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

Kesheng Li[1,2], Chuanxiao Liu[1*], Weihang Kong[1], Yuhan Geng[1], Wenshuo Xu[1]

(1. *College of Water Conservancy and Civil Engineering, Shandong Agricultural University, Tai'an 271018, Shandong, China*;
2. *State Key Laboratory for Geomechanics and Deep Underground Engineering, China University of Mining and Technology, Xuzhou 221116, Jiangsu, China*)

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, in this study, laboratory investigations were made 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 when the soil salt content tends 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, and the vertical shaft. The two-parameter exponential function indicates the relationship between the soil desalination rate and the horizontal distance from the pipe, the ditch or the shaft. The maximum spacing to build the salt drainage engineering of the concealed pipe, the open ditch or the vertical shaft in the laboratory is 4.79 m, 2.88 m, and 2.19 m, respectively. The effectiveness of salt drainage for coastal saline soils can be ranked from largest to smallest as the concealed pipe, the open ditch and 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 decreasing areas and deteriorative quality of cultivated land, especially the saline soil, the 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, the saline land treatment, as an effective approach to improve the quality and areas of cultivated land, is essential to agricultural engineering and civil engineering subjects. Through about semi-centenary practices of saline land treatment, many remediation methods have been developed, including chemical, physical, biological and engineering technology[3-6]. Herein, the 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 the concealed pipe, digging the open ditch, drilling the vertical shaft, and building the platform field[7]. In the 17th century, water drainage technology by the concealed pipe was originated in England, while it was later applied and developed in the Netherlands and the United States[8-11]. In the early 20th century, the technology was introduced to Japan. In the first half of the 20th century, water drainage technology by the concealed pipe 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 the secondary salinization by laying the concealed pipes under the saline soil[13]. With the experiment of large-scale application of the concealed pipe, Yang[14] has treated the saline land in the Yellow River Delta, receiving a remarkable outcome. Through the experiment of the concealed pipe under drip irrigation covered with mulch, Shi et al.[15] finds that this water drainage technology contributes to irrigation in 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 area with an obvious effect of desalination. Studying the application of the water drainage technology by the concealed pipe in paddy field of coastal saline land, Wei et al.[17] find that this technology can significantly reduce the groundwater level, salinity and the salt content. Based on the experiment of the leakage in paddy filed of coastal saline land of Jiangsu Province, Zhou et al.[18] find that the water drainage technology by the concealed pipe has improved the soil structure characteristics, increased the content of available phosphorus, and decreased the salt content. Smedema[19] finds that the salt content in soil can meet the security growth need of crop even though the buried depth of the concealed pipe is reduced to a certain extent. With Hydroluis model, Bahçeci et al.[20] find that the desalination effect to soil is almost the same when the buried depth of the concealed pipe is 1.2 m and 1.5 m, respectively. Through long-term water drainage experiment of the concealed pipe in Yinbei irrigation district of Ningxia and Hetao irrigation district of

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Biographies: Kesheng Li, PhD candidate, research interest: geotechnical engineering, Email: likesheng@cumt.edu.cn; **Weihang Kong**, MS, research interest: soil remediation, Email: 2019120640@sdau.edu.cn; **Yuhan Geng**, MS, research interest: agricultural water-soil engineering, Email: gengyhlm@163.com; **Wenshuo Xu**, MS, research interest: frozen soil engineering and soil remediation, Email: 2019110564@sdau.edu.cn.
***Corresponding author: Chuanxiao Liu**, Professor, research interest: geotechnical engineering and soil remediation. College of Water Conservancy and Civil Engineering, Shandong Agricultural University, Tai'an 271018, China. Tel: +86-538-8241865, E-mail: lchuanx@163.com.

Inner Mongolia, Wang[21], Jing and Liu[22] have observed that this 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. By salt exchanging experiment between bottom mud and water in the open ditch, Pan et al.[24] find that the engineering technology has a positive effect on water and salt transport. After simulating water and salt migration in soil under water drainage technology of the open ditch, Li et al.[25] find that it can promote the discharge of soil salt. Based on Chen et al.[26], this technology of the open ditch can significantly reduce the soil salinity. Through engineering examples, Jiang et al.[27] prove that water drainage technology of the 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 caused the fragile ecological environment. Besides, large saline lands seriously hinder the agricultural development. The saline land in the Yellow River Delta is 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, which 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 environment and Yellow River sediment can improve the physical properties of the soil better 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 researches on traditional engineering measures to manage the coastal saline land are 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 decide 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 treated of the concealed pipe, the open ditch and the 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 are 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 studying area is about 1.0 m above the 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 is 0-20 cm in the field which is disturbance soil, while specimens in the laboratory are sampled with soil drill according to experimental plan. After passing through 2 mm sieve, the soil texture is proved to be loam via analyzing 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 the salt content, the salt contents of the saline soils are all beyond 1.0%, therefore they are typical coastal saline soils.

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

2.2 Experimental design

Experiments have been carried out in the laboratory of geotechnical engineering and soil physics of Shandong Agricultural University, focusing on the relationship between rainfall time and the salt content of the saline soil. Besides, 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 have been considered in these tests[33,34].

2.2.1 Experiment on the relationship between rainfall time and the salt content

The length×width×height of soil tank manufactured with organic glass is 120 cm×40 cm×30 cm. The saline soil with the bulk density of 1.46 g/cm^3 is filled in layers into the soil tank. The upper soil material is 20 cm thick while the lower soil layer is 5 cm and the middle layer is the large porosity material with the 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 are drilled at bottom of the soil tank. To simulate the leaching experiment, we employ the MSR-S20-W1000 (1500) portable artificial rainfall simulator (Shandong Agricultural University, China) with its rainfall intensity designed as 100 mm/h. Experimental model to study the relationship between rainfall time and the salt content of saline soil is shown in Figure 2.

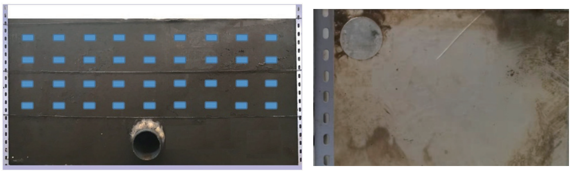

Figure 2 Experimental model of the relationship between rainfall time and the salt content

In the process of experimental rainfall, soil specimens at different depths of 0-5 cm, 10-15 cm and 15-20 cm have been sampled at regular intervals to determine the salt content with an initial value of 2.12%. Based on salt contents of samples determined with drying method, relationship between salt content and conductivity was established to get 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 the concealed pipe

The length×width×height of soil tank manufactured with organic glass is 100 cm×50 cm×70 cm. The overflow hole is set at 10 cm from the top of the soil tank and the outlet hole is set at 5 cm from its bottom. The concealed pipe is manufactured by PVC pipe with the diameter of 90 mm while its side is symmetrically and evenly drilled by round holes with the diameter of 4 mm. If the opening rate is defined as a ratio of the round hole area to the side area of the concealed pipe, it will be set as 9%. Two layers of permeable absorbent gauze are wrapped around outer the 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 is 60 cm thick and the concealed pipe is buried at 50 cm depth in the vertical direction. The rainfall intensity of the leaching experiment is designed as 100 mm/h. Figure 3 shows the experimental model of saline land treatment with the concealed pipe.

Figure 3 Experimental model of water drainage technology of the concealed pipe

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

2.2.3 Leaching experiment of saline soil by open ditch

The length×width×height of soil tank manufactured with organic glass is 100 cm×50 cm×60 cm. The depth of the open ditch is 50 cm with a 60º slope angle and the width of the ditch top is 50 cm. The filling height of soil is 50 cm in the tank. Several outlet drainage holes are at the bottom of the open ditch. In addition, two layers of permeable absorbent gauze are covered on the soil slope surface, ensuring its stability during the leaching experiment. The rainfall intensity of the leaching system is 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 water drainage technology of the open ditch

In the horizontal direction, soil specimens are sampled 10 cm away from the soil slope top with a spacing of 10 cm while in the vertical direction, sampling points are taken from the slope top with the same spacing. When the saline soil is saturated in the soil tank under leaching, it will be marked as 0 time for the first sampling, leading to a generally low initial the salt content. After the first sampling, outlet drainage holes are opened and the leaching system continually works. When the salt drainage effect tends to be constant, another sampling is taken at the same position of the previous one. Through comparing the newly measured the salt content with the initial value, the desalination rate can be calculated.

2.2.4 Leaching experiment of saline soil by vertical shaft

The length×width×height of soil tank manufactured with organic glass is 60 cm×60 cm×60 cm. The shaft is manufactured by PVC pipe with a diameter of 90 mm, whose opening rate is set as 9%. The vertical shaft is placed in the center of the soil tank and fixed along the joint with glass glue. Small holes are 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 is 50 cm and the rainfall intensity of the leaching system is 100 mm/h. Figure 5 shows the experimental model of saline land treatment by the vertical shaft engineering.

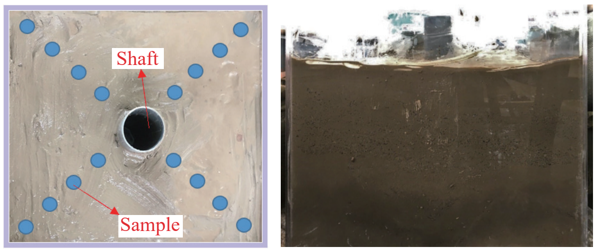

Figure 5 Experimental model of water drainage technology of the vertical shaft

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

2.3 Data analysis

Site layout of the hydraulic measures including concealed pipe, open ditch and vertical shaft depends on its salt drainage effect in laboratory. When the soil desalination rate tends to be 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:

$$\eta = ab^x \quad (1)$$

where η is the soil desalination rate, %; x is 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 the salt content of the saline soil

During the leaching experiment of rainfall intensity of 100 mm/h, the salt content of soil specimens at depth of 0-5 cm, 5-

10 cm, 10-15 cm, and 15-20 cm are measured. The variation relationships of the salt content in different soil layers with time can be achieved, as shown in Figure 6.

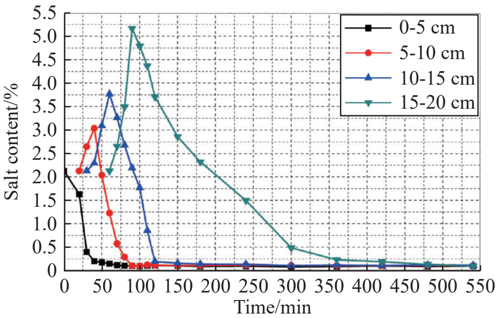

Figure 6 The relationship of the salt content with time

Only the salt content (2.12%) in the surface layer (0-5 cm) decreases rapidly with rainfall time. Although the salt content in the deep layer increases first and then decreases with rainfall time, the peak value of the salt content increase 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 moves with water downwards the lower layer under leaching effect, resulting in the initial accumulation of salt in the deep soil layer. With continuous rainfall leaching, the ultimate the salt content of the soil will be reduced to near zero. Under the rainfall intensity of 100 mm/h, it takes 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 the concealed pipe

Under the rainfall intensity of 100 mm/h, the 6-hour leaching experiment is carried out with the concealed pipe with the diameter of 90 mm and opening rate at 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 decreases with the increase of the horizontal distance from the pipe, the salt content distribution in the saline soil above the concealed pipe presents a typically symmetrical shape. The shorter the horizontal distance from the pipe at different depths of 10 cm, 20 cm, 30 cm, and 40 cm is, the higher the salt drainage efficiency will be. Therefore, the salt content of every soil layer is the lowest near the pipe, which is 0.06%, 0.08%, 0.09% and 0.13%, respectively.

Table 1 Experimental data of the salt content with the 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

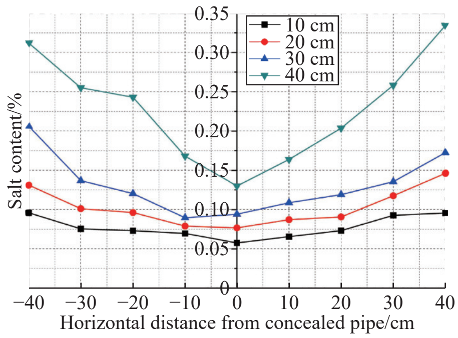

Figure 7 The symmetrical shape of the salt content with the concealed pipe technology

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

Under the rainfall intensity of 100 mm/h, the 8 hours leaching experiment is carried out with open ditch whose slope angle is 60º. 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 the 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	--	0.42
8	10	0.14	--	0.20	--	--	--	0.21	--	--	--	0.25	--	--	--	0.28	--	--	--	--	--
	20	--	0.21	--	--	0.31	--	--	--	0.33	--	--	--	0.34	--	--	--	0.35	--	--	--
	30	--	--	--	0.27	--	--	--	0.33	--	--	--	0.35	--	--	--	0.36	--	--	0.36	--
	40	--	--	--	--	--	0.31	--	--	--	0.39	--	--	--	0.45	--	--	--	0.46	--	0.49

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

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

Under the rainfall intensity of 100 mm/h, the 6-hour leaching experiment is carried out with vertical shaft with the 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.

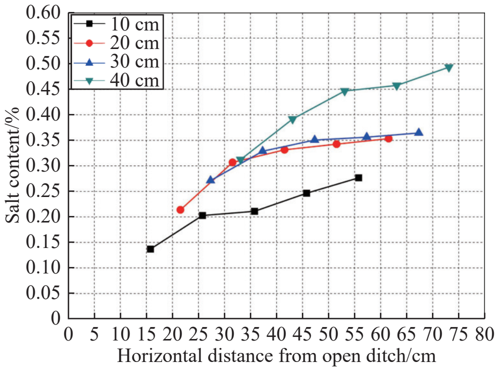

Figure 8 The semi symmetric shape of the salt content with open ditch technology

Table 3 Experimental data of the 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

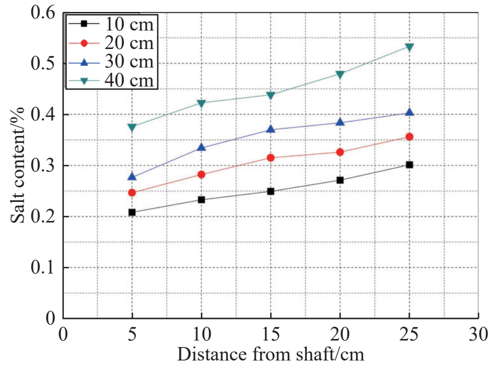

Figure 9 The semi symmetric shape of the salt content with vertical shaft technology

The salt drainage efficiency of the shaft decreases with the increase of the horizontal distance from the shaft, resulting 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 different depths of 10 cm, 20 cm, 30 cm, and 40 cm is, the higher the salt drainage efficiency will be. Hence, the salt content of every soil layer is the lowest near the shaft, which is 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 Table 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 spacing laying the concealed pipes, open ditch and shaft can be calculated as 4.79 m, 2.88 m, 2.19 m, respectively.

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

Depth/cm	Monitoring location	Function	Correlation (R^2)	Radius of salt drainage effect at η_1 = 0.1%/cm		
				x	Maximum radiation radii/cm	Average radiation radii/cm
10	Left	$\eta_1 = 0.521\,92\times1.021\,65^x$	0.823 38	−292.15	321.63	239.30
	Right	$\eta_1 = 0.502\,78\times0.982\,44^x$	0.981 82	+351.10		
20	Left	$\eta_1 = 0.515\,65\times1.033\,42^x$	0.913 83	−189.98	204.76	
	Right	$\eta_1 = 0.482\,19\times0.972\,25^x$	0.861 07	+219.54		
30	Left	$\eta_1 = 0.550\,42\times1.030\,25^x$	0.947 28	−211.76	226.28	
	Right	$\eta_1 = 0.510\,08\times0.974\,44^x$	0.942 24	+240.79		
40	Left	$\eta_1 = 0.527\,95\times1.031\,45^x$	0.827 45	−202.45	204.51	
	Right	$\eta_1 = 0.532\,09\times0.970\,07^x$	0.978 55	+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 η_2 = 0.1%/cm	
			y	Average
10	$\eta_2 = 0.961\,14\times0.969\,78^y$	0.926 72	223.82	143.77
20	$\eta_2 = 1.927\,35\times0.931\,54^y$	0.943 29	106.66	
30	$\eta_2 = 0.788\,91\times0.962\,25^y$	0.907 38	173.35	
40	$\eta_2 = 42.6190\times0.861\,04^y$	0.602 08	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 η_3 = 0.1%/cm	
			z	Average
10	$\eta_3 = 0.530\,11\times0.966\,38^z$	0.966 55	183.43	109.26
20	$\eta_3 = 0.525\,00\times0.939\,45^z$	0.984 16	100.28	
30	$\eta_3 = 0.538\,92\times0.928\,59^z$	0.971 80	84.89	
40	$\eta_3 = 0.403\,76\times0.916\,06^z$	0.776 49	68.45	

4 Discussion

In this study, the ratio of soil particles with 0.002-0.200 mm is 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 is 1.46 g/cm^3, 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 is 2.40×10^{-5} cm/s, which belongs to weak permeability grade[29]. This study finds that it takes 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 takes 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. By studying buried depths of 1.2 m and 1.5 m of the concealed pipe, Bahceci and Nacar[36] have proved that their desalination effects are similar and the desalination rate of topsoil (20 cm depth) is as high as 80%. Moreover, they also found that the shallow buried depth can save investment and reduce irrigation water consumption. In addition, the groundwater level in the area is about 1.0 m, which is incapable of the construction conditions of deep burial of concealed pipes[37]. In this study, building depths of salt drainage engineering are 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 is 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 a better engineering effect. In other words, the larger the effective radius, the service years of traditional hydraulic engineering (concealed pipe, open ditch, and vertical shaft) may be enlarged. In 2-3 years of study under higher rainfall intensity in India, the distance between the concealed pipes reaches 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% is determined as the maximum radius of a salt drainage engineering. It means the position with little desalination effect in the test must be the effective location in controlling the saline land in field[38,39]. In this study, the maximum spacings of the concealed pipe, open ditch and shaft are 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 single factor are 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 are corresponding to those in field which 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's impossible for their united applications with so small distances. That the tests have been done only once would have influence on application of the results, therefore engineering recommendations would have certain referential value.

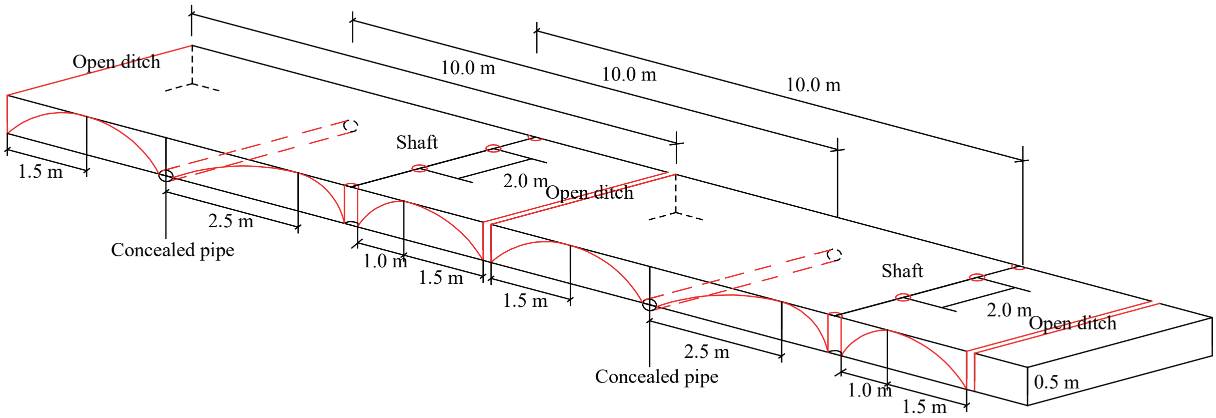

Figure 10 Behaviour of salt content over time at different sampling depths in the subsurface drainage pipe experiment

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, which 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 this 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. The study employed 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 presents a typically symmetrical shape. The relationship between the soil desalination rate and horizontal distance from the pipe, ditch or the shaft can be expressed by a two-parameter exponential function. The maximum spacings 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 practice, 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 the further research.

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