 1998. Leaching of nutrients: Performance evaluation of the advective-dispersion-reaction equation and a two-region preferential flow model. CD: Symp. 05, Scientific registration 1614. 16th World Congress of Soil Science, Montpellier, France, 20–26 August.

Stanga N., 1978. Contributions to the methodology for the characterization of soil total porosity, testing, zoning and graduation of the requirements for deep loosening. Analele ICPA, MAIA-ASAS, Bucharest, 43, 169–175.

Trafford B.D. and Rycroft D.W., 1973. Observations on the soil-water regimes in a drained clay soil. J. Soil Sci., 24, 3, 380–391.

Trafford B.D. and Masey W., 1975. A design philosophy for heavy soils. MAFF, FDEU, Technical Bull., 75/5.

Trafford B.D. and Oliphant J.M., 1977. The effect of different drainage systems on soil conditions and crop yield of a heavy clay soil. Expl. Husb., 32, 75–85.