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Analysis of Ground Freezing Process by Unfrozen Water Content Obtained from TDR Data in Hetao Irrigation District of China

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Abstract

In this paper, the ground temperatures and the unfrozen water contents estimated from Time Domain Reflectometry (TDR) measurements at experimental site A(cultivated land) and C (salinized land) , were applied to analyze the ground freezing in Hetao Irrigation District, Inner Mongolia of China. Based on the different transportation status of unfrozen water, the frozen soils were divided into extensively frozen and partially frozen layer. In extensively frozen layer the unfrozen water content is kept as constant without remarkable changes, whereas below this layer, the unfrozen water content changed abruptly, the layer is referred partially frozen layer. It is found the isotherms of −1.2 and −2.1℃ are the boundary temperatures between extensively and partially frozen layers at site A and C, respectively. The estimated unfrozen water content showed the partially frozen layers still existed in the depth of 0.70～0.90 m at the end of April.

Key word : Unfrozen water content, Ground temperature, Extensively frozen layer, Partially frozen layer

1. Introduction

Inner Mongolia Hetao Irrigation District is a typical arid, cold agricultural area in western China. Salt and alkali accumulation occurs every year, especially going through a ground freezing- thawing course. It is considered that the water transportation in freezing-thawing ground is a significant factor on the evolution and transition of soil salinity and alkalinity.

Although in some theoretical approaches, mass and heat transfer mechanisms are focused on freezing soils as a successive process (Kinosita, 1982 ; Chen, *et al.,* 1998), the field facts show there exists a transitional freezing zone between frozen and unfrozen layer in finely dispersed media. It is considered the transportation mechanisms of the dissolved salts in soil solution are different in the frozen, freezing and thawing stages. Therefore, to detect the soil freezing stages is essential for the analysis of salinity in this region.

Some experiments have been done with frozen soil in Hetao during 1983-1987, it realized that the transportation of the unfrozen water was a most effective factor for salinity accumulation (Wang, *et al.,* 1993). However, because of the limitation of experimental techniques, to obtain unfrozen water content was impossible at that time.

To analyze soil freezing stage, moisture status, temperature range, advancement rate is the purpose of this paper. The measured ground temperatures on experiment spots and the unfrozen water contents which were estimated from TDR data are applied to the analysis.

2. Materials and Methods

The experiment sites are located in the fields which belong to Shaohaoqu Experiment Station, Hetao Irrigation District of Inner Mongolia. The mean annual air temperature here is 6.3～7.7℃, the wind average speed is 2.5～3 ms^{-1}, but it always gets stronger in spring and the maximum rate is up to 19.6 ms^{-1}. It is cold and has a little snow in winter. Therefore only single cropping is available round a year. The ground begins to freeze from the end of November and thaws in the head of May. The lowest air temperature, which is about −24℃ during recent years, appears in January. The coldness sum is calculated as 540～690℃・day. The maximum soil frost depth changes in a range of 1.00～1.30 m.

In Hetao, according to the land utilization and irrigation status, the lands are separated into cultivated land with regular irrigation and waste salinized land without irrigation. For comparison, site A and C were chosen from the cultivated land and salinized land as the investigation spots, respectively. The location is shown in Fig. 1. The soil texture, particle density, specific surface area, dry bulk density, $EC_{1:5}$ and pH values were measured.

The soil volumetric water contents were monitored by a portable TDR, type of TRIME-FM, P3Z, in each 0.10 m layer from surface to the depth of 1.60 m once a week through a year from 1997. The measurements were obtained by extending the probe along a polyvinyl chloride pipe which was buried into ground beforehand. It had been a difficult object to measure liquid water in frozen soil till the TDR technique was ensured to be reliable *in situ* (Stein and Kane, 1983 ; Patterson and Smith, 1984 ; Spaans and Baker, 1995 ; Derby and Knighton, 2001). The authors combined Birchak model to estimate the liquid water content along the soil layers and improved its validity (Wang and Akae, 2003).

Simultaneously, 3～4 meters away from TDR observation point, the ground temperatures were surveyed by thermocouples in each 0.10 m layer till 2.50 m.

In order to detect the total gravimetric water content, dry bulk density and salinity, the soil sections were excavated artificially three times through the freezing-thawing period (for example, initial freezing stage : Dec.11, 1997 ; maximum freezing stage ; March 3rd, 1998 ; thawing stage : April 27, 1998), the undisturbed soil samples were taken and investigated in each 0.10 m depth till 1.60 m.

3. Result and Discussion

3.1 The properties of the soils

Table 1 shows the fundamental properties of the soils at site A and C. The soils are classified

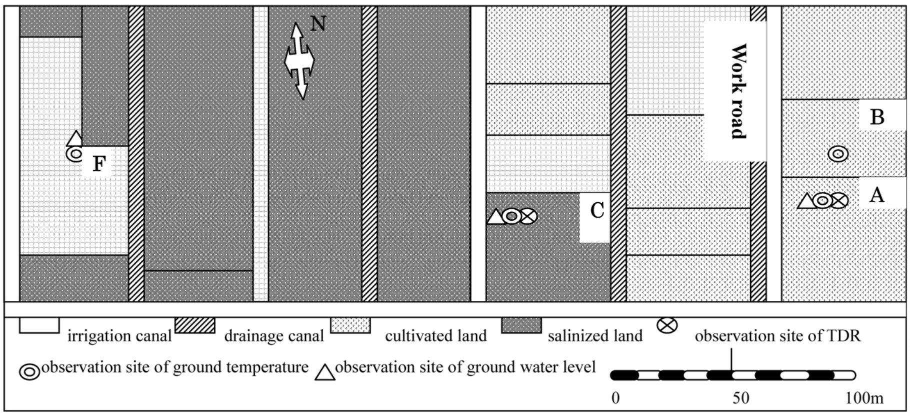

Fig. 1 Sketch of the experiment sites.

Table 1　The basic properties of soils at site A and C

Sample	Particle size distribution (%)			Texture	Particle density	Specific surface area	Dry bulk density	$EC_{1:5}$ (mS/cm) in thawing period		pH in thawing period	
	Clay	Silt	Sand		(g/cm^3)	(m2/g)	(g/cm^3)	top 0～10 cm	average below 10～200 cm	top 0～10 cm	average below 10～200 cm
Cultivated Site A	29.30	43.50	27.20	Light Clay	2.66	20.72	1.42	0.93	0.69	7.90	8.00
Salinized Site C	24.50	35.50	40.00	Clay Loam	2.68	15.48	1.45	7.9	2.39	8.50	8.40

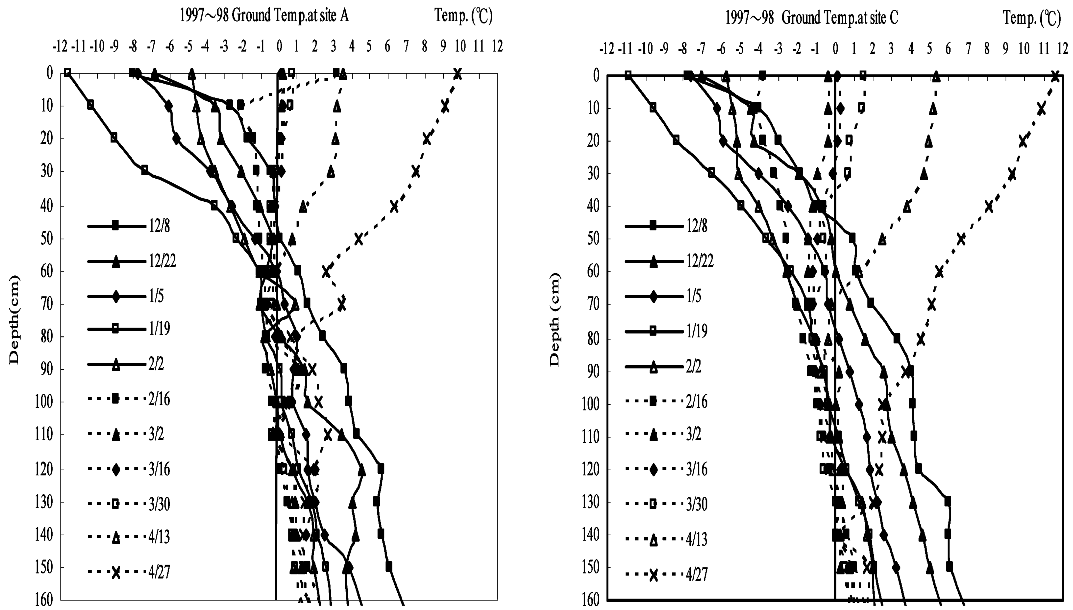

Fig. 2　The soil temperature profiles during freezing-thawing period of 1997～1998 at site A and C.

into light clay and clay loam at site A and C, respectively, which are the most common soil textures in Hetao. The two sites show few differences in physical properties except specific surface area because of the different fraction of clay component. Moreover, the salinity and alkalinity at site C are stronger than those at site A, especially in the surface layer.

3.2　Ground temperature profiles

The ground temperatures during freezing-thawing period in 1997 to 2000 were collected and analyzed. In Fig. 2 1997–1998's data are shown. All of the three years' data demonstrated that from the end of January to the beginning of February the surface ground temperature became the lowest. In the same period, the soils froze up to the depth of 0.90～1.10 m. Then the soils began to thaw firstly from the surface and then both of surface and bottom. The temperatures were found to be below 0℃ in the depth of 0.90～1.10 m till middle of April. And the frozen soils thawed at the beginning of May.

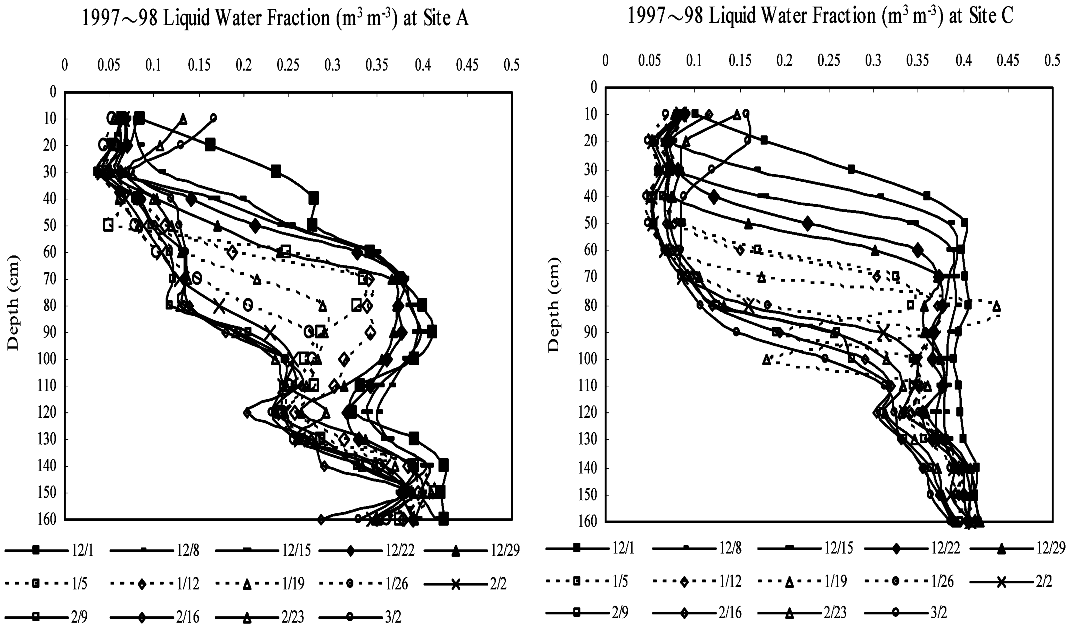

Fig. 3 The liquid water content profiles in freezing processes of 1997～1998 at site A and C.

3.3 Depression of freezing point

The presence of the solute always decreases the freezing point of the solvent. The following equation is generally used to determine the freezing point depression ΔT_m of dilute solution (Kubo, *et al.,* 1987).

$$\Delta T_m = -iK_f m \qquad (1)$$

Assuming the equation is also fit for soil water solution and the main solute is NaCl in this paper. Where, m (mol kg^{-1}) is the gravimetric molar concentration of the solution ; i is van't Hoff's coefficient, $i=2$ when the main solute is NaCl ; K_f (K・kg mol^{-1}) is the molar cryoscopic constant, $K_f=1.86$ when the solvent is water. According to Eq. (1), the freezing point depressions in site A and C are calculated to be between −0.30 and −3.08℃ in surface layer of 0～10 cm, between −0.27 and −0.93℃ below the surface layer, respectively.

3.4 Liquid water profiles in freezing period

The profiles of liquid water contents in freezing period in 1997～1998 are shown in Fig. 3. Some differences between site A and C can be observed. The reason is the original difference of soil structure and initial water content condition. However, with the time, the tendency of freezing advancement took on similar with each other. In the surface layers, the unfrozen water content kept unchanged in range of 0.05～0.1 m^3 m^{-3}. These layers developed thicker downward with time but the unfrozen water content did not change significantly. Therefore, these layers are considered to be extensively frozen. Below these layers the unfrozen water content became increasing dramatically up to 0.35～0.40 m^3 m^{-3} under subzero temperature condition. The thickness of the layer was about 0.30-0.40 m. The big difference makes it necessary to decide a borderline for the analysis and management.

The ground temperature, liquid water and the water retention curve were plotted in Fig. 4. The points are all not on a single line but dispersed to some extent. It is partly due to the different circumstances of the soil water and partly due to the error in ground temperature

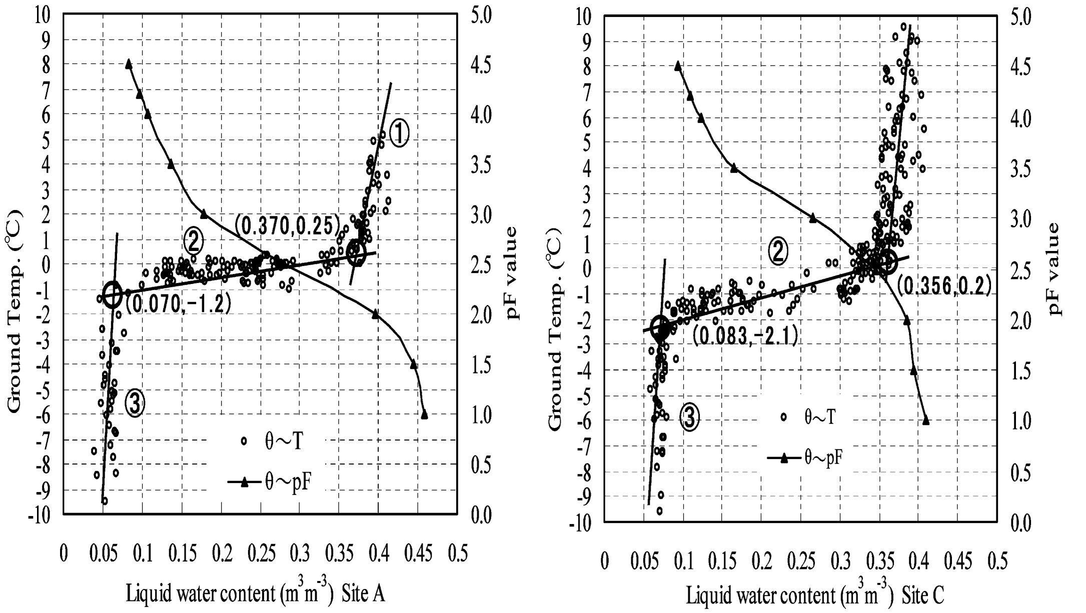

Fig. 4 The soil water retention curves and the liquid water contents vs. soil temperatures at site A and C.

and water content measurements. The direct lines are applied to approximate the development of liquid water content vs. ground temperature : Line ① represents the unfrozen stage ; line ② : the freezing stage ; line ③ : the frozen stage. The intersection points of line ② and ③ at site A and C are (0.07 $m^3 m^{-3}$, −1.2℃) and (0.08 $m^3 m^{-3}$, −2.1℃). According to the water retention curves, when the unfrozen water content are 0.07 and 0.08 $m^3 m^{-3}$, the coincident pF values are greater than pF 4.2. It is known that if the pF value is larger than 4.2, the water will be kept in intensively bound state around the surface of soil particles (Association of Soil Physics, Japan, 1979), that means the movement of the unfrozen water in the extensively frozen layers becomes extremely difficult and therefore can be actually neglected. As a result, the unfrozen water contents of 0.07 $m^3 m^{-3}$ and 0.08 $m^3 m^{-3}$, the ground temperatures of −1.2 and −2.1℃ can be regarded as the boundary values between extensively frozen layers and partially frozen layers. The difference of the boundary temperature between site A and C is mainly due to the difference of salt concentration of the two soils.

It is noted that the liquid water contents decreased at the depth where the temperature were +0.25 and +0.2℃ at site A and C, respectively. It is considered that the water in the unfrozen layers just below the freezing front was strongly absorbed due to the suction yielded at the freezing front. The same phenomena are also found in some experiments in laboratory (Mizoguchi, *et al.,* 1986 ; Inoue, 2002) and observations *in situ* (Stein and Kane, 1983 ; Cary, 1987). In fact, the line ① and ② should intersect theoretically on the depressed freezing points of −0.27 and −0.93℃ at site A and C, respectively.

3.5 Delimitation of freezing soils

Through the evidences in the liquid water content and ground temperature, it reveals that −1.2℃ and −2.1℃ can be used as the discrimination between frozen and freezing for the site A and C. Here, following definitions are proposed :

1. "extensively frozen layers" : In these layers, the unfrozen water contents are smaller than the amount of 0.07 or 0.08 $m^3 m^{-3}$ and are

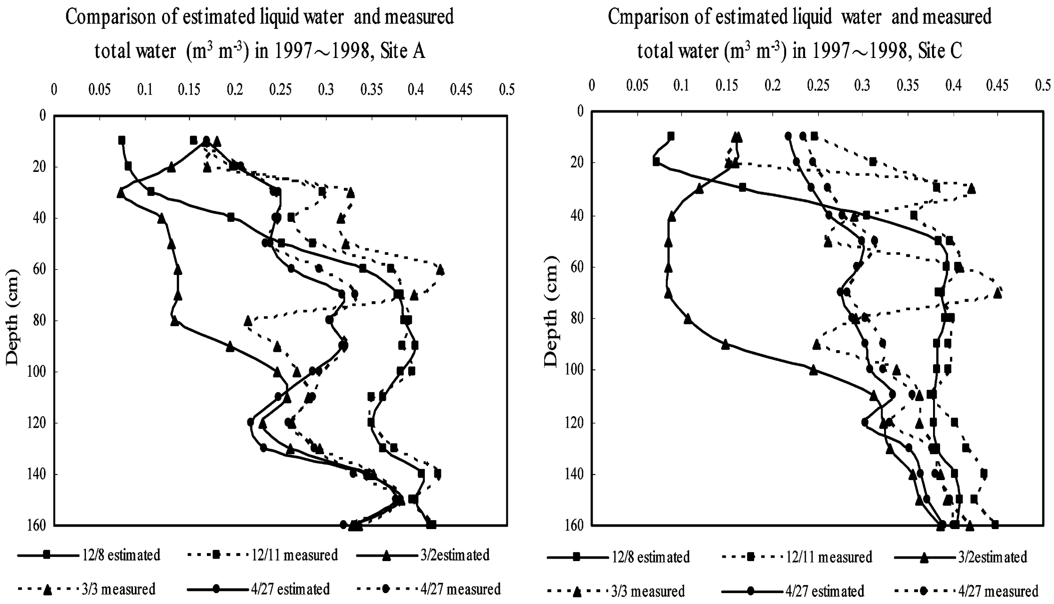

Fig. 5 The comparison of estimated liquid water content and measured total water content in 1997 ～1998 at site A and C.

kept almost unchanged. The ground temperatures are lower than －1.2 or －2.1℃ at site A or C, respectively. The transformation of water to ice is so small that can be neglected.

2. "partially frozen layers" : In these layers, the unfrozen water contents increase abruptly from 0.07 or 0.08 to 0.35～0.36 $m^3 m^{-3}$. The ground temperatures are within －1.2～－0.21℃ or －2.1～－0.63℃ for site A or C, respectively. The transforming amount of liquid water to ice is relatively large.

The liquid water contents estimated from the TDR data and the total water contents measured gravimetrically from the soil samples are compared in Fig. 5. In thawed soils which are judged by ground temperature, the estimated liquid water contents are in good agreement with those measured ones. When the soil freezes, the estimated liquid water content represents the unfrozen water content. There seems no reason why the estimated unfrozen water contents in frozen soil are not reliable.

3.6 Penetration rates of frozen and freezing layers

From the profiles of ground temperatures and liquid water contents in Fig. 2 and 3, the freezing penetration rates were investigated. The average rates of extensively partially frozen layers were 0.72 cm d^{-1} and 0.69 cm d^{-1} at site A and C, at the same time they were 1.17 cm d^{-1} and 0.96 cm d^{-1} of partially frozen layers at site A and C, respectively. The fronts of extensively and partially frozen layers are showed in Fig. 6.

3.7 Liquid water profiles in thawing period

The soil started to thaw from the beginning of March. At site A and C, the layers those liquid water contents were lower than 0.1m^3 m^{-3} still existed in the depth of 0.30～0.40 m and 0.30～0.60 m in the beginning of March (Fig. 7). Such layers disappeared in the end of March. The layers those temperatures were below the depression of freezing points were present in depth of 0.70～0.90 m till the end of April. The average thawing rate was 1.43 cmd^{-1} in March and 2.86～3.57 cm d^{-1} in April,

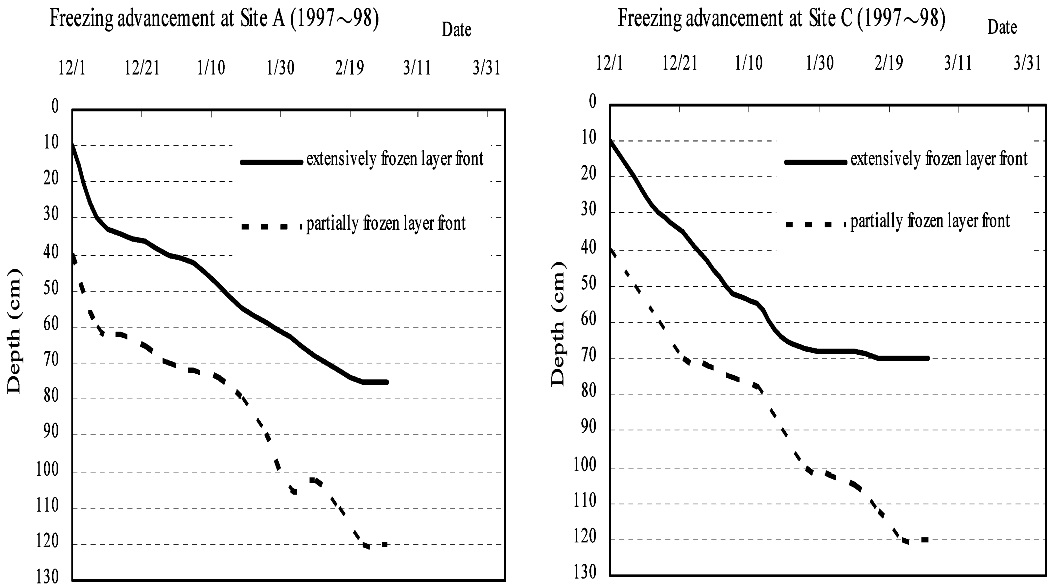

Fig. 6 The advancement of extensively frozen layers and partially frozen layers in 1997～1998 at site A and C.

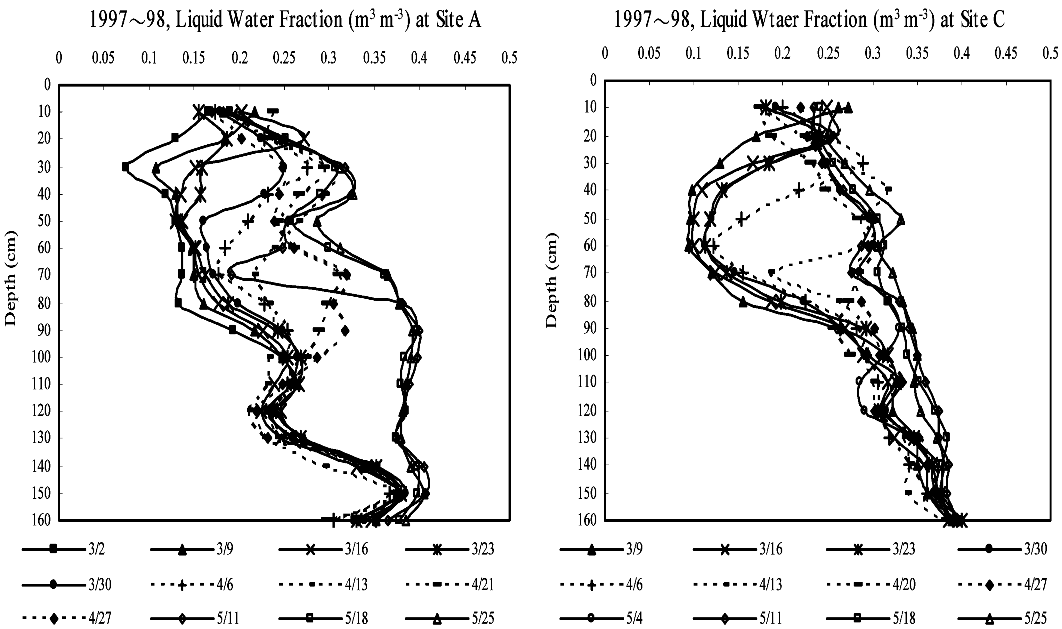

Fig. 7 The liquid water profiles in thawing period in 1997～1998 at site A and C.

which is estimated corresponding to the ground temperature.

4. Conclusion

Through the analysis of ground temperature and unfrozen water content, the soil freezing stages and properties are revealed at site A and C in Hetao. The unfrozen water content of 0.07 $m^3 m^{-3}$ and 0.08 $m^3 m^{-3}$, isotherm of −1.2℃ and −2.1℃ can be applied to distinguish different freezing stages, that is helpful for the study of salts transportation in this region. The definitions of "extensively frozen layer" and "partially frozen layer" are proposed and their penetration rates are also evaluated. The thawing rate was higher than freezing rate and it became faster in April than in March.

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中国河套灌区における TDR で測定した不凍水量による土壌の凍結過程の解析

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要　　旨

TDR で推定した液状水分量と地温データを用い，中国内蒙古河套灌区にある耕地 A，塩害地 C における凍結の進行過程について検討した。不凍水の移動特徴から，凍結土層は“完全凍結層”と“部分凍結層”に区別された。現地の試験スポットの Site A と C において，完全凍結層はそれぞれ 0.07 $m^3 m^{-3}$, 0.08 $m^3 m^{-3}$ 以下の不凍水分量を保ち，鉛直下方へ進行するのに対し，部分凍結層は厚さ 0.30〜0.40 m の土層内で不凍水分量がそれぞれ 0.07 $m^3 m^{-3}$, 0.08 $m^3 m^{-3}$ から 0.35 $m^3 m^{-3}$, 0.36 $m^3 m^{-3}$ へ急激に変化する傾向を示した。地温 −1.2℃，−2.1℃ はそれぞれの試験スポットの“完全凍結層”と“部分凍結層”の境界になっていることが判明した。

キーワード : 不凍水分量，地温，完全凍結層，部分凍結層

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