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ORIGINAL ARTICLE

Cyclic freeze–thaw as a mechanism for water and salt migration in soil

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Abstract Freeze–thaw action acts as a controlling mechanism for redistributing soil water and salt. The paper focuses on the factors that influence soil water and salt migration and uses experimental results to analyze the mechanism of cyclic freeze–thaw in which the temperature gradient is the principal factor for water and salt transfer. Salt redistribution in soil occurs as a result of the integrated effects of convection, diffusion, and numerous chemical and physicochemical processes.

Keywords Cyclic freeze–thaw · Water and salt redistribution · Temperature gradient · Convection

Introduction

Water and salt movement during cyclic freeze–thaw is a fundamental issue in geocryology. Péwé (1983) noted that determining the principles of water and salt transfer during the cyclic freeze–thaw is a way to control salinization. Due to the various factors influencing the freeze–thaw cycle and instrument limitations, a number of studies have been done in unfrozen soil such as farmland and groundwater (Rubin and James 1973; Rushton and Redshaw 1979; Mackay 2001; Almasri and Kaluarachch2007; Xu et al. 2010; Jamin et al. 2012; Chen et al. 2014), but a little work has been done particularly on the effect of cyclic freeze–thaw on the water and salt migration. So it is urgent to answer the question that why the water and salt migrated during cyclic freezing and thawing and what is the mechanism. In order to control the further trend of salinization in mid-latitudes, the main objective of this research is to study the mechanism of water and salt transfer during the cyclic freeze–thaw which is very useful on the theory and practice. The factors influencing water and salt migration during cyclic freeze-thaw are put forward in upcoming section, the results of the experiments are discussed further in another two sections, before offering a few concluding and summary remarks.

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Factors influencing water migration in frozen soil

Water migration in frozen ground requires special consideration. Yershov (1995) explains the water transfer by changes in the surface energy of soil particles. The existence of such water migration in frozen soil is established in numerous publications (Anderson and Tice 1972; Williams and Smith 1989; Yershov 1998). But this has been proven wrong (Rempel et al. 2001). There are no contacts between the ice and particle surfaces because the water wets the particle surface, so it is quite different from the case of capillary rise, which is driven by the net force produced by surface tension at the air–water-particle contacts. The Gibbs–Thomson effect does play an important role in fluid flow. So it can been seen obviously from the effect that the water migration is predominantly affected by temperature, the initial moisture content of soil, salt content, and soil structure (Xu et al. 1987). The micro mechanism of water migration include the adsorptive ability of the hydrogen bond, the difference of saturation vapor pressure, and capillary mechanisms (Na and Xu 1996).

Temperature gradient

There is a general recognition that when soil undergoes freezing, the surface tension and the viscosity of water in the soil are higher in the zones with higher temperature, causing soil water to transfer to the zones with lower temperature. The migration speed of the water is slow once it enters the zones with lower temperature. Under stable, non-freezing conditions, capillary water and hygroscopic water in the soil pores are in equilibrium (Xu et al. 1994). Yet, the thickness of the unfrozen water film decreases as ice lens increases during freezing process. Temperature variations causes the redistribution of intermolecular forces. Thus, temperature gradient influences water migration, either directly or indirectly, by influencing other factors.

Initial moisture content

The initial moisture content of the soil plays an important role in water migration during the freeze–thaw cycle (Zhang and Wang 2001). The water and ice lens in soil can control the permeability and the hydraulic conductivity of the soil by controlling the amount of soil pore, the formation of ice lens and the viscosity of water (Xu and Deng 1991). With a higher initial moisture content, there is sufficient water for ice growth and a continuous ice lens forms, limiting water migration in the dense frozen zone. The migration space deceases in the soil as more ice lens forms and the water migration path increases. In contrast, the ability of the soil to support water migration increases when the ice content is low, as the soil has more open space for water movement. For a specific soil, the depth of freezing in inversely related to the initial water content (Pikul et al. 1991). The thermal conductivity of the soil increases as water content increases, but the moving speed of the phase transition interface decreases due to the latent heat, thus decreasing the frozen depth (Guo et al. 2002).

Salt content

Salt has a substantial impact on water pressure, unfrozen water content, and water movement during freezing. The presence of salt in soil lowers the freezing temperature to below 0 °C, with different salts and concentrations having different influences on the freezing point (Bing and Ma 2011). At a given temperature, the unfrozen water content is greater in saline soil than in salt-free soil. The unfrozen water content in frozen soil increases sharply with increased salt content.

Soil structure

Water migration depends not only on external conditions, but also on the physical structure of soil itself. Variations in dry density have a significant influence on the flux of water migration. At the same temperature, soil with a lower dry density has numerous large pores and the unfrozen water film among soil particles has poorer continuity. With increasing dry density, the opportunity for water migration increases, because the continuity of unfrozen water is better. However, as the dry density continuously increases, the soil particles become denser and the pathways for water transfer are decreased, thus decreasing the water flux (Bing et al. 2004). The permeability is greater for the frozen soil with coarse particles than for fine-grained soils, but the potential for water movement is weaker.

Factors influencing salt migration during the cyclic freeze–thaw

Water is a main factor in salt migration. What is not only the solvent of salt, but also the transfer carrier of salt, so water transfer controls the salt migration except the salt variation for the physical and physicochemical causes. When a homogeneous solution is used in freezing experiment, salt separates from the zone where the phase is changing for ice self-purification, leading to the formation of a zone with higher salt concentration at the boundary of the freezing front. The solute moves from the high concentration zone, thus, the direction of salt movement is from the freezing zone to the unfrozen zone (Gray and Granger 1986). In this condition, the bigger of the initial solute concentration and the quicker of freezing speed, the fewer of transfer salt (Chen et al. 1988; Qiu and Huang 1983).

In the processes of salt migration in porous media, following various physical, chemical and biological processes, the amount of salt migration is fluctuating due to the stochastic distribution of micro structure of the soil and its variance at time and space (Celia and Bouloutas 1990). Numerous laboratory experiments (Qiu et al. 1989) on salt migration in freezing soil have shown that the direction of salt transfer differs in different media. Salt migrates from the freezing zone to the unfrozen zone in a highly permeable medium such as sandy soil; however, the direction of salt transfer is reversed in a low-permeability medium. The main transfer direction corresponds to the direction in which the freezing front is moving. The migration process is more complete provide that the permeability is higher and the freezing rate is slower. If the freezing rate is high, the freezing front moves rapidly and it make possible that ice occupy transfer channel which plays a major role in the salt migration. During freezing salts can be transferred with water, but the transfer becomes increasingly difficult as pore spaces become occupied; thus the main direction of salt migration is to the freezing zone (Bing et al. 2007). In fact as to the salt transfer there are three processes as follows. First, salt content and moisture content in the freezing zone will increase when salt going along with the unfrozen water moves; second, salt separates out from growing ice lenses during icing, finally, opposite transfer will take due to solute gradient, however, following the second process the salt concentration increases in the freezing zone, so the quantity of opposite transfer is less than the quantity of the first process (Zhou et al. 2000)

Salt migration is complex during freezing and is influenced by soil type, initial moisture content, salt content, temperature, temperature gradient, and cooling rate.

Methods and materials

A redsilty clay (Table 1) collected from the Beiluhe test site was used in the experiments. The Beiluhe test site is in the dry climate region of the Qinghai-Tibet Plateau. The frozen period is about 8 months long, from September to April, and the annual evaporation in the region is much higher than annual precipitation. The mean annual air temperature in the region is −3.8 °C and the mean annual ground temperature (MAGT) at a depth of 15.0 m ranges between −1.6 and −0.9 °C. The MAGT over most of the test site is below −1.0 °C. According to the permafrost zone theory based on ground temperatures in China, the district is classified as basically stable zone with low temperature permafrost. The maximum wind speed is 40 m/s and the annual average wind speed is 4.1 m/s. The maximum thickness of snow is about 14 cm. At the site, the soil consists predominantly of the lacustrine deposits of the upper Tertiary and the diluvium flood deposits of the Quaternary Holocene Series. The ground surface is generally covered by red silty clay and partly gritty soils.

The sample, at a fixed water content of 30 % (exceeding the liquid limit of the soil), was contained in cylindrical organic glass drum with 10 cm in inner diameter and 18.5 cm in height and tamped it to a density of 1.44 g cm^{-3} and a height of 14.0 cm. The inside wall of the cylinder was lubricated with a thin layer of mineral butter in order to minimize wall friction during freezing and thawing.

The freeze–thaw equipment used in the experiments is shown schematically in Fig. 1. The ambient temperature of the surrounding environmental chamber (internal dimensions approximately 20 cm × 20 cm × 45 cm) can be controlled over a range of temperatures from −40 to +70 °C. It consists of an upper and a lower cooling plate, the temperature of which can be controlled separately using alcohol as a refrigeration agent. The sample container is positioned in the cold chamber which can provide a controlled environmental temperature. The temperature of the sample is measured continuously by a row of thermistor sensors inserted into the soil every 1 cm along the vertical direction and the amount of soil deformation is measured by a deformation sensor mounted at the top of the upper cooling plate. The accuracy of the deformation sensor is about 0.001 mm, and that of the temperature-controlled is about 0.01 °C. The test data is recorded every 30 min by a data logger (Data taker 500 made in Australia) with 10 channels, and stored on disk. The liquid supplied through the replenishment system was a sodium sulfate solute with a concentration of 5 %.

Three types of experiments were performed with the same soil, all with a bottom boundary temperature of +2 °C: (a) unidirectional freezing with the upper surface of the sample at −10 °C to model perennial frozen soil; (b) cyclic freeze–thaw with the upper surface temperature varying sinusoidally from −10 to +10 °C to model seasonal frozen soil and (c) cyclic freeze–thaw with the upper surface temperature varying sinusoidally from −10 to 0 °C to model seasonal frozen soil in the region where the highest air temperature is near 0 °C (Fig. 2a–c). The three experiments had a solution reservoir connected to the sample through the bottom cap in order to provide an open system during freezing and thawing. The initial moisture content of the samples was 30 %, and the initial salt (sodium sulfate) content was 0.037 %. At the end of the experiments the samples were divided into 1 cm thick discs to measure the moisture content (drying method) and the salt content (using ion chromatograph). The freezing sample experienced short thaw after freezing so that it can

Table 1 Grain-size distribution and physical properties of the silty-clay test soil

Grain-size distribution (%)					Liquid limit (%)	Plastic limit (%)	Permeability cm s^{-1}	Dry density g cm^{-3}
0.2 ~ 0.1 mm	0.1 ~ 0.05 mm	0.05 ~ 0.01 mm	0.01 ~ 0.005 mm	0.005 ~ 0.001 mm				
0.4	35.7	18.9	12.7	32.5	27.9	16.4	5.7 × 10^{-6}	1.606

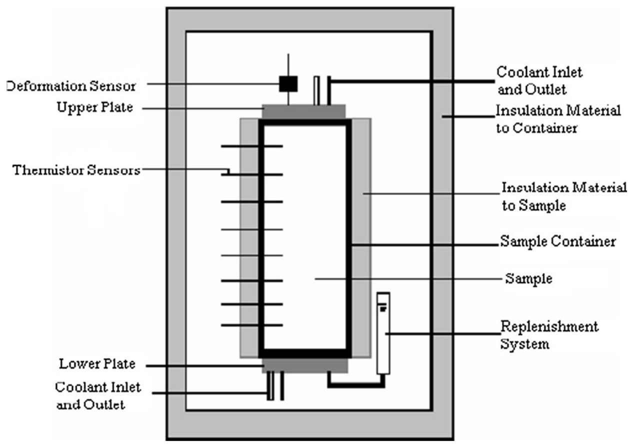

Fig. 1 Schematic diagram of a thermally controlled frost heave cell

be taken out the cylindrical container with little difficulty, this has hardly any influence on the results of the moisture content. The frozen samples were briefly warmed at the end of the experiment in the room temperature so that they could be easily removed from the cylindrical container. This procedure might have a minimal impact on the moisture content and the condition of the three samples after the experiments can be seen in Fig. 3.

Results and discussions

Figures 4, 5 show the resulting moisture and salt content profiles after the experiments. To the unidirectional freezing experiment, the potential of unfrozen water induced water to move from the unfrozen zone to the freezing zone, causing an increased moisture content in the freezing zones and reduced values in the unfrozen zones (Fig. 4a). It should be noted that the upper part of the soil remained frozen at the end of the experiment. The two cyclic freeze–thaw experiments, which ended with thawed soils, developed a high moisture content further up the profile. This was especially true of the soil cycled from −10 to 0 °C at the surface which showed the maximum moisture content in the near-surface layer (Fig. 4b, c). And the condition of the samples after the experiments show the location of the maximum water content.

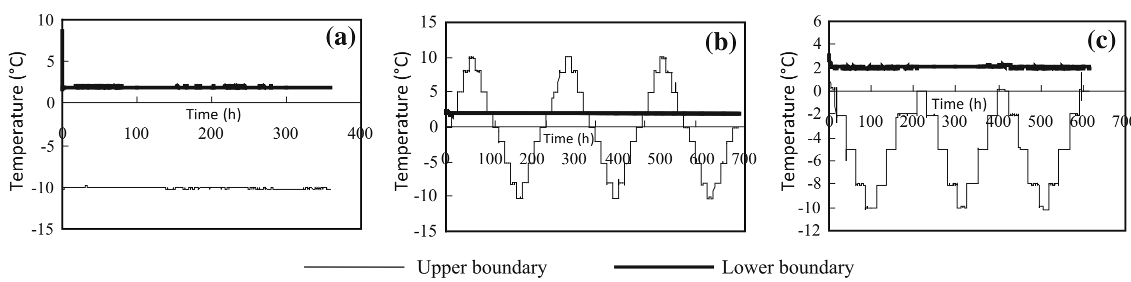

Fig. 2 Boundary temperatures during **a** experiment A, unidirectional freezing; **b** experiment B, cyclic freeze–thaw from −10 to +10 °C; **c** experiment C, cyclic freeze–thaw from −10 to 0 °C

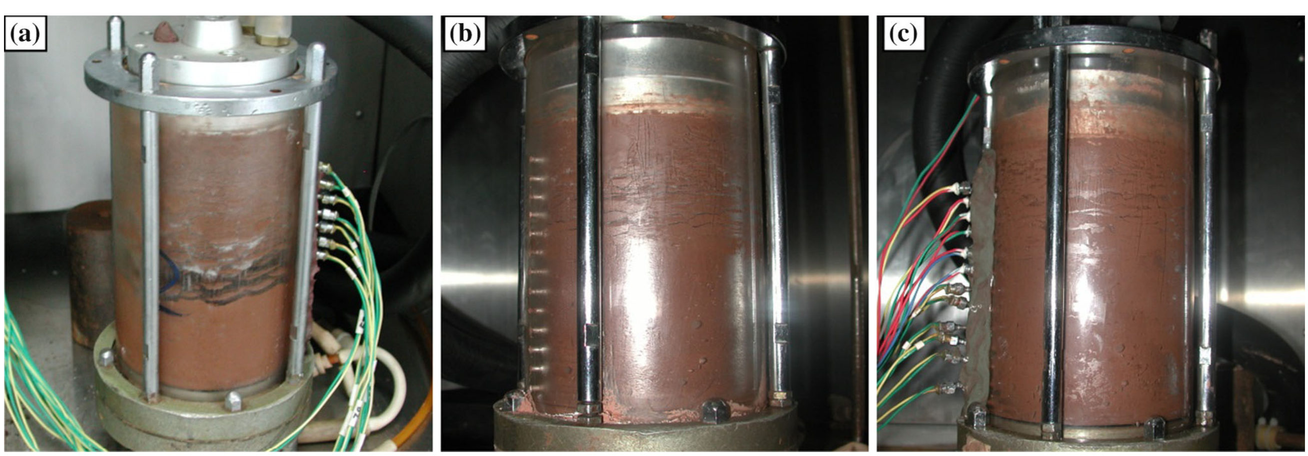

Fig. 3 Condition of the samples after the experiment **a** experiment A, unidirectional freezing; **b** experiment B, cyclic freeze–thaw from −10 to +10 °C; **c** experiment C, cyclic freeze–thaw from −10 to 0 °C

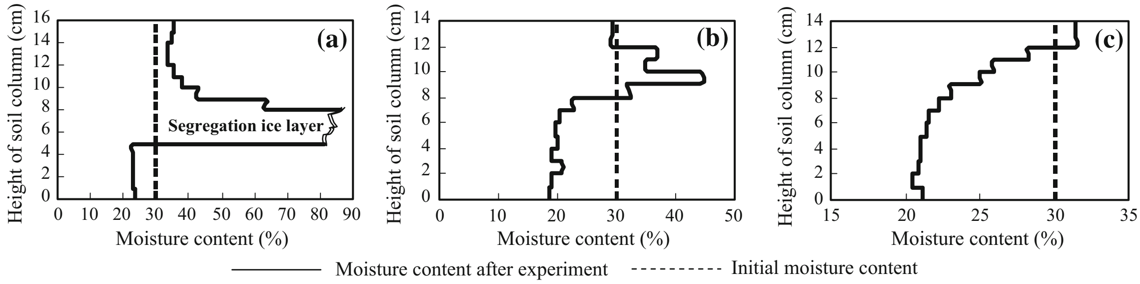

Fig. 4 Moisture content profiles following **a** experiment A, unidirectional freezing; **b** experiment B, cyclic freeze–thaw from −10 to +10 °C; **c** experiment C, cyclic freeze–thaw from −10 to 0 °C

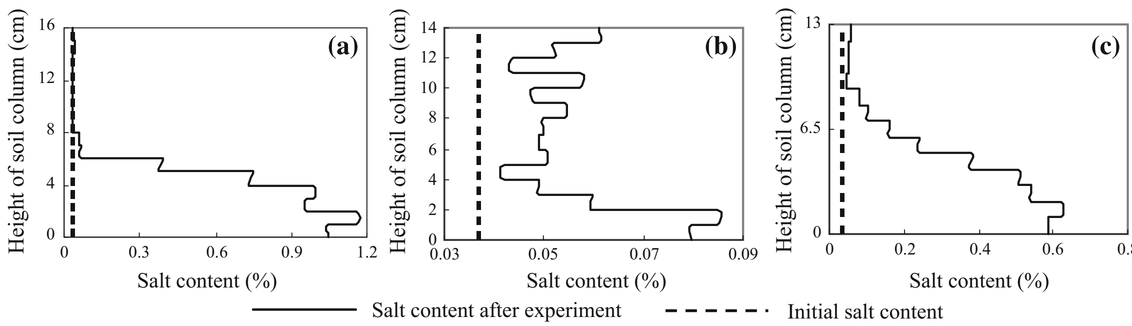

Fig. 5 Salt content profiles after **a** experiment A, unidirectional freezing; **b** experiment B, cyclic freeze–thaw from −10 to +10 °C; **c** experiment C, cyclic freeze–thaw from −10 to 0 °C

To the unidirectional freezing experiment with a constant temperature gradient, the potential of the unfrozen water induces pore water to transfer from the unfrozen zone to the freezing zone. The ice lens (segregational ice) developed when the freezing front drove forward. The maximum moisture content layer was lower compared to the experiment with the upper surface temperature varying sinusoidally from −10 to +10 °C (Fig. 4b). During the freezing process water migrated from the lower section to the upper, which led to the drainage of the whole soil column and a lower permeability, and macro segregation ice was decreased when the permeability of the soil and the dendrite arrays were decreased (Fig. 3). The amount of segregation ice was mainly controlled by the permeability of the soil in the direction of gravity except the temperature gradient. Thus, the migrated water cannot infiltrate to the original site when thawing. A thawing interlayer caused moisture retention and resulted in greater moisture content after several freezing and thawing cycles. But when the soil only experienced freezing and thawing actions at minus temperature, no interlayer water accumulated. Sensible heat flux in the soil exist due to small temperature gradients in the transition layer between the frozen and the unfrozen layer, but the latent heat of freezing appeared to be greater than the sensible heat because of the water and ice phase change during the freezing front advanced (Leyasu et al. 2010), so a segregational ice layer and the potential gradient of the unfrozen water exist at all times. Thus, water continues to migrate to the upper layer.

Due to the ice self-purification processes of ice formation during the unidirectional freezing, the freezing front serves as a partition layer to salt, such that very little amount of salt migration occurs in the frozen zone even though the moisture content in the zone is high. The phase change of water and sulfate crystallization affected the freezing of the salt solution by offering an additional resistance to the water transfer and salt migration (Song and Viskanta 2001). However,to the unfrozen zone, salt migrates with water and the amount of salt migration decreases from the bottom to the upper section of the soil column. So salt migrates due to the convection with soil water.

When the soil experienced freezing and thawing, the temperature gradient varies with time. The variation trend of the moisture content after the experiment in the unfrozen zone is the same as the unidirectional freezing; the moisture content after the experiment is smaller than the initial one because of the water drainage and the soil consolidation. The highest moisture content exists at the middle of the soil column, since only the upper part of the soil experienced freezing and thawing. At the beginning of the experiments, the pore, the particle grain size, and the mineral composition of the soil sample were random, and the ice and the salt migration had not yet begun. With increased freeze–thaw cycles the access for the salt and the water migrating formed. After the first freezing period (similar to the unidirectional freezing), the soil would undergo thawing. The water that had migrated during freezing was not able to completely return to its original site due to the influence of gravity and water potential. Thus, water migrated to upper and bottom at the first cyclic freeze–thaw and with increasing the number of cyclic freeze–thaw, the amount of migrated water increased, accumulating a large amount of water near the middle of the soil column. The amount of salt content was larger at the detention layer of the water, partly because the source of salt for the convection at the early stage created a higher value of salt content at the top of the soil column. There was a concentration gradient between the upper and the lower part of the soil water, and ice was melt until the salt solution reached the concentration level at the freezing temperature during freezing, the salt solution was diluted, so the salt would diffuse to the lower part of soil column after several numbers of cyclical freeze–thaw (Fujimoto et al. 2014). So the salt migration was a result of the convection and the diffusion during the cyclic freezing and thawing.

The unfrozen water potential existed all the time to the soil experienced cyclic freeze–thaw from −10 to 0 °C, but it was various with time also, so the constant flow of water migrated to the upper part of the soil column, making a higher value of water content at the top of the soil column. Compared with the unidirectional freezing experiment, the salt content increased in the unfrozen zone because the supplement of the solution at the bottom of the soil during freezing and thaw. After experienced several cyclic freezing and thawing, the salt content would be greater. All the same, the salt content had hardly changed at a little upper part of the soil column. However, water took salt to migrate to the upper part of the soil sample due to the temperature gradient. Though the temperature at the top of the soil is −10 °C, which was given stage by stage, the freezing front at the early stage of the experiment formed at the higher of the soil column and was forward slowly to the lower part, so the salt content is higher.

The water and salt migrated in the soil to the three experiments due to the freezing and thawing, where was a temperature gradient between the upper part and the bottom part of the soil. It is evident that the amount of migrated salt to the upper part of the soil column was substantial for the migration along with moving freezing front (Umer et al. 2011).The water was the carrier of the salt, so the great number of salt migrated for the convection, and the amount of salt diffused due to the concentration gradient was little. Therefore, the migration of the water and the salt was the result of the temperature gradient which existed since the experiments began.

Conclusions

Cyclical freeze–thaw causes the redistribution water and salt in soil. Temperature gradient is one of the external agents of the soil water movement. The salt migration is influenced by factors influencing water movement in addition to various physical and physicochemical matters. The mechanism of water movement determines, to a large extent, the mechanism of the salt migration. The three fundamental elements of water movement during freeze–thaw are the temperature gradient, the unfrozen water content and the water potential. Salt migrates with water during the cyclic freezing and thaw because of the convection accompanying the diffusion due to the concentration gradient.

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References

Almasri MN, Kaluarachch JJ (2007) Modeling nitrate contamination of groundwater in agricultural watersheds. J Hydrol 343(3–4):211–229

Anderson DM, Tice AR (1972) Predicting unfrozen water contents in frozen soils from surface area measurements. Highway Res Rec 373:12–18

Anwar J, Umer S, Munawar MA et al (2011) Chemistry of ice: migration of ions and gased by directional freezing of water. Arab J Chem. doi:10.1016/j.arabjc.2011.02.019

Bing H, Ma W (2011) Laboratory investigation of the freezing point of saline soil. Cold Reg Sci Technol 67:79–88

Bing H, He P, Yang CS (2004) Research in the field of salt in freezing soils. In: Proceedings of the Sixth International Symposium on Permafrost Engineering, pp 44–50

Bing H, He P, Yang CS (2007) Impact of sodium sulfate on soil frost heaving in an open system. Appl Clay Sci 35:189–193

Celia MA, Bouloutas EF (1990) A general mass-conservative numerical solution for the unsaturated flow equation. Water Resour Res 26:258–262

Chen XB, QiuGQ, Wang YQ (1988) Physical chemistry and mechanics properties of heavy salty soil during temperature changing. Science 4: 429–438

Chen LJ, Feng Q, Li FR et al (2014) A bidirectional model for simulating soil water flow and salt transport under mulched drip irrigation with saline water. Agric Water Manag 146:24–33

Fujimoto A, Tokunaga RA, Kiriishi M (2014) A road surface freezing model using heat, water and salt balance and its validation by field experiments. Cold Reg Sci Technol 106–107:1–10

Gray Granger (1986) In situ measurement of moisture and salt movement in freezing soils. Can J Earth Sci 23:696–704

Guo ZR, Jing EC, Nie ZL (2002) Analysis on the characteristics of soil moisture transfer during freezing and thawing period. Adv Water Sci 13:298–302

Jamin P, Dolle F, Chisala B et al (2012) A regional flux-based risk assessment approach for multiple contaminated sites on groundwater bodies. J Contam Hydrol 127(1–4):65–75

Mackay R (2001) Simulating groundwater contaminant migration at Villa Farm. Q J Eng Geol Hydrogeol 34:215–224

Na PS, Xu SL (1996) An approach to the formation mechanism of frozen perched ground water. J Glaciol Geocryol 18:273–277

Noborio K, Tokumoto L, Koga K (2010) Coupled water and heat floe in a grass field with aggregated Andisol during soil-freezing period. Cold Reg Sci Technol 62:98–106

PéwéTL (1983) The periglacial environment in North America during Wisconsin Time. In: Late-Quaternary Environments of the United States 1: The Late Pleistocene, pp 157–189

Pikul JL, Zuzel JF, Wilkins DE (1991) Water infiltration into frozen soil: field measurements and simulation. In: Proceedings of the National Symposium, pp 357–366

Qiu GQ, Huang CL (1983) Ion migration during water freezing. In: Proceedings of the Second National Conference on Geocryology, pp 314–320

Qiu GQ, Sheng WK, Huang CL (1989) The discussion on the transferring direction of solute during freezing. In: Proceedings of the Third National Conference on Geocryology, pp 211–217

Rempel AW, Worster MG, Wettlaufer JS (2001) Interfacial premelting and the thermomolecular force: thermodynamic buoyancy. Phys Rev Lett 87:088501

Rubin J, James RV (1973) Dispersion affected transport of reacting solutes in saturated porous media-Galerkin method applied to equilibrium controlled exchange in unidirectional steady water flow. Water Resour Res 9(5):1332–1356

Rushton KR, Redshaw SC (1979) Seepage and groundwater flow-numerical analysis by analog and digital methods. Wiley, New York

Song M, Viskanta R (2001) Lateral freezing of an anisotropic porous medium saturated with an aqueous salt solution. Heat Mass Transf 44:733–751

Williams PJ, Smith MW (1989) The frozen earth. Cambridge University Press, Cambridge

Xu XZ, Deng YS (1991) The experiment study on water movement in frozen soil. Science Press, Beijing

Xu XZ, Oliphant JL, Tice AR (1987) Factors affecting water migration in frozen soil. U.S. Army Cold Regions Research and Engineering Laboratory Report CRREL-87-9

Xu XZ, Wang JC, Zhang LX (1994) Influence of cooling rate on frost heave of freezing soils in open systems. In: Proceedings of 7th International Symposium on Permafrost, pp 65–68

XuX HuangGH, Qu ZY et al (2010) Assessing the groundwater dynamics and impacts of water saving in the hetao irrigation district yellow river basin. Agric Water Manag 98(2):301–313

Yershov ED (1995) Foundations of geocryoloy: physical and chemical foundations. Moscow State University, Moscow

Yershov ED (1998) General geocryology. Cambridge University Press, Cambridge

Zhang DF, Wang SJ (2001) Mechanism of freeze-thaw action in the process of soil salinization in northeast China. Environ Geol 41:96–100

Zhou YW, Guo DX, Qiu GQ (2000) Frozen ground in China. Science Press, Beijing