Deep Tillage Plough down to 600 mm for Improvement of

Salt-affected Soils^{*}

- Part 3: Field Experiments -

Azuma ARAYA^{*1}, Xuanrui XIONG^{*2}, Huijun ZHANG^{*3}, Ken ARAYA^{*4},
Chiniao TERAMOTO^{*5}, Takashi KATAOKA^{*6}, Kazuhiko OHMIYA^{*6}, Feng LIU^{*7},
Huibin JIA^{*8}, Chunfeng ZHANG^{*8}, Baoguo ZHU^{*8}, Nannan WANG^{*8}, Qingying MENG^{*8},
Yoshiyuki HARANO^{*9}, Masaru OZIMA^{*9}

Abstract

A method is proposed for soil improvement of salt-affected soils to till down to about 600 mm in depth by a special plough. The goal is to cut off the capillary rise of the groundwater by creating a coarse layer of tilled subsoil. Earlier, a plough configuration to produce soil clods with the proper size in the subsoil was determined in an indoor soil bin. In this paper, we designed and tested prototypical plough bodies in field experiments. A plough blade length less than 130 mm produced large soil clods and a blade length more than 130 mm generated small ones. With any length, deeper operating depth caused larger soil clods to form. The proper specifications of the third and fourth plough bodies of the special plough are as follows: the plough blade length is 130 mm, the operating width is 300 mm, the operating depth is 200 mm and the cutting angle is 20°.

[Keywords] salt-affected soils (solonchak and solonetz), soil improvement, subsoil, soil clods, plough configuration, field tests

I Introduction

Salt-affected soils [saline soil (solonchak) and sodic soil (solonetz)] are formed in dry areas of the world (Abrol *et al.*, 1988). In this paper, these two kinds of salt-affected soils distributed in China are of concern in our research.

In the previous paper (Guo *et al.*, 2006), a method of soil improvement was discussed for salt-affected soils with sufficient rainfall to percolate into subsoil in summer; it consisted of providing a coarse layer below the subsoil (B horizon). Soil column experiments in an indoor test room demonstrated that the capillary water from groundwater could be cut off at the coarse layer, thus preventing the rise of dissolved salts to the soil surface. The salts normally accumulating in the topsoil (A horizon) were otherwise leached out by every rainfall, which would then make pH values to decrease.

In order to cut the capillarity, deep ploughing has been previously performed (Antipov, 1954; Botov, 1959; Fesko & Strugeleva, 1959; Maksimuk, 1958; Rasmussen *et al.*, 1972; Cairns, 1962; 1976a; Bowser & Cairns, 1967; Karkanis & Cairns, 1981; Buckland & Pawluk, 1985). However, such ploughing was performed by a back-hoe (Cairns, 1962) or a single mouldboard plough (Bowser & Cairns, 1967), and so every soil horizon was evenly mixed. The topsoil (A horizon) contains a fair amount of organic matter and is fertile, so it should not be mixed into the lower infertile horizons (Guo *et al.*, 2002). Antipov & Pak (1965) and Cairns (1976b) also reported that the A horizon should be retained on the surface during ploughing.

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^{*1} NEC Electronics Corporation, Kawasaki 211-8668, Japan

^{*2} Environmental Science, University of Hokkaido, Sapporo 060-8610, Japan

^{*3} Faculty of Engineering, University of Hokkaido, Sapporo 060-8628, Japan

^{*4} JSAM Member, Corresponding author, Environmental Science Laboratory, Senshu University, Bibai, Hokkaido 079-0197, Japan, araya@senshu-hc.ac.jp

^{*5} Environmental Science Laboratory, Senshu University, Bibai, Hokkaido 079-0197, Japan

^{*6} JSAM Member, Faculty of Agriculture, University of Hokkaido, Sapporo 060-0009, Japan

^{*7} Academy of Agricultural Sciences, Harbin, Heilongjiang Province, People's Republic of China

^{*8} Jamusi Branch, Academy of Agricultural Science, Jamusi, Heilongjiang Province, People's Republic of China

^{*9} Pipoly Machinery Corporation, Bibai, Hokkaido 079-0197, Japan

Fig. 1 Schematic diagram of plough bodies of a four-stage subsoil plough for improvement of salt-affected soils. The third and fourth plough bodies are identical. A, B and C are soil horizons; all dimensions are in mm (Araya *et al.*, 2011a).

We developed a four-stage subsoil plough (Fig. 1) which tills the layers down to 600 mm (to the C horizon) and retains the topsoil (A horizon). The plough consists of four plough bodies. The first plough body is a conventional mouldboard plough which tills and inverts the A horizon at a depth of 0-200 mm. When there is efflorescence (alkali spots) on the soil surface, the second plough body scrapes an adjacent furrow on the land side which runs next to the first, third and fourth plough bodies, precisely 50 mm deep below the surface of the A horizon and transfers this thin soil slice to the preceding furrow onto the third plough body. If there is no efflorescence on the soil surface, the second plough is not operated by rising the plough body. The B horizon (200-400 mm) is then tilled by the third plough body, and the soil clods are produced here in the B horizon. The C horizon (400-600

mm) is then tilled by the fourth plough body, and soil clods are produced also in the C horizon. Subsequently, the first mouldboard plough body tills the remainder of the A horizon, inverting the A furrow slice, thus covering the tilled soil in the preceding furrow (Guo *et al.*, 2002).

This plough had been originally developed for improvement of the planosol (Araya *et al.*, 1996a; 1996b; 1996c; Guo *et al.*, 2002), but the configuration of the No. 3 and No. 4 plough bodies for improvement of salt-affected soils is different from that for improvement of the planosol. In another previous paper (Araya *et al.*, 2012a), a proper plough configuration of the No. 3 or No. 4 plough body (each has the same design) was determined in an indoor soil bin to produce soil clods with the proper size (100-140 mm, Araya *et al.*, 2010) for cutting capillary rise. In the present paper, a prototypical No. 3 or No. 4 plough body was designed and built from the results of the soil bin tests, and its field experiments were carried out.

II Materials and Methods

1. Field in this study

The test site was in Japan, and the field experiments were carried out in an indoor test field. The soil in the indoor test field was a pseudogley soil from Japan. In the previous paper (Zhang *et al.*, 2009), one of the salt-affected soils in China is a saline soil (solonchak) which is found in Hebei and Inner Mongolia provinces (Table 1), and the other is a sodic soil (solonetz) which is common in the Heilongjiang, Jilin and Liaoning provinces. The previous paper (Guo *et al.*, 2004) reported that the subsoils of both salt-affected soils in China are heavy clay soils (Table 1), and the distribution of their soil particle size is similar to that of pseudogley soil in Japan, which is a typical Japanese clay and is not a salt-affected soil

Fig. 2 Components of 3rd and 4th plough bodies. Cutting angle (cutting angle) $\alpha=20^\circ$; cutting angle $\gamma=45^\circ$; operating width $w=300$ mm; (a) Blade length $h_p=50$ mm; (b) $h_p=80$ mm; (c) $h_p=130$ mm; (d) $h_p=200$ mm; (e) $h_p=250$ mm; (f) plough standard.

Fig. 3 Schematic diagram of soil failure produced by brittle fracture (tensile failure).

Table 1 Physical properties of soils in this study

	Saline soil (solonchak)		Sodic soil (solonetz)					Pseudogley soil + cement (soil bin, 2009)	Pseudogley soil (indoor field, 2010)
Horizon	Ap	Bca	C	Ana	A	B	C	-	-
Particle density ρ_s , kg m ⁻³	2615(21)	2583(34)	2598(29)	2490(41)	2340(21)	2500(19)	2500(23)	2540(31)	2540(21)
Bulk density ρ_b , kg m ⁻³	1614(12)	1610(17)	1580(14)	1720(19)	1541(11)	1613(10)	1670(11)	1656(17)	1656(16)
Tensile strength σ_t , kPa	50(6)	250(12)	150(8)	128(9)	314(6)	301(11)	329(12)	357(13)	230(10)
Cohesion c , kPa	10(3)	10(4)	10(3)	80(9)	250(12)	250(14)	250(13)	250(14)	27.5(5)
Angle of internal friction ϕ , °	50	55	10	0	0	0	0	0	68
Adhesion a , kPa	4	4	4	1	2.2	1.3	1	1.3	0.43
Angle of soil-metal friction δ , °	20	25	17	15.1	9.7	13.8	11.9	12.4	14
Texture (USDA)	silty clay	clay	clay	sandy clay	clay	clay	clay	silty clay	silty clay

(), standard deviation

but an acidic soil (pH 5.9). Therefore, the pseudogley soil field was used in this study because it could be easily prepared in large amounts at the test site.

Field soil was compacted by a roller and water was spread on the indoor site and left for about one week. After confirming that the soil water content had reached about 10% d.b. and the soil had cohered, we started experiments. This soil condition simulated the subsoil of the Chinese salt-affected soil of a single layer (the B or C horizon) because the salt-affected soils are located in dry areas in China and are generally dry except in rainy seasons; the measured soil water content of the subsoil is about 10% d.b., and the soil coheres perfectly (Sun *et al.*, 2007; Zhu *et al.*, 2007).

Table 1 shows the physical properties of the two kinds of salt-affected soils (solonchak and solonetz), the pseudogley soil with cement used in the soil bin tests in 2009 (Araya *et al.*, 2011b), and the pseudogley soil used in the indoor field tests in 2011. The soil tensile strength was determined by a radial compression test by Kawamoto (1972), whereby a cylindrical soil specimen with a diameter of 29 mm and a length of 15 mm was radially compressed (Zhang & Araya, 2001). The soil shear and the interface friction tests were conducted with

Fig. 4 Traction dynamometer with a plough body mounted on a tractor.

a commercial ring (annular) shear tester (100 mm outer diameter and 60 mm inner diameter). A ring with vanes was used for the soil shear tests, and a flat steel ring plated with chromium was used for the soil-metal friction tests.

The tensile strength σ_t and the cohesion c of the pseudogley soil with cement used in the soil bin tests (2009) are close to those of the subsoils (B and C horizons) of the solonetz soil. The tensile strength σ_t and the cohesion c of the pseudogley soil used in the indoor field tests (2011) are

close to those of the subsoils (Bca and C horizons) of the solonchak soil. Hence, the tensile strength σ_t of the subsoils of the solonchak is roughly half that of the solonetz, and the cohesion c of the subsoils of solonchak is roughly one-twenty fifth that of the solonetz.

2. Methods

Prototypical plough bodies (Fig. 2) were used. These plough bodies corresponds to the third and fourth plough bodies in Fig. 1. When the soil is collapsed by tensile failure (brittle fracture) induced by a plough body, the soil failure shown in Fig. 3 occurs. That is, when a plough blade with width w operates in soil of operating depth d , a horizontal and splitting crack with a distance l is first produced at the tip of the plough blade, and then another crack (slant crack) with angle β is produced toward the soil surface (soil clod I). With more forward progress of the plough body, the next horizontal crack and slant crack with the same angle β are induced (soil clod II). With the continuous progress of the plough body, the two cracks successively produces a similar soil clod III.

The width of the plough body w (hereafter, operating width) was fixed at 300 mm (Figs 1, 2 and 3) because of the mechanical arrangement of the plough bodies (Fig. 1). The cutting angle (rake angle) α (Figs 1 and 3) was fixed at 20° , which was optimal in the soil bin tests (Araya *et al.*, 2011a). Bosoi, *et al.*, (1987) fixed the angle of inclination of the share to the furrow wall γ (Fig. 1) at 45° for the heavy clay soils.

The plough body with share blade length h_p (hereafter, blade length) of 50 mm (Fig. 2a) was firstly set on the plough standard (Fig. 2f) and then, this assembly was mounted on a wheel tractor through a traction dynamometer (Fig. 4). The operating depth d was firstly set at 50 mm adjusting the gauge wheel (Fig. 4) and the field was tilled and the soil clods were produced. The one tillage distance was about 10 m. Five soil clods were collected at random, and with their shapes, the angle of the cracks β in deg (Fig. 3) was determined with a slant rule, the distance between cracks l in mm was determined with a scale and the mass of the each soil clod M in kg was determined with a pan balance. Two tests were repeated for each set of conditions; therefore, the average values of β , l and M were determined from ten data points, respectively.

Then, the operating depth d was varied at 4 levels adjusting the gauge wheel: 50, 100, 150 and 200 mm. After that, the plough bodies with blade length h_p of 50, 80, 130, 200 and 250 mm (Fig. 2, total 5 levels) were mounted on the plough standard, and the same experiment was carried out.

The horizontal force (draught, F_x) and the vertical force (downward force, suction, F_y) induced on the plough body were detected by a traction dynamometer (Fig. 4, Araya *et al.*,

Fig. 5 Measured average angle of cracks produced by brittle fracture as a function of plough blade length. Cutting angle, 20° ; $\circ$, operating depth $d=100$ mm; Δ , $d=150$ mm; $\diamond$, $d=200$ mm.

1990) mounted on the three-point linkage of the tractor. The mean forward speed of the tractor was $0.9\text{--}1.1\text{ m s}^{-1}$.

III Results and Discussion

1. Angle of cracks produced by brittle fracture

Figure 5 shows the measured average angle of cracks β (Fig. 3). The angle β ranged between 34° and 91° , and the mean value was about 55° (standard deviation, 13°), regardless of the blade length h_p and operating depth d . In the previous paper (Araya *et al.*, 2011a), the average β of the pseudogley soil with cement (Table 1) used in the soil bin tests was about 40° . Therefore, this angle is determined by the properties of the soil, regardless of the blade length h_p and operating depth d .

2. Distance between cracks

Figure 6 shows the measured average distance l (Fig. 3) between the cracks produced by brittle fracture. When the blade length was short, such as 50 mm, the distance between cracks l became great, and when the blade length was more than 130 mm, the distance became constant at about 200 mm,

Fig. 6 Measured average distance between cracks as a function of plough blade length. Cutting angle, 20° ; $\square$, operating depth $d=50$ mm; $\circ$, $d=100$ mm; Δ , $d=150$ mm; $\diamond$, $d=200$ mm.

Fig. 7 Measured average mass of unit soil clod produced as a function of plough blade length. Cutting angle, 20° ; operating width, 300 mm; $\square$, operating depth $d=50$ mm; $\circ$, $d=100$ mm; Δ , $d=150$ mm; $\diamond$, $d=200$ mm.

regardless of the blade length. This is because shorter blades tend to produce larger soil clods, and the longer blades produce smaller soil clods because the soil clods have to rise further with the longer blade, and the probability of soil crumbling becomes higher (Araya *et al.*, 2011a). With any blade length, a deeper operating depth d caused larger distance to form between cracks.

3. Mass of soil clods produced

Figure 7 shows the measured average mass of each unit soil clod M . The operating width was constant at 300 mm, and cutting angle was also constant at 20° . In this case, too, when the blade length was less than 130 mm, large soil clods were produced, and when the blade length was more than 130 mm, soil clods with nearly equal mass were produced. With any plough blade length, deeper operating depth d caused larger soil clods to form.

Fig. 8 The trace of ploughing. (a) Blade length, 130 mm; operating depth, 200 mm; operating width, 300 mm; cutting angle, 20° . (b) Blade length, 50 mm; operating depth, 200 mm; operating width, 300 mm; cutting angle, 20° .

Fig. 9 Typical soil clods produced by brittle fracture.

(a) Blade length, 130 mm; operating depth, 200 mm; operating width, 300 mm; rake angle, 20° . (b) Blade length, 50 mm; operating depth, 200 mm; operating width, 300 mm; rake angle, 20° .

Figure 8 shows the trace of ploughing produced with an operating depth $d=200$ mm (normal depth), the operating width $w=300$ mm, the cutting angle $\alpha=20^\circ$ and the blade length $h_p=50$ mm and 130 mm were used as representatives. Figure 9 shows the soil clods produced at this time. Both soil clods were caused by the brittle fracture (tensile failure). When the blade length was 50 mm, soil clods were produced with a long and narrow shape in the travel direction (Fig. 9b). In the pseudogley soil with cement (which had greater tensile strength σ_t and cohesion c , Table 1), when the blade length was 50 mm, the cutting angle was 20° , the operating width was 300 mm, and the operating depth was 200 mm, huge soil clods with a unit mass of about 25 kg were produced. In this pseudogley soil in the field also, the huge soil clods with about 25 kg were produced.

If the soil clods are perfect spheres, the mean diameter e of the soil clods is calculated from the following equation (Araya *et al.*, 2010).

$$e = \sqrt[3]{\frac{6M}{\pi\rho_b}} \quad (1)$$

where ρ_b is the soil bulk density in kg m^{-3} (Table 1).

Figure 10 shows the mean diameter e calculated with the mass results from Fig. 7. The ideal size of soil clods e is 100-140 mm, based on the results from the previous paper (Araya *et al.*, 2010). That is, when the size of soil clods produced in the subsoil (B horizon) is more than 140 mm, the topsoil (A horizon) collapses into the clearance of the soil

clods of the B horizon and the volume of the A horizon decreases. When the size of soil clods is less than 100 mm, a long capillary interception cannot be achieved. These values are indicated by the two horizontal chain lines in Fig. 10.

When the operating depth d is 200 mm (normal), the diameter of soil clods e is more than 140 mm for any blade length. Therefore, when the operating depth has to be more than 200 mm with the mechanical arrangement of the plough bodies (Fig. 1), some soil pulverizing tool such as a harrow is required. The proper blade length must be more than 130 mm to produce the desired size of the soil clods.

Figure 11 shows the measured average mass of each soil clod M with the different soils when the plough blade length $h_p=130$ mm, the cutting angle $\alpha=20^\circ$ and operating width $w=300$ mm. The pseudogley soil with cement (small $\circ$, Araya *et al.*, 2011a), which had stronger soil properties, produced larger soil clods than the field pseudogley soil (small $\square$).

If the initial soil clods produced (Fig. 3) are not crumbled, the predicted mass of each unit soil clod M_t is

$$M_t = \rho_b d l w \quad (2)$$

where d is the operating depth in m (Fig. 3), l is the distance between cracks in m and w is the operating width (0.3 m).

The predicted mass of unit soil clod with Eqn (2) is calculated for the pseudogley soil with cement and the pseudogley soil in the field (Fig. 11; large $\circ$ and large $\square$, respectively). These predicted masses of soil clods are much greater than that of the measured mass of soil clod (small $\circ$ and small $\square$). Therefore, the produced soil clods are actually crumbled into smaller pieces.

The average mass of soil clods of the pseudogley soil with cement and the pseudogley soil in the field are nearly same in

Fig. 10 Measured average diameter of soil clods as a function of plough blade length. Cutting angle, 20° ; operating width, 300 mm; $\square$, operating depth $d=50$ mm; $\circ$, $d=100$ mm; Δ , $d=150$ mm; $\diamond$, $d=200$ mm.

Fig. 11 Average mass of soil clods produced as a function of operating depth when plough blade length was 130 mm and operating width was 300 mm. Small $\square$, pseudogley soil (measured); large $\square$, same soil (predicted); small $\circ$, pseudogley soil with cement (measured); large $\circ$, same soil (predicted).

Fig. 11. This is because there is no difference in the distances l between cracks (Fig. 6) between both soils.

The soil crumbling ratio s_c is defined as follow

$$s_c = \frac{M_t}{M} \quad (3)$$

where M_t is the predicted mass without crumbling of each unit soil clod in kg determined by Eqn (2), and M is the measured mass of each unit soil clod in kg.

Figure 12 shows the soil crumbling ratio s_c calculated when the plough blade length $h_p=130$ mm, the cutting angle $\alpha=20^\circ$ and operating width $w=300$ mm. As a result, the soil clods of the pseudogley soil in the field were crumbled into about 5 pieces, while those of the pseudogley soil with cement were crumbled into about 2 pieces. Thus, the soil crumbling ratio is determined by the soil physical properties.

Fig. 12 Soil crumbling ratio as a function of operating depth when plough blade length was 130 mm and operating width was 300 mm. $\square$, pseudogley soil in the field; $\circ$, pseudogley soil with cement.

Fig. 13 (a) Measured average peak draught as a function of blade length; (b) Measured average downward peak vertical force. Cutting angle, 20° ; operating width, 300 mm; $\square$, operating depth $d=50$ mm; $\circ$, $d=100$ mm; Δ , $d=150$ mm; $\diamond$, $d=200$ mm.

4. Draught and downward vertical force

Figure 13a shows the measured average peak draught F_x . The measured draught F_x fluctuated and the average maximum peak value was adopted. The peak draught F_x became minimum at the blade length of 130 mm. The deeper operating depth increased this tendency. This is because large soil clods are produced when the blade length is short (such as 50 and 80 mm, Fig. 7), and when the blade length is long such as 200 and 250 mm, the soil clods produced have to rise further.

Figure 13b shows the measured downward average peak vertical force F_y . The measured downward vertical force F_y also fluctuated and the average maximum peak value was adopted. The peak vertical force F_y reached a minimum also at the blade length of 130 mm. The peak vertical forces were roughly one-fourth as great as those of the peak draughts. In the pseudogley soil with cement, the peak vertical force F_y was about 10 times greater than the peak draught F_x (Araya *et al.*, 2012b). This is because the cohesion c of the pseudogley soil with cement is extremely great at 250 kPa, while that of the pseudogley soil in the field is much small at 27.5 kPa (Table 1).

The theoretical analysis of the peak draught F_x and downward peak vertical force F_y induced on the plough body by brittle fracture (Araya *et al.*, 2012b) is applied to this field pseudogley soil. The values of the angle of cracks β (the average value, 55° in Fig. 5) and the distance between cracks l (Fig. 6) and the soil properties in Table 1 are used for the calculation. The cutting angle is 20° and the operating width is 300 mm.

Fig. 14 (a) Predicted peak draught (lines) as a function of operating depth; (b) Predicted downward peak vertical force (lines). Blade length $h_p=130$ mm; cutting angle $\alpha=20^\circ$; operating width $w=300$ mm; —, total; —, cohesion; ----, tensile; -.-, acceleration; ..., adhesion; -.-.-, lifting; $\square$, measured values.

Figure 14a shows the predicted peak draught F_x calculated when the blade length is 130 mm. The force by tensile resistance occupies the greatest percentage in the total draught F_x , and the resistances by the acceleration, adhesion, and lifting are all negligibly small. The measured peak draughts (Fig. 13a) are shown in Fig. 14a ($\square$ symbols), and they coincide well with the lines of the predicted peak draught.

Figure 14b shows the predicted downward peak vertical force F_y calculated when the plough blade length is 130 mm. The force by cohesion resistance occupies 70%, and the force

by lifting resistance occupies 30% in the total vertical force F_y , and the tensile, acceleration, and adhesion resistances are all negligible. The measured values of F_y (Fig. 13b) are also shown in Fig. 14b ($\square$ symbols) and they coincide well with the lines of the predicted peak vertical force.

Hence, from the results of Figs 13 and 14, the proper length of the plough blade is determined to be 130 mm in this study based on the minimum draught and minimum vertical force.

IV Summary and Conclusions

We envisaged for improvement of salt-affected soils that layers down to about 600 mm (subsoil) in depth could be tilled by a special plough to retain the topsoil at the surface and to produce a layer of soil clods in the subsoil which would cut off the capillary rise of groundwater. In this paper, a prototypical third or fourth plough body (each has the same design) was designed and built, and its field experiments were carried out.

- 1) The angle of cracks produced by brittle fracture was determined by the properties of the soil, regardless of the plough blade length and operating depth.
- 2) When the plough blade length was less than 130 mm, large soil clods were produced. When the plough blade length was more than 130 mm, small soil clods were produced.
- 3) With any plough blade length, deeper operating depth caused larger soil clods to form.
- 4) The peak draught and downward peak vertical forces reached a minimum at the plough blade length of 130 mm.
- 5) The proper specifications of the third and fourth plough bodies of the special plough are as follows: the plough blade length is 130 mm, the operating width is 300 mm, the operating depth is 200 mm and the cutting angle is 20° .

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