

Research Article

Construction and Engineering Application of Salt-Discharging Model for Local Saline-Alkali Soil with Compact Structure in the Yellow River Delta

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Structural characteristics of local saline-alkali soil in the Yellow River Delta were studied by microscopic test methods of liquid nitrogen vacuum freeze-drying machine, fully automatic mercury intrusion porosimetry, X-ray diffractometer, and high- and low-vacuum scanning electron microscope. Permeability of the saline-alkali soil belongs to two grades of microporous water and extremely microporous water. Average volume ratio of pores with diameters no more than $2\ \mu\text{m}$ is 86.25%; therefore, the saline-alkali soil may mainly consist of micropores and ultramicropores. Most void ratios of the soil are not beyond 0.5, and its dry densities are all greater than $1.6\ \text{g}/\text{cm}^3$. Because average proportion of the clay minerals is only 12.24%, they are obviously not the main reason for poor permeability of the local saline-alkali soil. Based on the structural characteristics of compact structure and slightly developed fracture, mechanisms of surface runoff, and water-salt migration of the local saline-alkali soil, a salt-discharging engineering model mainly with surface runoff was established considering auxiliary infiltration and without interflow. Salt content distribution of the local saline-alkali soil is studied experimentally, by which relationship between salt content and conductivity has been fitted as $y = 2.74x$. The relationships between depth and salt content in the saline-alkali soil region present that the depth of salt-discharging engineering as open ditch should be beyond 60 cm. From the relationships between precipitation and salt content, the effectiveness of engineering measure shown in the salt-discharging model has been verified immediately or indirectly, and the engineering salt-discharging model may be suitable for managing saline-alkali soil in the Yellow River Delta.

1. Introduction

Agricultural development in the world has been seriously limited by the saline-alkali soils. In China, area with saline-alkali degrees are increasing every year, especially in the Yellow River Delta region, where irrigation farming is mainly dependent on water from the Yellow River; severe saline-alkali soil may be due to these reasons, including lower and even land, poor drainage, side infiltration of the Yellow River water, and ascending seawater or its infiltration. The key measures to manage saline-alkali soil are to exclude soluble salt in soil and stop salt from rising. At present, combined measures involving physical, hydraulic, chemical, and biological methods are commonly recommended [1–3].

Engineering measure is a direct and effective method to control saline-alkali soil, but engineering effectiveness is easy to be lost, the material cost is high, and the economic benefit is low. To manage saline-alkali soil fundamentally, microstructure of the soil should be studied for revealing its engineering features and physical characteristics. The microstructure of soil is a determined factor and its engineering characteristics have been verified by many researchers [4, 5]. Analyzing microstructures from consolidation test results of clay soils by X-ray diffractometer and scanning electron microscope, their deformation features of expansion, compressibility, and permeability are studied by different minerals and microstructures when ameliorating the soil with limes [6]. Microstructures and minerals of soft clay soil were identified by scanning electron microscope and X-ray

diffractometer; meanwhile, its axial compressive strength was examined [7]. Relationships between microstructure and physical or mechanical parameters of clay soil, in Zhanjiang city, were studied by scanning electron microscope, mercury intrusion porosimetry, and gas adsorption test [8]. The results provide an important reference for the study of the relationship between the microstructure of soil and its physical and mechanical properties. These references are mainly about clay soil, soft soil, and loess, while the research on the microstructure of saline-alkali soil is less.

2. Basic Situation of Saline-Alkali Land in the Yellow River Delta

2.1. Natural Conditions. The Yellow River Delta is located at $118^{\circ}07' - 119^{\circ}10'E$ and $37^{\circ}14' - 38^{\circ}12'N$, and the topographic feature is level because its elevation is only between +1.0 m and +13.3 m. Annual average precipitation in the area is about 530–630 mm, while evaporation can be up to 750–2400 mm. The extreme temperature of the Yellow River Delta is $-23.3^{\circ}C$ in winter; hence, the maximum depth of frozen soil in the Yellow River Delta is no more than 60 cm. The depth of groundwater in the Yellow River Delta is only 0–3 m, which is determined to form saline-alkali land [9]. Natural moisture content of the saline-alkali soil is about 22%.

2.2. Influencing Factors of the Saline-Alkali Land. Formation of saline-alkali land in the Yellow River Delta has been influenced by many factors including sediment deposition, climate, salt return from seawater, and rise of groundwater level.

The sediment from the Yellow River contained a lot of salt and alkali components and buried amount of seawater, which would make the soil become saline-alkali land. The Yellow River Delta belongs to warm temperate continental monsoon climate; therefore, the groundwater and the soil water evaporate quickly. Meanwhile, soluble salts in the soil and groundwater accumulate continuously on the soil surface with evaporation of water. Development of the saline-alkali land has been affected by the return of salt from seawater by trench reverse irrigation to the groundwater and sea tide invasion to the soil. The salt and alkali gradually deposited in the soil had eventually formed unique saline-alkali land in the Yellow River Delta. Rise of the groundwater level by irrigation of the Yellow River and other factors led to evaporation of the groundwater and accumulation of salt on the surface of the soil [6, 7, 10].

2.3. Spatial and Temporal Distribution Characteristics of the Salt Content in the Saline-Alkali Land. From 1987 to 2007, the area of severe saline-alkali land in the Yellow River Delta increased rapidly. However, the area of light saline-alkali land increased and the area of heavy saline-alkali land decreased significantly from 2007 to 2014, which indicated that the degree of soil salinization was greatly related to the treatment and time [11–13].

In traditional opinion, the salinization degree of coastal saline-alkali land will be severe with the increase in depth because deeper soil may be eroded by seawater, in which conclusion should be conditional. Within 45 cm depth of the saline-alkali land in the Yellow River Delta, the average values of salt content are 0.68% (0–15 cm depth), 0.72% (15–30 cm depth), and 0.77% (30–45 cm depth), respectively [14, 15]. At the depth of 0–20 cm below the surface of the soil in the Yellow River Delta, salt contents of the saline-alkali soil tend to be higher with the closer distance from the sea, which has been considered a general rule [16, 17].

2.4. Initial Effect of Research on Soil Structures to Salt-Discharging Engineering. Particle sizes of the sediments in the Yellow River will become smaller with her flowing into the sea through the estuary. In upper reaches of the Yellow River, sediments were mainly coarse-grained with a particle size greater than 0.05 mm, loose structure, and good permeability. In her middle reaches, sediments were mainly medium coarse-grained with a particle size less than 0.05 mm and some developed pores. In her lower reaches, sediments were mainly fine sand with a diameter less than 0.025 mm, a compact structure, undeveloped pores, and poor permeability, while at the estuary of the Yellow River, sediments were mainly very fine with a particle size of 0.004–0.032 mm, very compact structure, and poor permeability [18–23].

According to structural characteristics of saline-alkali soil in the Yellow River Delta, the particle structure which was fine, uniform, and compact should be broken to improve the permeability of the soil, which was determined to harness saline-alkali soil with engineering measures. Microstructures of the local saline-alkali soil involving water permeability, porosity, dry density, mineral composition, and compact structure were studied by several microscopic test methods in this project. Considering microstructure characteristics of the local saline-alkali soil, its surface runoff mechanism, and water-salt migration mechanism, the salt-discharging engineering model is established, in which the surface runoff is determined, infiltration is auxiliary, and interflow is not included. Relationships between salt content and depth or precipitation are analyzed to evaluate the effectiveness of the salt-discharging engineering model and submit the depth of the open pitch.

3. Structure Characteristics of the Local Saline-Alkali Soil

In the Yellow River Delta, experimental samples of the local saline-alkali soil lie in Alfalfa grassland adjoining Shangdong Meiao Biological Engineering Co. Ltd (Guangrao County, Dongying City, Shandong Province, China; $37^{\circ}18'8''N$, $118^{\circ}38'7''E$), as presented in Figure 1; sampling depths are from surface to 100 cm, the macroscopical performance of the soil samples collected is almost no stratification and compact structure, and the capillary phenomenon of groundwater may not be obvious.



FIGURE 1: The local saline-alkali soil.

3.1. Permeability of the Local Saline-Alkali Soil. Permeability coefficients of surface saline-alkali soil at 30 cm depth and 60 cm depth are 7.14×10^{-5} cm/s, 3.06×10^{-6} cm/s, and 8.33×10^{-7} cm/s, respectively. Surface soil has looser structures and well permeability because of farming. The average permeability coefficient of the saline-alkali soil without surface soil is only 1.95×10^{-6} cm/s, in which water permeability belongs to microporous water or extremely microporous water in accordance with code for engineering geological investigation of water resources and hydropower [24].

3.2. Porosity of the Local Saline-Alkali Soil. To analyze porosity of the local saline-alkali soil, soil specimens are prepared by LGJ-12N liquid nitrogen vacuum freeze-drying machine for mercury intrusion test using PM-33-18 fully automatic mercury intrusion porosimetry made in the US.

3.2.1. Volume Ratios of Pores. The volume ratio of pores is the ratio of stage cumulative mercury intrusion and complete cumulative mercury intrusion from test, and volume ratios of pores of soil samples in the surface layer and depth of 10, 20, 30, 40, 50, and 60 cm of regional saline-alkali soil are shown in Table 1.

Average volume ratio of pores whose diameters are all no more than $2 \mu\text{m}$ is 86.25% and that of surface soil is lower, which states that pores of the local saline-alkali soil are mainly constructed with micropores and ultramicropores.

That is to say, intergranular pores and intragranular pores are the main bodies [25]; therefore, the permeability could be extremely weak.

3.2.2. Void Ratio. By using mercury intrusion porosimetry, void ratios of the local saline-alkali soil at depths of 0, 10, 20, 30, 40, 50, and 60 cm are shown in Table 2.

Apart from void ratio of surface soil, which is higher due to farming, void ratios increase with underground depth up to 60 cm, but are almost not beyond 0.500.

3.3. Dry Density of the Local Saline-Alkali Soil. Distribution of dry densities of the local saline-alkali soil is coupling with that of void ratios, as shown in Table 3.

Apart from dry density of surface soil, which is lower due to farming, the dry densities decrease with underground depth up to 60 cm, but are all beyond 1.600 g/cm^3 .

3.4. Mineral Composition of the Saline-Alkali Soil. Mineral composition of the local saline-alkali soil is studied by using TD-3500 X-ray diffractometer, as shown in Table 4.

Because the average ratio of clay minerals of illite, kaolinite, and chlorite is only 12.24%, the saline-alkali soil in the study area does not have typical clay properties; that is to say, clay minerals are not the main reason for poor water permeability of the saline-alkali soil.

3.5. Compact Structure of the Saline-Alkali Soil. After preparing soil samples by the liquid nitrogen vacuum freeze-drying method and processing them by IB-5 ion sputtering instrument, scanning pictures of the local saline-alkali soil at depths of 0, 10, 20, 30, 40, 50, and 60 cm have been received by FEI Quanta250 high- and low-vacuum scanning electron microscope in the US. Scanning pictures enlarged 1000 times are shown in Figure 2.

In microscopic space, the local saline-alkali soil may be with compact structure and extremely weak permeability, among which developing degree of the surface soil is only lower. Water infiltration passageway will mainly depend on slightly developing fracture in the local saline-alkali soil, especially the surface soil; hence, there should not be typical interflow in it.

4. Surface Runoff Mechanism and Water-Salt Migration Rule of the Local Saline-Alkali Soil

In research area of the saline-alkali soil in the Yellow River Delta, the weather from July to December 2018 was mainly cloudy, so little precipitation would return to the atmosphere due to ground evaporation. Surface soil is easy to form saturated layer because of its relatively developed fractures, looser structures, developed pores, and well permeability. The other parts of the soil will not present typical interflow because of compact structures, limited fractures, and weak permeability. In the studying period, each saturated state of surface soil was followed with a heavy rainfall which increased the surface runoff coefficient. Therefore, the

TABLE 1: Volume ratios of pores of the local saline-alkali soil (%).

Pore diameter (μm)	Depth of soil specimen (cm)							Average volume ratio (%)
	0	10	20	30	40	50	60	
$d \geq 20$	9.67	8.82	4.61	3.42	6.38	3.58	2.39	13.75
$10 \leq d < 20$	10.30	1.56	1.32	2.15	2.16	0.76	0.49	
$2 \leq d < 10$	13.03	1.35	0.37	1.37	4.39	9.28	8.88	
$0.1 \leq d < 2$	46.02	34.02	44.26	39.93	47.81	46.77	51.41	86.25
$d < 0.1$	20.98	54.25	49.44	53.13	39.26	39.61	36.83	

TABLE 2: Void ratios of the local saline-alkali soil.

Depth (cm)	Void ratio
0	0.536
10	0.243
20	0.263
30	0.257
40	0.331
50	0.353
60	0.511

TABLE 3: Dry densities of the local saline-alkali soil.

Depth (cm)	Dry density (g/cm^{-3})
0	1.671
10	2.025
20	1.955
30	1.998
40	1.849
50	1.795
60	1.651

surface runoff mode is slope flow above saturated layer and without miscible flow.

If the permeability of the middle and lower saline-alkali soil is very weak, the water could not carry salt to deeper area. However, the surface soil will immediately produce surface runoff if it meets a heavy rainfall when it is in saturated state, which would migrate together with salt.

5. Salt-Discharging Engineering Model for the Local Saline-Alkali Soil

The surface soil will produce surface runoff after being saturated and the other parts may be with compact structures, poor permeability, and lack of interflow, so the salt-discharging engineering model considering mainly surface runoff, auxiliary infiltration, and no interflow is constructed for the local saline-alkali soil, in which the slope of open pitch is designed as 3~5‰, as shown in Figure 3. Salt in the surface soil will be carried to the open pitch by surface runoff, which would significantly reduce its salt content.

6. Distribution of Salt Contents of the Local Saline-Alkali Soil

6.1. Relationship between Salt Content and Conductivity of the Local Saline-Alkali Soil. Sampling 84 specimens of the saline-alkali soil with deep positions ranging from 0 to

1000 mm was performed 3 times (2018.08.13; 2018.11.07~11.08; 2018.11.30~12.01); salt contents of 42 samples of these are determined using the drying method; and relationship between salt content and conductivity is shown in Figure 4.

Equation (1) was established by fitting relationship between salt content and conductivity of the local saline-alkali soil, based on which salt contents of the other soil samples will be determined only by testing their conductivities:

$$y = -0.00186 + 2.74139x \approx 2.74x. \quad (1)$$

In the formula, correlation coefficient is 0.9967, y is the salt content (%), and x is the conductivity (mS/mm).

6.2. Relationship between Salt Content and Depth of the Local Saline-Alkali Soil. Based on the experiment, the salt content of samples was measured, and the relationship between the salt content and the depth of saline-alkali soil was established, as shown in Figure 5.

Salt contents of the local saline-alkali soil decrease with increasing depths and will tend towards steady level when its depth reaches 60 cm; therefore, the depth of salt-discharging engineering such as open pitch should be deeper than 60 cm.

7. Engineering Application of the Salt-Discharging Model

The designing depth of open pitch is 60 cm which is used to verify the applied effectiveness of the salt-discharging engineering model, as shown in Figure 6.

7.1. Lower and Steady Salt Contents in the Middle and Lower Area of the Saline-Alkali Soil. Salt contents of the middle and lower area of the saline-alkali soil were lower and steady in the studying period (Figure 5), which states that rainfall cannot produce typical infiltration and interflow, so there is no salt-discharging effect on the soil. Meanwhile, compact structure and poor permeability of the middle and lower area of the saline-alkali soil have been verified, and the salt-discharging engineering model having mechanisms of auxiliary infiltration and no interflow is suitable.

7.2. Significantly Decreased Salt Contents in the Surface Soil. Corresponding with distribution of daily rainfalls from national rainfall recording stations (2018, Guangrao County, Dongying City, Shandong Province, China), 3 times of sampling dates and 2 times of saturated soil dates are marked, as shown in Figure 7.

TABLE 4: Proportions of minerals of the local saline-alkali soil (%).

Mineral	Depth of soil specimen (cm)							Average proportion (%)
	0	10	20	30	40	50	60	
Quartz	53.6	55.1	43.4	44.2	51.9	60.9	50.8	51.43
Calcite	14.3	17.0	11.6	19.1	15.8	13.6	13.9	15.04
Orthoclase	0	4.3	2.6	7.1	3.6	5.3	3.1	3.71
Kozulite	0	1.3	0	0	0	0	2.1	0.48
Albite	19.1	7.7	32.6	19.4	15.7	11.7	10.7	16.69
Hematite	0.8	0.9	0	0	0	0	1.2	0.41
Illite	7.4	9.7	3.8	5.7	8.3	6.2	9.1	7.17
Kaolinite	3.3	1.5	3.1	1.6	2.5	0.6	7.1	2.81
Chlorite	1.5	2.5	2.9	2.9	2.1	1.8	2.1	2.26

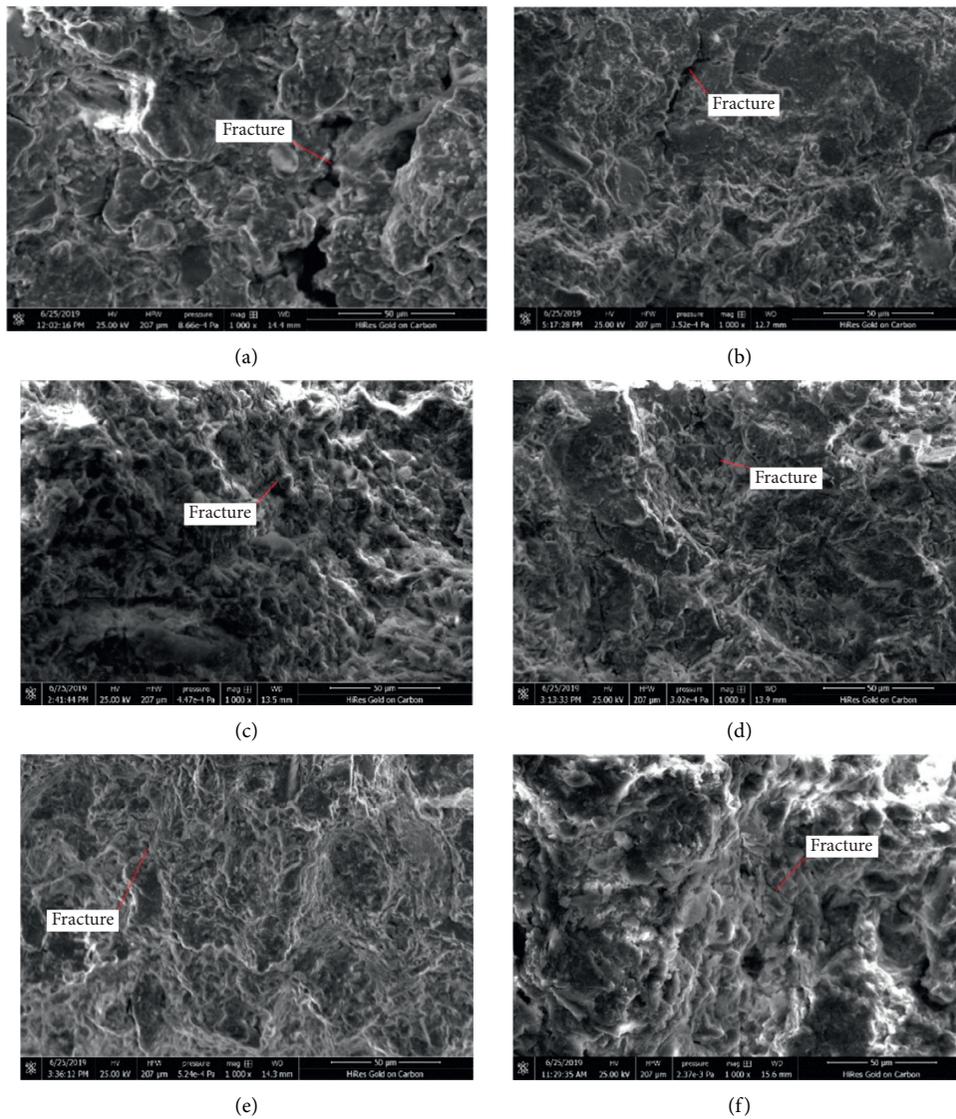
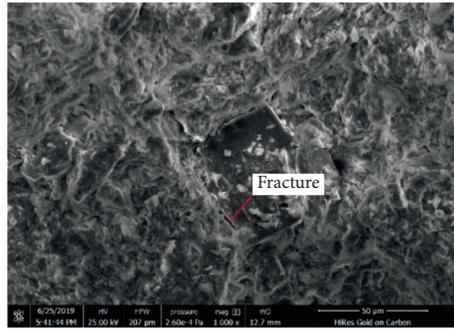


FIGURE 2: Continued.



(g)

FIGURE 2: Scanning pictures of the local saline-alkali soil (enlarge 1000 times). (a) Surface soil. (b) Soil at depth 10 cm underground. (c) Soil at depth 20 cm underground. (d) Soil at depth 30 cm underground. (e) Soil at depth 40 cm underground. (f) Soil at depth 50 cm underground. (g) Soil at depth 60 cm underground.

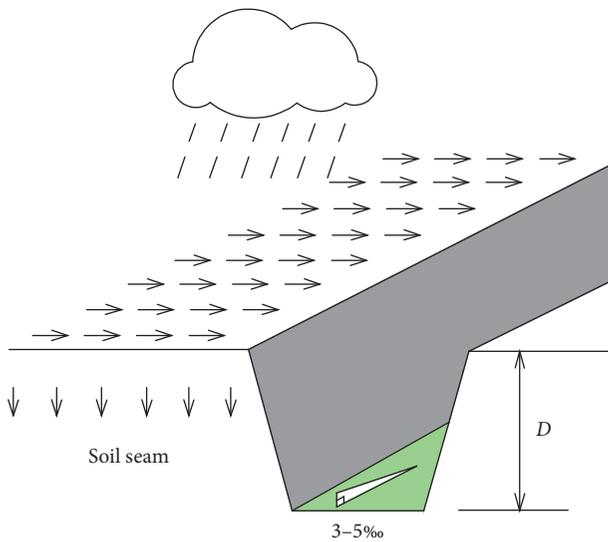


FIGURE 3: Sketch of the salt-discharging engineering model.

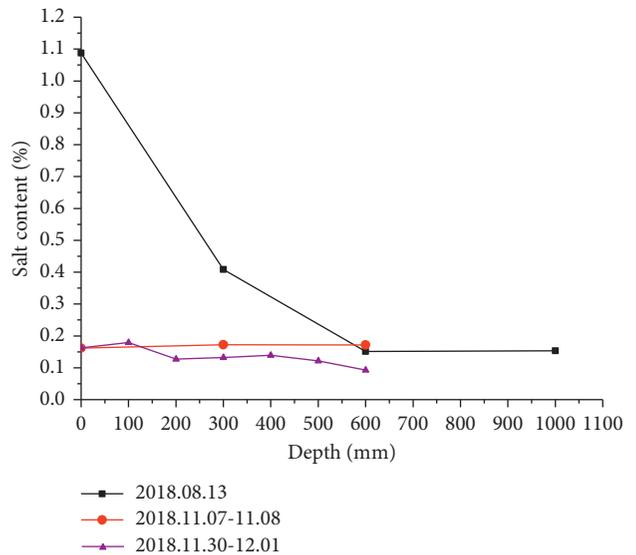


FIGURE 5: Relationship between salt content and depth of the saline-alkali soil.

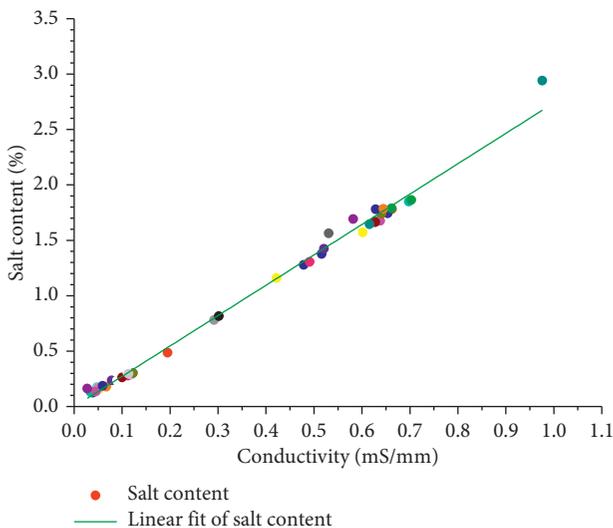


FIGURE 4: Relationship between salt content and conductivity of the local saline-alkali soil.

Analyzing daily rainfalls we have found that the local saline-alkali soil has presented 2 times (before August 13 and before August 30) of surface saturated states from July to December, in 2018, each time with a heavy rainfall, which are the adequate and necessary conditions to produce surface runoff. Salt contents of samples of the surface saline-alkali soil decrease significantly (Figure 5) after 2 times of surface runoff actions on saturated soil layer. Obvious salt-discharging effectiveness verifies that surface saline-alkali soil has looser structure, well permeability, and developed pores, and the salt-discharging engineering model mainly considering surface runoff is correctable.

7.3. Auxiliary Evidences of the Salt-Discharging Model Dominated by the Surface Runoff. In Figure 7, the sampling period between the second date and the third date is 23 days (2018.11.08–2018.11.30), and rainfall is only 23 mm and not concentrated. Obviously, there is no surface runoff in the

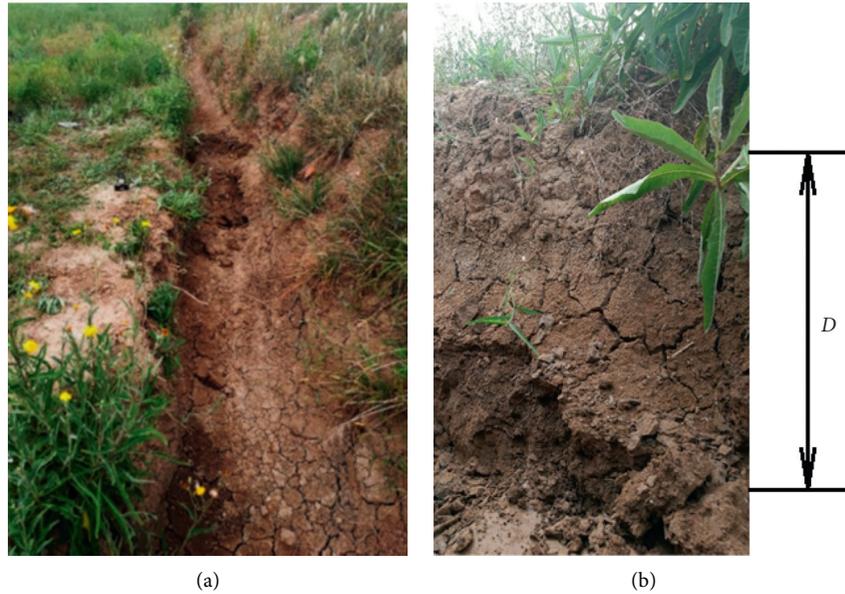


FIGURE 6: Open pitch used in salt-discharging field.

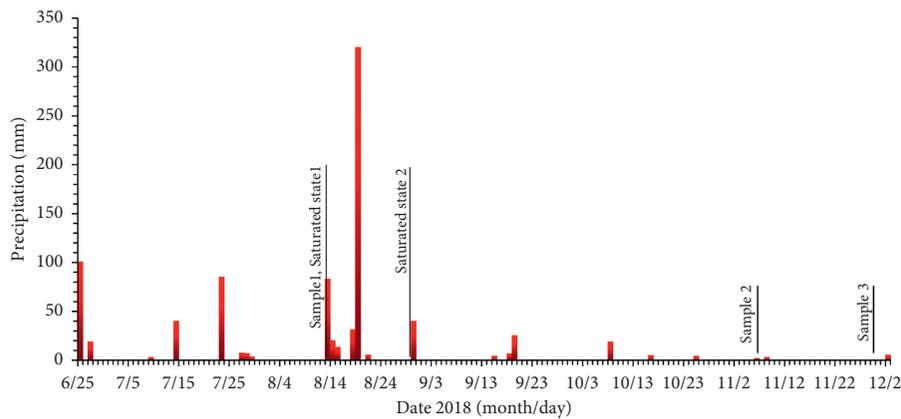


FIGURE 7: Daily rainfalls in the local saline-alkali soil (2018).

period, and the difference of salt contents between the two soil samples is very small (Figure 5), which indirectly proved that surface runoff is the determined reason for salt-discharging methods, and the salt-discharging engineering model would be suitable to manage the local saline-alkali soil.

8. Main Conclusions

- (1) Structural characteristics of the local saline-alkali soil in the Yellow River Delta region are compact structures and slightly developed fractures, which mainly consisted of micropores and ultramicropores, lower void ratios, higher dry densities, lack of clay minerals, and micropore and extremely micropore water.
- (2) The surface runoff mode of the local saline-alkali soil is slope flow above saturated layer and without miscible flow; therefore, salt in the surface soil would be carried to open pitch by surface runoff and that in the other parts of the soil must not migrate.
- (3) The salt-discharging engineering model considering mainly surface runoff, auxiliary infiltration, and no interflow was established based on structural characteristics, mechanisms of surface runoff, and water-salt migration.
- (4) Salt contents of experimental samples in the local saline-alkali soil region decrease with increasing depths, so the depth of the salt-discharging engineering of open pitch should not be beyond 60 cm.
- (5) The relationship between rainfall and salt content shows that salt contents in the middle and lower soil are lower and steady. In the surface of the saline-alkali soil, the salt contents decrease significantly after two times of surface runoff, and the salt contents did not change without surface runoff, and it is directly or indirectly proved that the salt-discharging

engineering model is suitable for managing the local saline-alkali soil.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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