

Water-salt transport characteristics of saline soil under hydraulic remediation measures in the Yellow River Delta region of China

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Abstract: To understand the water-salt transport process of saline soils in the Yellow River Delta region under traditional hydraulic remediation measures and to determine its engineering parameters, this study made laboratory investigations to measure the soil salt content using three remediation practices under simulated rainfall conditions. The results indicated that under the rainfall intensity of 100 mm/h, 6-8 h are needed for the soil salt content to tend to be constant. The distribution of the salt content presents a typically symmetrical shape regardless of the position of the saline soil relative to the concealed pipe, the open ditch, or the vertical shaft. The two-parameter exponential function indicates the relationship between the soil desalination rate and the horizontal distance from the pipe, ditch, or shaft. The maximum spacings to build the salt drainage engineering projects of the concealed pipe, open ditch, or vertical shaft in the laboratory are 4.79 m, 2.88 m, and 2.19 m, respectively. The effectiveness of salt drainage for coastal saline soils can be ranked from highest to lowest as first the concealed pipe, then the open ditch, and finally the vertical shaft. The findings provide an experimental basis and reference for the application of hydraulic measures to remediate saline soils in this region.

Keywords: water-salt transport, hydraulic measures, saline soil, Yellow River Delta

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1 Introduction

Food is essential to human civilization, but its production has been restricted by the decreasing area and deteriorative quality of cultivated land, especially saline soil, lack of water resources, and desertification^[1,2]. Food security influences the harmonious relationship between humanity and the earth, as well as sustainable development. Therefore, saline land treatment, as an effective approach to improve the quality and area of cultivated land, is essential to agricultural and civil engineering. Through the experience of about fifty years of saline land treatment practices, many remediation methods have been developed, including chemical, physical, biological, and engineering technology^[3-6]. Among these, engineering restoration is the most common and useful approach, especially suitable in terms of managing the coastal saline land.

Traditional engineering measures to improve saline land include laying concealed pipes, digging open ditches, drilling vertical shafts, and building platform fields^[7]. In the 17th century, water drainage technology by concealed pipe originated in England, and it was later applied and developed in the Netherlands and the United States^[8-11]. In the early 20th century, this technology was

introduced to Japan, and within the first half of the same century, it had been popularized in the United States, the Soviet Union, the Netherlands, Czechoslovakia, Poland, Egypt, Pakistan, Turkey, and China^[12]. Saline soil will suffer from salinization for the second time because of the raised ground water level; therefore, according to Li et al.^[13], the groundwater level can be controlled artificially to prevent secondary salinization by laying concealed pipes under the saline soil^[13]. With the experiment of large-scale application of the concealed pipe, Yang^[14] treated the saline land in the Yellow River Delta, achieving a remarkable outcome. Through the experiment of the concealed pipe under drip irrigation covered with mulch, Shi et al.^[15] found that this water drainage technology contributes to irrigation in the saline land of Xinjiang. According to Shao et al.^[16], the water drainage technology of the concealed pipe is conducive to the migration of salt in new coastal reclamation areas with an obvious effect of desalination. Studying the application of water drainage technology by concealed pipe in paddy fields of coastal saline land, Wei et al.^[17] found that this technology can significantly reduce the groundwater level, salinity, and salt content. Based on the experiment of the leakage in the paddy field of coastal saline land of Jiangsu Province, Zhou et al.^[18] found that the water drainage technology by concealed pipe improved the soil structure characteristics, increased the content of available phosphorus, and decreased the salt content. Smedema^[19] found that the salt content in soil can meet the security growth need of crops even when the buried depth of the concealed pipe is reduced to a certain extent. With Hydroluis model, Bahçeci et al.^[20] found that the desalination effect to soil was almost the same when the buried depth of the concealed pipe was 1.2 m and 1.5 m, respectively. Through a long-term water drainage experiment of the concealed pipe in the Yinbei irrigation district of Ningxia and the Hetao irrigation district of Inner Mongolia, Wang^[21], Jing, and Liu^[22] observed that this

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technology is conducive to large-area farmland improvement, significant desalination effect, and obvious crop yield increase. According to Ritzema et al.^[23], under different agroclimatic conditions in India, the water drainage technology of the concealed pipe, combined with digging the open ditch, could reduce the groundwater level and the salt content and improve crop yield when its buried depth ranges from 0.9-1.2 m. Through a salt-exchanging experiment between bottom mud and water in the open ditch, Pan et al.^[24] found that this engineering technology has a positive effect on water and salt transport. After simulating water and salt migration in soil under open-ditch water drainage technology, Li et al.^[25] found that it can promote the discharge of soil salt. Based on Chen et al.^[26], this open-ditch technology can significantly reduce the soil salinity. Through engineering examples, Jiang et al.^[27] proved that water drainage technology using a vertical shaft can effectively reduce groundwater level. However, few literature reviews have comprehensively discussed hydraulic engineering parameters combined with measures of open trenches, shafts, and concealed pipes.

The Yellow River Delta is a plain formed by a large amount of sediment carried from the middle and upper reaches of the river. Its realignments in history have given rise to a fragile ecological environment. To compound this situation, large saline lands seriously hinder agricultural development. The saline land in the Yellow River Delta is a typical coastal region, the scientific exploitation and management of which is a national strategy in China^[28]. Pore space and permeability are both physical properties of the saline soil, and these structural characteristics have been related to its management^[29]. Previous studies have shown that the application of additives such as biochar, which is obtained from the slow and high-temperature decomposition of biomass in anaerobic environments, and Yellow River sediment can better improve the physical properties of the soil in the Yellow River Delta^[30,31]. However, in the long term, hydraulic measures are still the main means of saline soil remediation in the region. Moreover, existing research on traditional engineering measures to manage the coastal saline land is insufficient to determine field parameters scientifically.

Based on the traditional leaching experiments of the soil tank, this study analyzes the impact of salt drainage engineering measures, including the concealed pipe, the open ditch, and the shaft, on soil desalination rate, which will be applied to determine scientific engineering parameters.

Specifically, the objectives of the study are 1) to explore the water and salt movement process of saline soil under the traditional water conservancy remediation measures; 2) to compare the soil desalination rate under the treatments of concealed pipe, open ditch, and shaft; and 3) to determine the maximum laboratory spacing of concealed pipe, open ditch, and shaft.

2 Materials and methods

2.1 Saline soil of the coastal zone

Soil specimens in the experiment were taken from Coastal New District in the Yellow River Delta facing the Bohai bay, located in Guang-Rao County, Dongying City, Shandong Province of China. The area of study is about 1.0 m above sea level and 40 km away from the coastline. As shown in Figure 1 (118°45'37"E, 37°17'41"N), the soil salinization is serious. Soil sampling depth was 0-20 cm in the field, which is disturbance soil, while specimens in the laboratory were sampled with soil drill according to the experimental plan. After passing through a 2-mm sieve, the soil texture was proved to be loam via analyzing the composition of soil

particles with the laser particle analyzer (Dandong Baite Instrument Co., Ltd, China), which is an instrument for analyzing the size through diffraction or scattering spectrum of particles. According to the original conductivity measured by the conductivity meter (Shanghai Yifen Scientific Instrument Co., Ltd, China) and the calibration relationship^[32] which is between conductivity and salt content, the salt contents of the saline soils were all beyond 1.0%, and therefore are typical coastal saline soils.



Figure 1 Soil sampling zone (118°45'37"E, 37°17'41"N)

2.2 Experimental design

Experiments were carried out in the laboratory of geotechnical engineering and soil physics of Shandong Agricultural University, focusing on the relationship between rainfall time and salt content of the saline soil. In addition, the effectiveness and engineering parameters of traditional hydraulic remediation measures including concealed pipe, open ditch, and vertical shaft were studied. Infiltration, soil flow, and surface runoff are main movement types of water in soil under rainfall, which were considered in these tests^[33,34].

2.2.1 Experiment on the relationship between rainfall time and salt content

The length×width×height of the soil tank manufactured with organic glass was 120 cm×40 cm×30 cm. The saline soil with a bulk density of 1.46 g/cm³ was filled in layers into the soil tank. The upper soil material was 20 cm thick, the lower soil layer was 5 cm thick, and the middle layer was the large porosity material with a particle size of 4.75-9.50 mm and thickness of 5 cm. To avoid the impact of groundwater level on soil specimen, uniform water drainage holes were drilled at the bottom of the soil tank. To simulate the leaching experiment, we employed the MSR-S20-W1000 (1500) portable artificial rainfall simulator (Shandong Agricultural University, China) with its rainfall intensity designed as 100 mm/h. The experimental model to study the relationship between rainfall time and salt content of saline soil is shown in Figure 2.



Figure 2 Experimental model of the relationship between rainfall time and salt content

In the process of experimental rainfall, soil specimens at different depths of 0-5 cm, 10-15 cm, and 15-20 cm were sampled at regular intervals to determine the salt content with an initial value of 2.12%. Based on the salt contents of samples determined with the drying method, the relationship between salt content and conductivity was established to obtain the salt contents of the other saline soils only by testing their conductivities. Conductivity was measured with the conductivity meter (Shanghai Yifen Scientific

Instrument Co., Ltd, China).

2.2.2 Leaching experiment of saline soil by concealed pipe

The length×width×height of the soil tank manufactured with organic glass was 100 cm×50 cm×70 cm. The overflow hole was set at 10 cm from the top of the soil tank, and the outlet hole was set at 5 cm from its bottom. The concealed pipe was manufactured by PVC pipe with a diameter of 90 mm, while its side was symmetrically and evenly drilled with round holes with diameters of 4 mm. If the opening rate is defined as the ratio of the round hole area to the side area of the concealed pipe, it will be set at 9%. Two layers of permeable absorbent gauze were wrapped around the outer concealed pipe, which is not only a filter layer, but also can eliminate hole blockage. Buried in the center of the soil tank in the horizontal direction, the concealed pipe has a slope of 2% and holes at both ends. The filling soil layer in the soil tank was 60 cm thick, and the concealed pipe was buried at 50 cm depth in the vertical direction. The rainfall intensity of the leaching experiment was designed at 100 mm/h. Figure 3 shows the experimental model of saline land treatment with the concealed pipe.



Figure 3 Experimental model of concealed-pipe water drainage technology

In the horizontal direction, 9 sampling points were taken symmetrically to the concealed pipe with a spacing of 10 cm. In the vertical direction, specimens were sampled at the depths of 10 cm, 20 cm, 30 cm, and 40 cm, respectively. The outlet hole was blocked at 5 cm from the bottom, until the saline soil is saturated under leaching, which was marked as 0 time for the first sampling with soil drill. Therefore, the initial salt content was generally low. After the first sampling, outlet holes were all opened and the leaching system continually worked. Once the salt drainage effect tended to be stable, another sampling was taken at the same position of the previous one. Through comparing the salt content measured at different samplings with the initial value, the desalination rate could be calculated.

2.2.3 Leaching experiment of saline soil by open ditch

The length×width×height of the soil tank manufactured with organic glass was 100 cm×50 cm×60 cm. The depth of the open ditch was 50 cm with a 60° slope angle, and the width of the ditch top was 50 cm. The filling height of soil was 50 cm in the tank. Several outlet drainage holes were at the bottom of the open ditch. In addition, two layers of permeable absorbent gauze were covered on the soil slope surface, ensuring its stability during the leaching experiment. The rainfall intensity of the leaching system was set at 100 mm/h. Figure 4 shows the experimental model of saline land treatment by the open ditch engineering.



Figure 4 Experimental model of open-ditch water drainage technology

In the horizontal direction, soil specimens were sampled 10 cm away from the soil slope top with a spacing of 10 cm, while in the

vertical direction, sampling points were taken from the slope top with the same spacing. When the saline soil was saturated in the soil tank under leaching, it was marked as 0 time for the first sampling, leading to a generally low initial salt content. After the first sampling, outlet drainage holes were opened and the leaching system continually worked. When the salt drainage effect tended to be constant, another sampling was taken at the same position of the previous one. Through comparing the newly measured salt content with the initial value, the desalination rate could be calculated.

2.2.4 Leaching experiment of saline soil by vertical shaft

The length×width×height of the soil tank manufactured with organic glass was 60 cm×60 cm×60 cm. The shaft was manufactured by PVC pipe with a diameter of 90 mm, and the opening rate was set at 9%. The vertical shaft was placed in the center of the soil tank and fixed along the joint with glass glue. Small holes were drilled in the scope of the shaft at the bottom of the soil tank for water and salt drainage. The height of the filling soil in the tank was 50 cm and the rainfall intensity of the leaching system was 100 mm/h. Figure 5 shows the experimental model of saline land treatment by the vertical shaft engineering.

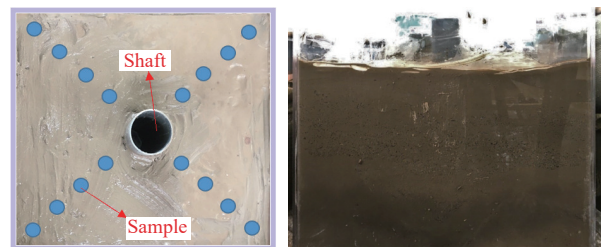


Figure 5 Experimental model of vertical-shaft water drainage technology

In the horizontal direction, soil specimens were taken along the diagonal line of the soil tank with a spacing of 10 cm, while in the vertical direction, specimens were sampled at a depth of 10 cm. The time condition of the first sampling, the working time of the leaching system, the time of additional sampling, and the sampling method are all the same as those in the section on the open-ditch technology.

2.3 Data analysis

Site layout of the hydraulic measures, including concealed pipe, open ditch, and vertical shaft, depended on their salt drainage effect in laboratory. When the soil desalination rate tends toward zero, the corresponding horizontal distance from the concealed pipe, open ditch, and vertical shaft is the maximum radius that can achieve the effect of soil remediation. In this study, the maximum radius is defined as the horizontal distance from the concealed pipe, open ditch, and vertical shaft where the soil desalination rate is 0.1%.

By fitting experimental data, the relationship between the soil desalination rate and the horizontal distance from the concealed pipe, open ditch, and vertical shaft can be expressed by a two-parameter exponential function:

$$\eta = ab^x \tag{1}$$

where, η is the soil desalination rate, %; x is the horizontal distance from the concealed pipe, open ditch and vertical shaft, cm; a and b are empirical constant parameters.

3 Results

3.1 Relationship between rainfall time and salt content of saline soil

During the leaching experiment with rainfall intensity of

100 mm/h, the salt content of soil specimens at depths of 0-5 cm, 5-10 cm, 10-15 cm, and 15-20 cm were measured. The variation relationships of the salt content in different soil layers with time could be found, as shown in Figure 6.

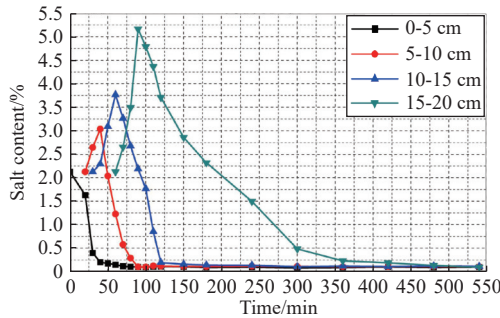


Figure 6 The relationship of salt content with time

Only the salt content (2.12%) in the surface layer (0-5 cm) decreased rapidly with rainfall time. Although the salt content in the deep layer increased first and then decreased with rainfall time, the peak value of the salt content increased along with the increase of the depth of the soil layer, since salt moves with water. In other words, the salt in the upper soil layer moved with water down towards the lower layer under the leaching effect, resulting in the initial accumulation of salt in the deep soil layer. With continuous rainfall leaching, the ultimate salt content of the soil was reduced to near zero. Under the rainfall intensity of 100 mm/h, it took about 6-8 hours for the salt drainage effect of the typical saline soil to stabilize, which is an important basis for designing experiments to control saline land with engineering measures.

3.2 Water and salt migration process in saline land treatment with concealed pipe

Under the rainfall intensity of 100 mm/h, the 6-hour leaching experiment was carried out with the concealed pipe with a diameter of 90 mm and opening rate of 9%. Table 1 lists the recorded data of the salt content in the concealed pipe experiment, while Figure 7 illustrates the relationship between the salt content of saline soil and the horizontal distance from the concealed pipe.

Because the salt drainage efficiency of the concealed pipe decreased with the increase of the horizontal distance from the pipe, the salt content distribution in the saline soil above the concealed

pipe presented a typically symmetrical shape. The shorter the horizontal distance from the pipe at the different depths of 10 cm, 20 cm, 30 cm, and 40 cm, the higher the salt drainage efficiency. Therefore, the salt content of every soil layer was the lowest near the pipe, which were 0.06%, 0.08%, 0.09%, and 0.13%, respectively.

Table 1 Experimental data of salt content with concealed-pipe technology (%)

Leaching/h	Depth/cm	Horizontal distance from pipe/cm								
		-40	-30	-20	-10	0	10	20	30	40
0	10	0.12	0.11	0.12	0.12	0.12	0.12	0.11	0.13	0.13
	20	0.14	0.13	0.14	0.13	0.15	0.13	0.13	0.16	0.17
	30	0.24	0.18	0.18	0.16	0.19	0.17	0.18	0.18	0.21
	40	0.33	0.34	0.36	0.27	0.27	0.27	0.29	0.33	0.38
6	10	0.10	0.08	0.07	0.07	0.06	0.07	0.07	0.09	0.10
	20	0.13	0.10	0.10	0.08	0.08	0.09	0.09	0.12	0.15
	30	0.21	0.14	0.12	0.09	0.09	0.11	0.12	0.14	0.17
	40	0.31	0.25	0.24	0.17	0.13	0.16	0.20	0.26	0.33

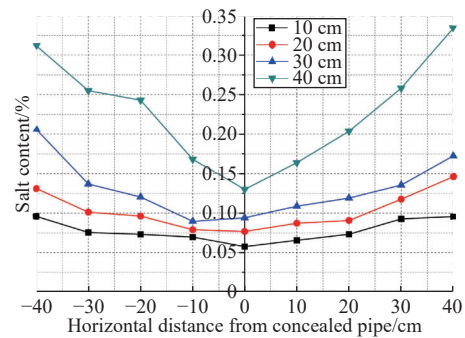


Figure 7 The symmetrical shape of salt content with concealed-pipe technology

3.3 Water and salt migration process in saline land treatment with open ditch

Under the rainfall intensity of 100 mm/h, the 8-hour leaching experiment was carried out with open ditch whose slope angle was 60°. Table 2 lists the salt content by experiment of saline land treatment with open ditch, and the relationship between the salt content and the horizontal distance is as shown in Figure 8.

Table 2 Experimental data of salt content with open-ditch technology (%)

Leaching/h	Depth/cm	Horizontal distance from ditch/cm																			
		15.77	21.55	25.77	27.32	31.55	33.09	35.77	37.32	41.55	43.09	45.77	47.32	51.55	53.09	55.77	57.32	61.55	63.09	67.32	73.09
0	10	0.34	--	0.34	--	--	--	0.34	--	--	--	0.33	--	--	0.32	--	--	--	--	--	--
	20	--	0.37	--	--	0.37	--	--	0.37	--	--	--	0.37	--	--	--	0.37	--	--	--	--
	30	--	--	--	0.38	--	--	--	0.39	--	--	--	0.41	--	--	0.39	--	--	--	0.39	--
	40	--	--	--	--	--	0.44	--	--	0.44	--	--	--	0.43	--	--	0.43	--	--	0.43	0.42
8	10	0.14	--	0.20	--	--	--	0.21	--	--	--	0.25	--	--	0.28	--	--	--	--	--	--
	20	--	0.21	--	--	0.31	--	--	0.33	--	--	--	0.34	--	--	0.35	--	--	0.35	--	--
	30	--	--	--	0.27	--	--	--	0.33	--	--	--	0.35	--	--	0.36	--	--	0.36	--	--
	40	--	--	--	--	--	0.31	--	--	0.39	--	--	--	0.45	--	--	0.46	--	--	0.46	0.49

As the soil desalination rate decreased with the increase of horizontal distance from the ditch, the salt content distribution in the saline soil on the side of open ditch presented a typically symmetrical shape. The shorter the horizontal distance from the ditch at the different depths of 10 cm, 20 cm, 30 cm, and 40 cm, the higher the salt drainage efficiency. Thus, the salt content of every soil layer was the lowest near the ditch, which were 0.14%, 0.21%, 0.27%, and 0.31%, respectively.

3.4 Water and salt migration process in saline land treatment with vertical shaft

Under the rainfall intensity of 100 mm/h, the 6-hour leaching experiment was carried out with vertical shaft with a diameter of 90 mm and opening rate at 9%. Table 3 lists the experimental results of the salt content in saline land treatment with the shaft while Figure 9 presents the relationship between the salt content and horizontal distance from the shaft.

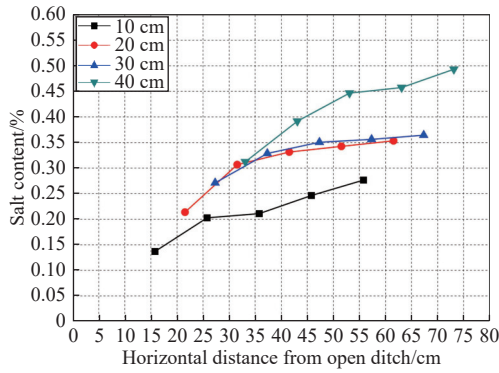


Figure 8 The semi-symmetric shape of salt content with open-ditch technology

Table 3 Experimental data of salt content with vertical-shaft technology (%)

Leaching/h	Depth/cm	Horizontal distance from shaft/cm				
		5	10	15	20	25
0	10	0.37	0.38	0.37	0.37	0.38
	20	0.40	0.40	0.40	0.39	0.40
	30	0.44	0.46	0.44	0.43	0.44
	40	0.50	0.52	0.52	0.51	0.52
6	10	0.21	0.23	0.25	0.27	0.30
	20	0.25	0.28	0.32	0.33	0.36
	30	0.28	0.33	0.37	0.38	0.40
	40	0.38	0.42	0.44	0.48	0.53

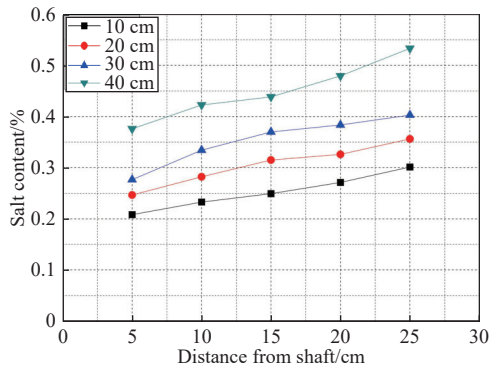


Figure 9 The semi-symmetric shape of salt content with vertical-shaft technology

The salt drainage efficiency of the shaft decreased with the increase of the horizontal distance from the shaft, resulting in a typically symmetrical shape for the salt content distribution in the saline soil around the shaft. The shorter the horizontal distance from the shaft at the different depths of 10 cm, 20 cm, 30 cm, and 40 cm, the higher the salt drainage efficiency. Hence, the salt content of every soil layer was the lowest near the shaft, which were 0.21%, 0.25%, 0.28%, and 0.38%, respectively.

3.5 Determination of engineering parameters for coastal saline land treatment

The fitting parameters of Equation (1) to soil desalination rate data are listed in Tables 4-6. All the coefficients of determination are in the range of 0.60 to 0.98, indicating that there is a good exponential relationship between the soil desalination rate and the horizontal distance. Mean radiation radius values generally followed the sequence of concealed pipes>open ditch>shaft. The maximum radiation radii were 2.39 m for concealed pipes (Table 4), 1.44 m for open ditch (Table 5), and 1.09 m for shaft (Table 6). Thus, the maximum spacings of laying the concealed pipes, open

ditch, and shaft can be calculated as 4.79 m, 2.88 m, and 2.19 m, respectively.

Table 4 Fitting functions of experimental data by concealed-pipe method

Depth/cm	Monitoring location	Function	Correlation (R^2)	Radius of salt drainage effect at $\eta_1 = 0.1\%/cm$	
				x	Average radiation radii/cm
10	Left	$\eta_1 = 0.52192 \times 1.02165^x$	0.82338	-292.15	321.63
	Right	$\eta_1 = 0.50278 \times 0.98244^x$	0.98182	+351.10	
20	Left	$\eta_1 = 0.51565 \times 1.03342^x$	0.91383	-189.98	204.76
	Right	$\eta_1 = 0.48219 \times 0.97225^x$	0.86107	+219.54	
30	Left	$\eta_1 = 0.55042 \times 1.03025^x$	0.94728	-211.76	226.28
	Right	$\eta_1 = 0.51008 \times 0.97444^x$	0.94224	+240.79	
40	Left	$\eta_1 = 0.52795 \times 1.03145^x$	0.82745	-202.45	204.51
	Right	$\eta_1 = 0.53209 \times 0.97007^x$	0.97855	+206.56	

Table 5 Fitting functions of experimental data by open ditch method

Depth/cm	Function	Correlation (R^2)	Radius of salt drainage effect at $\eta_2 = 0.1\%/cm$	
			y	Average
10	$\eta_2 = 0.96114 \times 0.96978^y$	0.92672	223.82	143.77
20	$\eta_2 = 1.92735 \times 0.93154^y$	0.94329	106.66	
30	$\eta_2 = 0.78891 \times 0.96225^y$	0.90738	173.35	
40	$\eta_2 = 42.6190 \times 0.86104^y$	0.60208	71.25	

Table 6 Fitting functions of experimental data by vertical-shaft method

Depth/cm	Function	Correlation (R^2)	Radius of salt drainage effect at $\eta_3 = 0.1\%/cm$	
			z	Average
10	$\eta_3 = 0.53011 \times 0.96638^z$	0.96655	183.43	109.26
20	$\eta_3 = 0.52500 \times 0.93945^z$	0.98416	100.28	
30	$\eta_3 = 0.53892 \times 0.92859^z$	0.97180	84.89	
40	$\eta_3 = 0.40376 \times 0.91606^z$	0.77649	68.45	

4 Discussion

In this study, the ratio of soil particles with 0.002-0.200 mm was 91.74%, which is a dominant arrangement of the typical coastal soil; therefore, the soil texture is loam according to the international soil texture grading standard^[35], characterized by poor permeability. Besides, the bulk density of the saline soil was 1.46 g/cm³, which indicates a negative impact of its compact structure on aeration. By permeability experiments of soil column and variable water heads, the permeability coefficient of the saline soil was found to be 2.40×10^{-5} cm/s, which belongs to weak permeability grade^[29]. This study found that it took 6-8 h for the salt drainage effect to be stable with only 20 cm thickness of soil, which proves the weak permeability of the typical saline soil.

The main movement types of water in soil include infiltration, soil flow, surface runoff, and even preferential flow under rainfall^[32,34]. In this study, free surface of water and salt migration took place under the saline soil for the concealed pipe, on the side for the open ditch, on the cylindrical surface for the shaft, and on the ground surface for each condition. By studying buried depths of 1.2 m and 1.5 m of the concealed pipe, Bahceci and Nacar^[36] proved that the desalination effects at both depths were similar and the desalination rate of topsoil (20-cm depth) was as high as 80%. Moreover, they also found that a shallow buried depth can save investment and reduce irrigation water consumption. Another study

pointed out that the groundwater level in the Yellow River Delta area is about 1.0 m, and therefore lacks the construction conditions for deep burial of concealed pipes^[37]. In this study, building depths of salt drainage engineering projects were all 50 cm, which is a shallow buried depth yet involves four water and salt migration types.

In this study, the maximum radius of salt drainage engineering project was no more than 2.5 m under the rainfall intensity of 100 mm/h. The actual rainfall intensity in nature is uneven and discontinuous, which may lead to a longer time for stabilization of the salt drainage effect but also to a better engineering effect. In other words, the larger effective radius may help to extend the service years of traditional hydraulic engineering methods (concealed pipe, open ditch, and vertical shaft). In 2-3 years of study under higher rainfall intensity in India, the distance between the concealed pipes reached 45-150 m combined with open-ditch technology^[23].

Desalination rate is the most important parameter for assessing the effectiveness of saline land remediation. The horizontal distance corresponding to the desalination rate of 0.1% has been determined as the maximum radius of a salt drainage engineering project. This means the position with little desalination effect in the test must be an effective location in controlling saline land in the field^[38,39]. In this study, the maximum spacings of the concealed pipe, open ditch, and shaft were 4.79 m, 2.88 m, and 2.19 m, respectively, in small-scale experiments (Table 4), which should be suggested as 5 m,

3 m, and 2 m, respectively, in the laboratory. Thus, from the perspective of desalination rates, effectiveness of saline soil remediation generally followed the sequence of concealed pipe>open ditch>shaft. The smaller the buried spacing of traditional water conservancy measures, the higher the efficiency of salt removal using the way that irrigation and drainage improvement saline soil, the higher the cost of engineering implementation. Therefore, key parameters such as spacing should be reasonably designed considering various factors.

Concentrated research on the change of a single factor is common in most saline land treatment studies^[40-42]. However, researchers recently have discovered that a combination of measures is more effective in remediating saline soils^[43,44]. Starting from the experimental design, this study has collaboratively studied three kinds of engineering treatment measures of the same coastal saline soil. Based on the layout parameters of these measures, the schematic diagram of joint technology in field application scheme has been determined, as shown in Figure 10, which realizes the goal of engineering application. Experimental conditions correspond to those in field whose depth is not beyond 0.5 m. Therefore, results of the study, particularly physical parameters in engineering, can be determined for a field scale application without adjustment. However, it is impossible for their united applications with such small distances. The fact that the tests have been done only once may have influence on application of the results; therefore, engineering recommendations would have certain referential value.

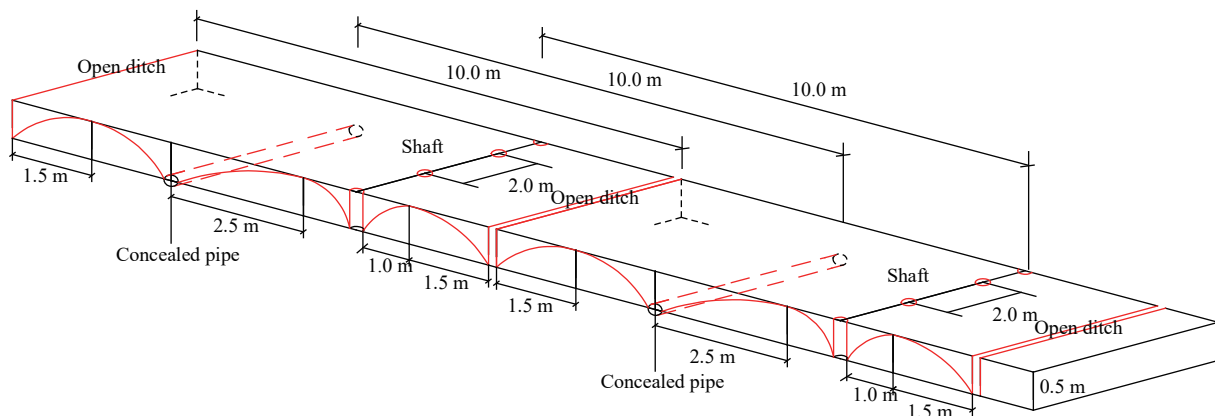


Figure 10 Behavior of salt content over time at different sampling depths in the subsurface drainage pipe experiment

In spite of the fact that the above findings can provide a reference for the key parameters for hydraulic remediation of salt-alkaline soils in the Yellow River Delta of China, there are still some limitations. This study evaluated the effectiveness of three hydraulic restoration measures, which is of significant relevance for the remediation of saline soils in this region, but the effective radius for the hydraulic restoration measures determined in the laboratory is significantly smaller, and is virtually impossible for on-site engineering. In addition, the long-term effectiveness and sustainability of the combined application of hydraulic remediation measures has not been explored. In subsequent studies, the reasonable radius of the three hydraulic remediation measures should be further optimized together with field trials, and the long-term effectiveness of the combination of these measures should be investigated.

5 Conclusions

The sustainable development of agriculture in coastal areas of China hinges in part on the effective remediation of extensive areas of saline soils. This study employed a laboratory experiment to

scientifically determine the key engineering parameters with traditional methods of saline land treatment. Results indicated that it takes 6-8 hours for the soil salt content to be at a constant level under the rainfall intensity of 100 mm/h. The distribution of the soil salt content above the concealed pipe, on the side of the open ditch, and around the vertical shaft all present a typically symmetrical shape. The relationship between the soil desalination rate and horizontal distance from the pipe, ditch, or shaft can be expressed by a two-parameter exponential function. The maximum spacings of laying the concealed pipe, the open ditch, and the vertical shaft in the laboratory are 4.79 m, 2.89 m, and 2.19 m, respectively. Considering the cost of engineering implementation, the laboratory results may not be directly applied to the field experiment. Therefore, how to extend the laying distance determined in this test to the field is the primary direction of further research.

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