

Article

Effects of Water-Storage Clay Particle Size, Addition Amount, and Mixed Application Depth on the Vertical Movement Characteristics of Soil Moisture

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Abstract

The Loess Plateau suffers from both drought and soil erosion, impeding regional sustainable development. Water-Storage Clay (WSC), a novel inorganic porous material with high porosity and water absorption, exhibits potential to enhance soil infiltration and storage capacity. This study integrated indoor experiments (repeated three times) with Hydrus-1D simulations to investigate the effects of the addition amount (5%, 10%, and 20%), particle size (A: <2 mm, B: 2–5 mm, C: 5–10 mm, and D: 10–20 mm), and mixed application depth (0–5, 0–10, 0–15, and 0–20 cm) of WSC on the vertical moisture migration of silt loam (sampled from Taiyuan, China) in the Loess Plateau. The D20 treatment (10–20 mm, 20%) was validated via a soil column experiment, showing high model accuracy ($R^2 > 0.988$). The simulation results showed that WSC significantly improved soil moisture movement, with the wetting front migration distance, cumulative infiltration, infiltration rate, and profile moisture distribution increased by 21.77–112.24%, 25.70–172.23%, 24.18–109.51%, and 6.26–22.64%, respectively, compared with CK. The addition amount and particle size interactively influenced soil infiltration, with efficacy increasing at higher addition amounts, while increasing mixed depth further improved soil infiltration and water retention. Through a comprehensive evaluation, the B20 treatment was determined as the optimal application plan. The research provides a novel approach for regional soil and water conservation, as well as drought mitigation.

Keywords: water-storage clay; Hydrus-1D; soil infiltration; water-holding capacity; Loess Plateau



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1. Introduction

Loess is widely distributed around the world, accounting for approximately 10% of the global land area, while the Loess Plateau in China is the largest and oldest loess deposit area in the world [1,2]. In this region, extensive sloping farmlands and the inherently loose soil texture, combined with concentrated rainfall and frequent rainstorms, make the soil prone to crust formation after wetting [3,4]. This leads to reduced infiltration, which, in turn, triggers soil and water loss, thereby diminishing soil productivity [5,6].

According to the 2024 *China Soil and Water Conservation Bulletin*, the soil erosion area in the Loess Plateau region is 194,400 km², accounting for approximately 33.81% of the total land area in this region. The low utilization efficiency of rainstorm runoff and declining soil fertility severely restrict the high-quality development of regional production and ecology. Therefore, improving the soil infiltration and water storage capacity of the Loess Plateau is the key to solving this problem.

Numerous studies have demonstrated that the application of soil amendments is an important means to improve soil hydraulic properties and enhance soil water infiltration and storage capacity, which has been widely adopted in the fields of agriculture and soil and water conservation [7–9]. For instance, Ma et al. [10] found that corn straw juice and fulvic acid treatments significantly increased soil infiltration capacity, whereas humic acid treatment exhibited the opposite effect. Wang et al. [11] found that composite amendments (polyacrylamide, super absorbent resin, and organic fertilizer) enhanced both the soil infiltration and water-holding capacity. However, organic amendments are relatively costly, prone to decomposition under hot and dry conditions, and can potentially cause secondary pollution, thereby imposing certain limitations on their application [12,13]. In contrast, inorganic amendments are low in cost, more resistant to decomposition, and less likely to cause pollution. Consequently, they can achieve longer-lasting soil improvement effects without endangering the ecological environment.

Water-Storage Clay (WSC), as a novel inorganic porous material, uses river and lake silt caused by soil erosion as its main raw material. It features high water absorption, high porosity, abundant raw material sources, low cost, environmental friendliness, and reusability. The internal pore structure of honeycomb-like particles gives it the potential to enhance soil infiltration and storage capacity. The current research on porous ceramic particles at home and abroad mainly focuses on material preparation, urban construction, water purification, etc [14–16]. Nevertheless, using WSC as a soil amendment and studying its impact on soil infiltration and storage capacity is relatively scarce. Chang et al. [17] previously investigated the effect of overlying WSC on soil water infiltration, and the results showed that the cumulative infiltration increased by 40–60% compared with CK treatment. However, systematic research on the interactive effects of different particle sizes, addition amounts, and mixed application depths of WSC (rather than surface overlay) on soil moisture movement characteristics remains lacking. In particular, quantitative multi-factor synergistic analyses and the corresponding numerical modeling framework remain largely unexplored. Based on the above gaps, this study proposed the core hypothesis that the porous structure and hydrophilicity of WSC could significantly improve the water conductivity and water-holding capacity of silt loam, and the improvement effect was enhanced with an increase in addition amounts, particle sizes, and mixed application depths.

Compared with traditional indoor soil column infiltration experiments, the numerical simulation method has been widely recognized because of its high efficiency and flexibility. In particular, the Hydrus-1D model, as a classical soil–water dynamics model, has been extensively applied to simulate soil moisture movement under various scenarios, and good results have been achieved [18–20]. Soudejani et al. [21] utilized Hydrus-1D to evaluate the effects of compost with modified zeolite on soil moisture balance components, finding that measured and simulated values were very close. Ibrahim et al. [13] simulated soil moisture and water storage in loamy sand soil amended with clinoptilolite using Hydrus-1D, reporting only a slight overestimation (2.4%) at depths ≤ 30 cm. Given the satisfactory performance of Hydrus-1D in simulating moisture movement under the influence of various soil types and amendments [22,23], this model can be employed to simulate the effects of WSC on the vertical migration characteristics of soil moisture in the Loess Plateau.

Nevertheless, it should be clarified that Hydrus-1D has certain limitations in layered soil and cannot clearly analyze the preferential flow in heterogeneous soil profiles.

Therefore, based on indoor experiments, this study developed a soil water movement model incorporating WSC using Hydrus-1D (Version 4.17.0140) to simulate the effects of different particle sizes, addition amounts, and mixed application depths on soil wetting front migration, cumulative infiltration, infiltration rates, and soil profile moisture distribution. The main objectives are as follows: (1) to establish the Hydrus-1D model based on measured soil water characteristic curve data, and accurately simulate the soil moisture infiltration process after mixing WSC into the soil, and (2) on this basis, to investigate the effects of particle sizes, addition amounts, and mixed application depths of WSC on soil moisture vertical movement characteristics, where the optimal application mode is identified.

2. Materials and Methods

2.1. Test Materials

The soil used in the experiment was taken from the surface layer of the farmland in Xishan of Taiyuan City (112°18' E~112°32' E, 37°40' N~38°05' N), with a sampling depth of 0–20 cm. The soil samples were air-dried naturally and then passed through a 2 mm sieve to remove gravel and impurities for subsequent use. The soil texture composition was determined by the Bettersize3000Plus laser (Dandong Bettersize Instruments Co., Ltd., Dandong City, Liaoning Province, China) particle size analyzer. Standard particles were used for optical system alignment and sensitivity verification (relative error $\leq 2\%$). Before measuring each batch of samples, the dispersion cell and tubing were cyclically cleaned three times with deionized water and anhydrous ethanol, followed by conducting a background measurement, revealing 23.5% sand, 70% silt, and 6.5% clay. The texture was silt loam (USDA standard) [24], with $D_{50} = 22.55 \mu\text{m}$ and a bulk density of 1.35 g/cm^3 . WSC was provided by Wuhan Mingchuang XinHai Ecological Technology Co., Ltd. (Wuhan City, Hubei Province, China), which was air-dried, crushed, and sieved to produce WSC of different particle sizes for the experiment. The main component composition of the WSC is shown in Table S1.

A scanning electron microscope (SEM) image of the internal section of the WSC (10 mm) is shown in Figure 1. At low magnification (100 μm), a notable gully-like pore network structure was observed inside the WSC particles. The pore size was large, forming a penetrating channel; the shape was observed to be irregular, and the edge was rough. At high magnification (5 μm), honeycomb-shaped pores were densely distributed within the particle matrix, characterized by small pore sizes, with some appearing as regular fine circular holes, forming a microporous structure resembling a “beehive”. These results demonstrate that the WSC possesses abundant macroporous and microporous structures, providing data support for our hypothesis.

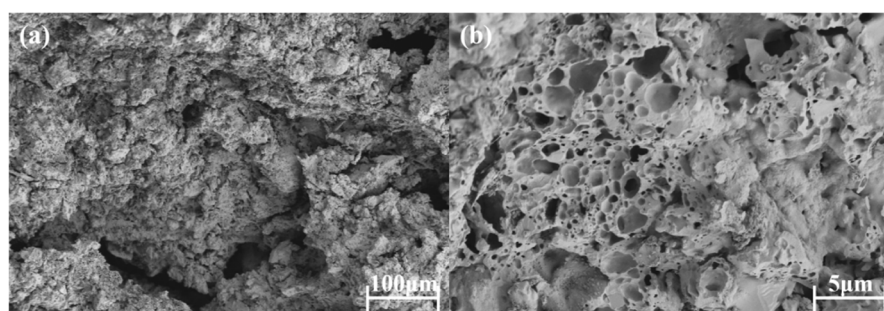


Figure 1. Scanning electron microscope image of internal section of WSC with a particle size of 10 mm: (a) 100 μm ; (b) 5 μm .

2.2. Model Construction

2.2.1. Basic Equation of Soil Moisture Movement

Assuming that each soil layer is homogeneous and isotropic, and neglecting the effects of the external environment and soil structure changes, the basic equation of moisture movement was numerically solved using the Richards equation [25].

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[K(h) \frac{\partial h}{\partial z} \right] \pm \frac{\partial K(h)}{\partial z}, \quad (1)$$

where θ denotes the soil water content ($\text{cm}^3 \cdot \text{cm}^{-3}$), $K(h)$ denotes the soil unsaturated hydraulic conductivity ($\text{cm} \cdot \text{min}^{-1}$), h denotes soil suction (cm), t denotes time (min), z denotes the spatial coordinate (cm), with the coordinate origin at the upper boundary of the soil layer, and upward being positive.

The soil hydraulic function adopted the Van Genuchten–Mualem equation [26,27] without considering the lag effect. Its expression is as follows:

$$\theta(h) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{[1 + |\alpha h|^n]^m} & (h < 0) \\ \theta_s & (h \geq 0) \end{cases}, \quad (2)$$

$$K(h) = K_s \cdot S_e^l \cdot [1 - (1 - S_e^{1/m})^m]^2, \quad (3)$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}, \quad (4)$$

where $\theta(h)$ denotes the soil water content ($\text{cm}^3 \cdot \text{cm}^{-3}$) under h (cm), θ_r denotes the residual soil water content ($\text{cm}^3 \cdot \text{cm}^{-3}$), θ_s denotes the soil saturated water content ($\text{cm}^3 \cdot \text{cm}^{-3}$), α is the reciprocal of the intake value ($1/\text{cm}$), and n and m are the soil pore size distribution parameters, limiting $m = 1 - 1/n$. K_s denotes the saturated hydraulic conductivity ($\text{cm} \cdot \text{min}^{-1}$), S_e denotes the saturation degree, and l is a parameter related to soil porosity.

2.2.2. Spatial Information and Time Information

According to the indoor soil column infiltration experiment setup, the one-dimensional soil column was simulated with a diameter of 15 cm and a height of 40 cm. Each 0.1 cm was regarded as a spatial step, thus dividing the soil layer vertically into 401 nodes. The soil column was divided into two layers: the upper layer was a soil layer mixed with WSC, and the lower layer was a silt loam layer (without WSC). The control group from 0 to 40 cm was all a soil layer without WSC. The schematic diagram of the soil column infiltration simulation is shown in Figure 2a.

The total simulation time for infiltration was 180 min. The time steps followed the principle of being dense at first and sparse later: output occurred every 1 min during 0–5 min, every 2 min during 5–15 min, every 5 min during 15–30 min, and every 10 min during 30–180 min, resulting in a total of 28 time nodes.

2.2.3. Initial and Boundary Conditions

This study simulated one-dimensional vertical infiltration in a soil column under constant water head. When investigating the moisture movement laws during the soil moisture infiltration process, the influences of groundwater, rainfall, and evaporation on the experiment were not considered.

The initial conditions of soil moisture movement are as follows:

$$\theta(z, 0) = \theta_0(z) \quad Z \leq z \leq 0, \quad (5)$$

where $\theta(z, 0)$ denotes the soil moisture content at $t = 0$, which is the initial soil moisture content ($\text{cm}^3 \cdot \text{cm}^{-3}$). In this simulation, the initial soil moisture content is the air-dried moisture content, and Z denotes the maximum vertical distance (cm) of the simulated calculation area, which is -40 cm.

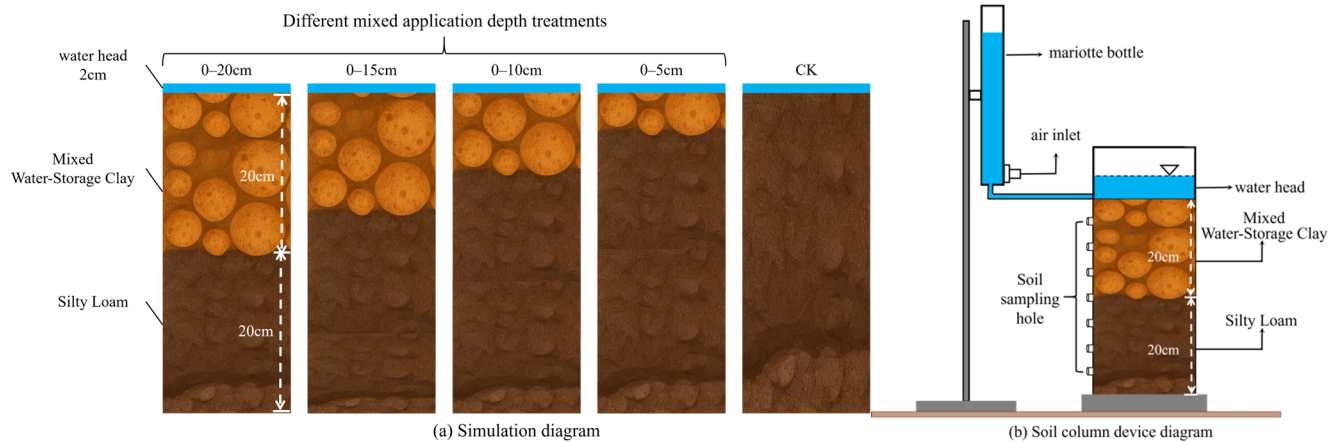


Figure 2. Experimental device and simulation diagram: (a) simulation diagram of constant-head soil column infiltration simulation; (b) soil column device diagram.

The boundary conditions of soil moisture movement are as follows:

The upper boundary was set to a constant pressure head, and the upper boundary of soil moisture movement is:

$$h(z, t) = h_i \quad t > 0, \quad (6)$$

The lower boundary was set to free drainage, and the lower boundary of soil moisture movement is:

$$h(z, t) = h_0 \quad t > 0, \quad (7)$$

where h_i denotes the pressure head (cm), $h_i = 2$ cm in this simulation, and h_0 denotes the initial negative pressure head of the soil profile (cm).

After defining the boundary and initial conditions, the finite element method was employed for a numerical solution.

2.3. Measurement of Soil Hydraulic Properties

Four particle sizes of WSC were set in the simulation as follows: A (<2 mm), B (2–5 mm), C (5–10 mm), and D (10–20 mm). The three addition amounts (mass ratio) were as follows: 5%, 10%, 20%, and one control group (CK, without WSC), totaling 13 treatments. Whether the established model can accurately reflect the actual soil moisture movement situation mainly depends on the accuracy of the soil hydraulic characteristic parameters. Therefore, in the preliminary stage of this study, the soil water characteristic curves (SWCC) of each treatment were measured using the HYPROP instrument (Hydraulic Property Analyzer, Meter Group Inc., Pullman, WA, USA), and RETC software (Version 6.02) was used for fitting to obtain the soil characteristic parameters required for Hydrus-1D simulation, including θ_r , θ_s , α , n , and m . Due to instrumental limitations, the SWCC was measured only over a range of 0–1000 hPa. Therefore, the θ_r was set to 0 during fitting (the fitting accuracy was high for all treatments, with $R^2 > 0.995$), and there were also similar studies reported. Zhang et al. experimentally measured the hydraulic properties of two loess soils in China and also found that θ_r was close to 0 (approximately 0.05) [28]. The saturated hydraulic conductivity (K_s) was measured using the KSAT instrument (METER Group, Inc., Pullman, WA, USA), while l was obtained by fitting Equation (3). The results are shown in Table 1. The detailed treatment procedures are provided in reference [29].

Table 1. Soil hydraulic characteristic parameters of each treatment.

Treatments	Particle Size (mm)	Addition Amount	θ_s (cm ³ ·cm ^{−3})	α (1/cm)	n	m	R ²	K _s (cm/min)	I	Bulk Density (g/cm ³)
CK	—	—	0.471	0.009	1.425	0.298	0.995	0.006	−1.560	1.35
A5	<2	5%	0.484	0.010	1.420	0.296	0.995	0.009	−1.805	1.30
A10		10%	0.504	0.012	1.375	0.272	0.996	0.012	−2.092	1.26
A20		20%	0.516	0.013	1.387	0.277	0.995	0.021	−1.949	1.18
B5		5%	0.494	0.012	1.360	0.264	0.997	0.013	−2.102	1.27
B10	2–5	10%	0.508	0.017	1.323	0.244	0.997	0.027	−2.600	1.20
B20		20%	0.527	0.029	1.274	0.215	0.997	0.074	−3.251	1.09
C5		5%	0.495	0.013	1.369	0.269	0.997	0.016	−2.666	1.26
C10	5–10	10%	0.512	0.016	1.336	0.251	0.997	0.026	−2.463	1.19
C20		20%	0.536	0.026	1.242	0.195	0.998	0.066	−3.475	1.06
D5	10–20	5%	0.501	0.012	1.374	0.272	0.995	0.012	−2.568	1.25
D10		10%	0.524	0.019	1.311	0.237	0.997	0.031	−2.880	1.16
D20		20%	0.541	0.022	1.240	0.193	0.997	0.063	−3.071	1.02

When investigating the particle size and addition amount of WSC under variable conditions, the mixed application depth of WSC was set to 0–20 cm. When investigating the mixed application depth of WSC as a variable condition, the upper layer was set to depths of 0–5 cm, 0–10 cm, 0–15 cm, and 0–20 cm, mixed with WSC, while the particle size and addition amount of WSC were kept consistent, using the B20 and C20 treatments. This was because preliminary studies indicated that the B20 and C20 treatments exhibited superior improvements in soil structure and hydraulic properties compared to other treatments [17,29].

2.4. Model Validation

2.4.1. Soil Column Test Design

The Hydrus-1D model was constructed based on the determined soil hydraulic characteristic properties. To validate the reliability of the model, an indoor soil column infiltration experiment (repeated three times) was conducted using the D20 treatment for verification (the effect on soil structure and hydraulic characteristics is the most complex under this treatment) [29]. The experimental soil columns were fabricated using 5 mm thick plexiglass, with an inner diameter of 15 cm and a height of 50 cm. Seven soil sampling ports with a diameter of 2 cm were installed vertically at 5 cm intervals, from 5 to 35 cm above the column bottom, allowing for soil sampling so as to analyze the profile moisture distribution. The 0–20 cm layer of the soil column was the mixed soil with WSC, having a bulk density of 1.02 g·cm^{−3}, and the lower 20–40 cm layer was silty loam with a bulk density of 1.35 g·cm^{−3}. The soil column was packed using a fixed-volume method and layered filling. Before packing each 5 cm soil layer, the interface of the adjacent layer was roughened to ensure adequate contact between the upper and lower soil layers, and the total height of the soil column was controlled at 40 cm.

A Mariotte bottle was used for the water supply, with the constant water head controlled at 2 cm [17]. The total infiltration duration was 180 min, during which the readings of the Mariotte bottle and wetting front distance were recorded at time intervals that were consistent with the simulation. Soil samples were collected immediately through the sampling ports upon completion of infiltration, and the soil moisture content was determined using the oven-drying method. The experiment was repeated three times. The schematic diagram of the soil column device is shown in Figure 2b.

2.4.2. Model Accuracy Assessment

The one-dimensional vertical infiltration process of the soil column under constant water head for the D20 treatment was simulated using the Hydrus-1D model, with the simulation conditions kept consistent with the indoor experiment. Based on the simulation results, the curves of soil wetting front migration and cumulative infiltration over time were obtained, along with the soil profile moisture content distribution curve after 180 min of infiltration.

Model accuracy was evaluated based on statistical analysis methods, using the mean absolute error (MAE), root mean square error (RMSE), and coefficient of determination (R^2) to assess the model fitting results.

$$\text{MAE} = \frac{1}{n} \sum_{i=1}^n |y_i - \hat{y}_i|, \quad (8)$$

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2}, \quad (9)$$

$$R^2 = 1 - \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (y_i - \bar{y})^2}, \quad (10)$$

where y_i denotes the i -th measured value, $\hat{y}_i$ denotes the i -th simulated value, $\bar{y}$ indicates the average of the measured values, and n indicates the total number of measured values. When MAE and RMSE are closer to 0, and R^2 is closer to 1, it indicates that the simulated values closely match the measured values, reflecting higher accuracy of the model.

Figure 3 shows the comparison between the simulated and measured results. Overall, the simulated curves of soil wetting front migration, cumulative infiltration over time, and soil moisture content distribution along the profile were in good agreement with the measured values. The MAE and RMSE values were both within 0.700, and the R^2 values were all greater than 0.988, indicating a high level of model fitting accuracy. A t -test was conducted on the measured and simulated values, and the results showed that the two-tailed probability values (p -values) for soil wetting front migration, cumulative infiltration, and profile water content were all greater than 0.05, with correlation coefficients ranging from 0.994 to 0.999. This indicates that there was no significant difference between the simulated and measured values, and their variation trends were highly consistent.

The high simulation accuracy of the typical D20 treatment further verified that the Hydrus-1D model, constructed based on the measured soil hydraulic parameters, could accurately simulate the soil moisture migration process after adding WSC under the given boundary conditions and layered soil structure, exhibiting strong applicability. In summary, the reasonableness and feasibility of the modeling framework constructed in this study were demonstrated through dual validation: measured soil hydraulic characteristic parameters and elaborated soil column experiments with the D20 treatment. Therefore, this method could be reasonably extended to other treatments.

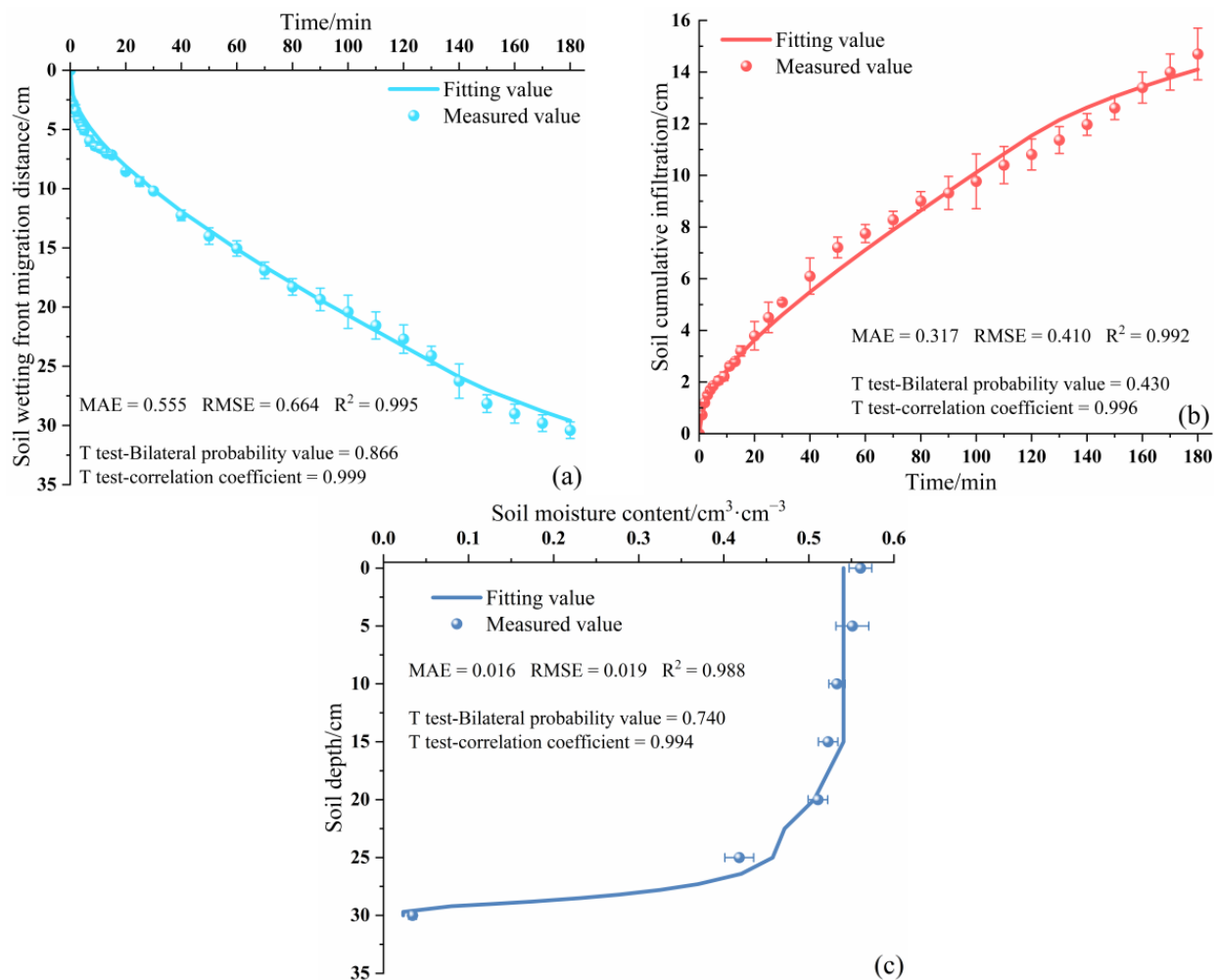


Figure 3. Comparison between Hydrus-1D simulated values and measured data: (a) soil wetting front migration distance; (b) cumulative infiltration; (c) soil profile moisture content distribution.

3. Results

3.1. Effects of WSC on Soil Wetting Front Migration

3.1.1. Addition Amount and Particle Size

As shown in Figure 4a, at the same time point, the wetting front migration distances in all treatments with WSC were greater than those in the CK treatment. Under the same particle size, the wetting front migration distance increased continuously with an increasing addition amount of WSC, and this enhancement became more pronounced as the infiltration time progressed (except for A10, which was slightly lower than A5). At the end of infiltration (180 min), compared with the CK, the wetting front migration distances for the A, B, C, and D particle sizes with 5%, 10%, and 20% additions increased by 23.81%, 21.77%, and 46.94%; 25.85%, 49.66%, and 112.24%; 36.05%, 51.02%, and 104.76%; and 36.73%, 53.06%, and 101.36%, respectively, in each treatment.

At a 5% addition amount, the wetting front migration distances among different particle size treatments exhibited minimal differences. At 180 min of infiltration, the wetting front migration distances for the A5, B5, C5, and D5 treatments were 18.2 cm, 18.5 cm, 20.0 cm, and 20.1 cm, respectively. At the 10% and 20% addition amounts, the differences among the B, C, and D particle sizes were small (within 0.6 cm), and all were significantly higher than that of the A particle, by 4.1–9.6 cm.

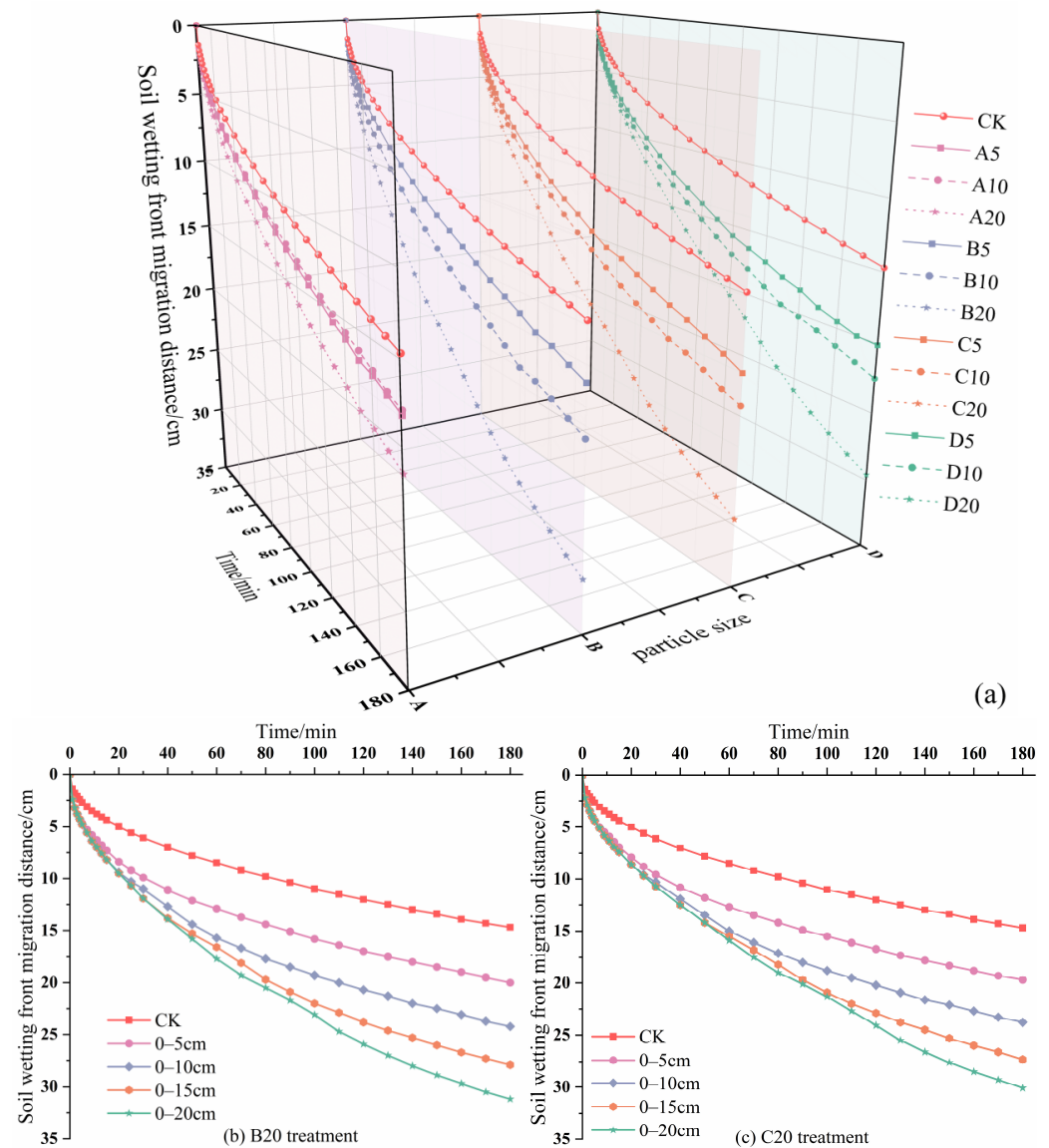


Figure 4. Effects of adding WSC on the soil wetting front migration distance: (a) addition amount and particle size; (b) mixed application depth—B20 treatment; (c) mixed application depth—C20 treatment.

3.1.2. Mixed Application Depth

Compared with the CK, all treatments with different mixed application depths significantly promoted wetting front migration, and the migration distance increased with increasing mixed application depths (Figure 4b,c). At 180 min, compared with CK, the wetting front migration distances under 0–5 cm, 0–10 cm, 0–15 cm, and 0–20 cm mixed application depths for the B20 treatment increased by 36.05%, 64.63%, 89.80%, and 112.24%, respectively; while for the C20 treatment, the corresponding increases were 34.01%, 61.90%, 85.71%, and 104.76%, respectively. It can be seen that the difference in the magnitude of increase between adjacent treatments gradually decreased with increasing mixed application depth.

3.1.3. Fitting Analysis of Soil Wetting Front Migration

To further investigate the effect of adding WSC on the temporal variation in soil wetting front migration distance, a power function was employed to fit the relationship:

$$H = et^f, \quad (11)$$

where H denotes the soil wetting front migration distance (cm), t is the infiltration time (min), e and f denote both the fitting parameters, e is the initial wetting front migration rate, a larger value of e indicates stronger initial soil water conductivity; f is the migration attenuation index, and a larger value corresponds to slower attenuation.

As shown in Table 2, the MAE of each treatment ranged from 0.0589 to 0.3162, the RMSE ranged from 0.0783 to 0.3609, and the R^2 ranged from 0.9983 to 0.9997. This indicates that the power function can accurately reflect the temporal variation in the soil wetting front migration distance in soils amended with WSC. After the addition of WSC, the e values for all treatments were higher than those of CK (especially the B20 treatment), with an increase ranging from 16.58% to 109.32%, and this decreased with an increase in mixed application depth. The e value reflects the wetting front migration rate during the initial infiltration stage, indicating that the addition of WSC can significantly promote the initial wetting front migration. The f value of most treatments was higher than that of CK and increased with an increase in the addition amount and mixed application depth. The f value is an attenuation index reflecting the wetting front migration, indicating that the addition of WSC can alleviate the attenuation effect of wetting front migration.

Table 2. Power function fitting results of soil wetting front migration under WSC addition.

Treatments		e	f	MAE	RMSE	R^2
CK		1.1901	0.4831	0.0589	0.0783	0.9997
A5		1.4688	0.4852	0.0686	0.0889	0.9997
A10		1.3874	0.4917	0.0757	0.0932	0.9997
A20		1.6474	0.4960	0.0872	0.1088	0.9997
B5		1.4782	0.4862	0.0798	0.0999	0.9996
B10		1.6909	0.4958	0.1197	0.1448	0.9995
B20	0–20 cm	1.9598	0.5361	0.2070	0.2446	0.9994
C5		1.6736	0.4768	0.0735	0.0931	0.9997
C10		1.7094	0.4953	0.1019	0.1213	0.9997
C20		1.6025	0.5655	0.2669	0.3114	0.9989
D5		1.7045	0.4798	0.0904	0.1317	0.9995
D10		1.7520	0.4939	0.1326	0.1725	0.9994
D20		1.4130	0.5856	0.3162	0.3609	0.9983
B20	0–5 cm	2.4685	0.4028	0.0769	0.0992	0.9997
	0–10 cm	2.4911	0.4414	0.2170	0.2633	0.9988
	0–15 cm	2.2378	0.4907	0.2323	0.2962	0.9989
	0–20 cm	1.9598	0.5361	0.2070	0.2446	0.9994
C20	0–5 cm	2.2533	0.4188	0.0974	0.1229	0.9996
	0–10 cm	2.1409	0.4678	0.2084	0.2566	0.9988
	0–15 cm	1.8502	0.5219	0.2114	0.2550	0.9991
	0–20 cm	1.6025	0.5655	0.2669	0.3114	0.9989

In summary, increasing the application rate and particle size can enhance the initial migration rate of the wetting front and delay its attenuation; although increasing the mixed application depth slightly reduces the initial migration rate, it improves the long-term migration capacity.

3.2. Effects of WSC on Soil Cumulative Infiltration

3.2.1. Addition Amount and Particle Size

As shown in Figure 5a, the cumulative infiltration in all treatments with the WSC addition was significantly greater than that of CK. Under the same particle size, the addition amount of WSC was positively correlated with the soil cumulative infiltration, and the enhancement effect became more significant over time. Compared with CK, at 180 min of infiltration, the cumulative infiltration for the A, B, C, and D particle sizes with 5%, 10%, and 20% additions increased by 25.70%, 30.94%, and 72.42%; 34.65%, 78.05%, and 172.23%; 26.02%, 80.52%, and 167.28%; and 35.70%, 89.93%, and 165.39%, respectively, in each treatment.

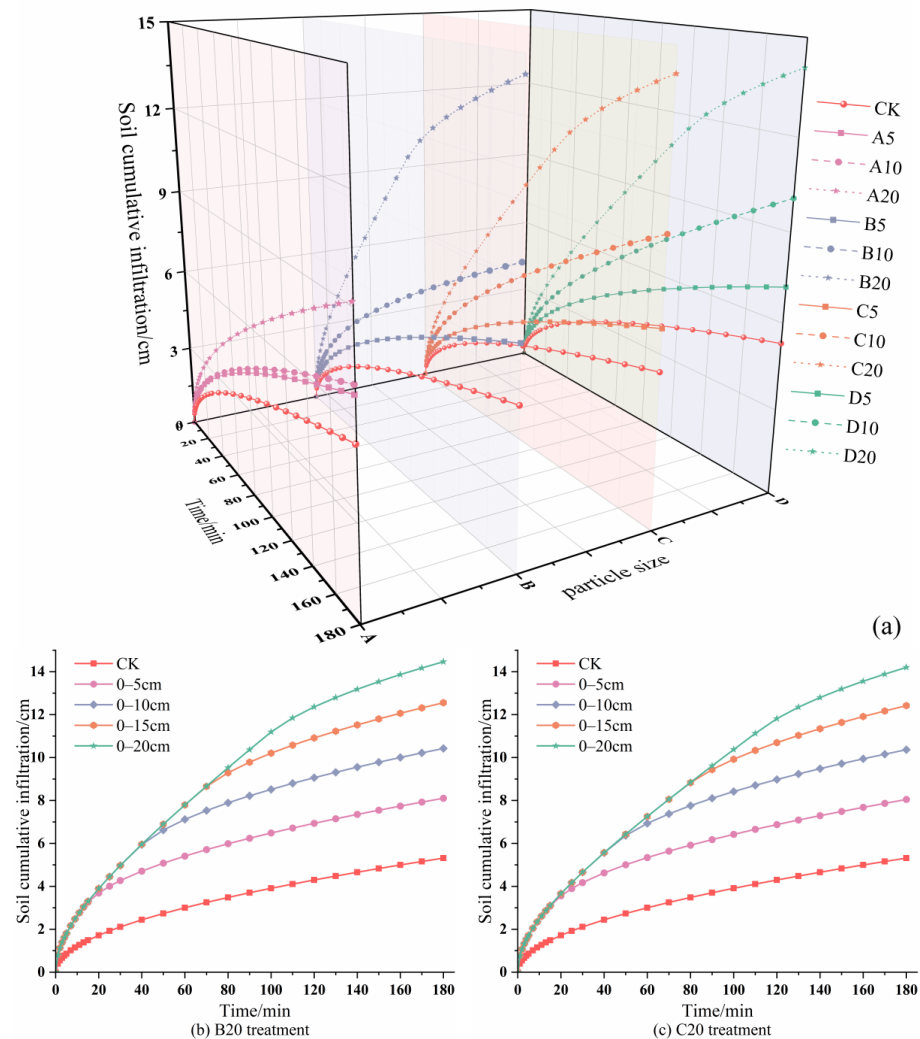


Figure 5. Effects of adding WSC on the soil cumulative infiltration: (a) addition amount and particle size; (b) mixed application depth—B20 treatment; (c) mixed application depth—C20 treatment.

With the increase in the addition amount, the influence of the particle size of WSC on the soil cumulative infiltration became increasingly pronounced. Under the 5% addition amount, the cumulative infiltration of each particle size treatment was not significantly different, with values of 6.68 cm, 7.15 cm, 6.70 cm, and 7.21 cm, respectively. At the 10% and 20% addition amounts, the cumulative infiltration for the B, C, and D particle sizes was significantly higher than that of the A particle size, and the differences among the three were minor, with the difference between any two treatments being less than 0.63 cm. At 180 min of infiltration, the cumulative infiltration for the B10, C10, and D10 treatments increased by 35.98%, 37.87%, and 45.05%, respectively, compared to the A10 treatment; for

the B20, C20, and D20 treatments, the cumulative infiltration increased by 57.89%, 55.01%, and 53.92%, respectively, compared to the A20 treatment.

3.2.2. Mixed Application Depth

At all infiltration time points, the cumulative infiltration of each mixed application depth treatment was higher than that of CK. With the increase in mixed application depth, the cumulative infiltration amount showed a continuous upward trend, but the rate of increase gradually slowed down. Compared with CK, the soil cumulative infiltration under 0–5 cm, 0–10 cm, 0–15 cm, and 0–20 cm mixed application depths for the B20 treatment at 180 min increased by 52.49%, 96.18%, 136.30%, and 172.23%, respectively; for the C20 treatment, the corresponding increases were 51.42%, 95.10%, 133.74%, and 167.28%, respectively (Figure 5b,c).

3.2.3. Fitting Analysis of Soil Cumulative Infiltration

In order to further study the effect of adding WSC on the temporal variation in soil cumulative infiltration, the Kostiakov model was employed to fit the cumulative infiltration curve of each treatment. The formula is as follows:

$$I(t) = kt^n, \quad (12)$$

where $I(t)$ denotes the cumulative infiltration (cm), t denotes the infiltration time (min), k and n denote both model parameters, and k represents the cumulative infiltration per unit time, reflecting the initial soil infiltration capacity, which is related to the number of soil macropores and K_s . n characterizes the attenuation rate of the infiltration process, and a larger value indicates slower infiltration attenuation.

The fitting results are presented in Table 3. The R^2 values of all treatments were greater than 0.992, and the MAE and RMSE values were all less than 0.337, indicating that the Kostiakov model can accurately describe the temporal variation in soil cumulative infiltration after adding WSC. The k values for all treatments were greater than those of CK, with increases ranging from 19.27% to 189.53%. Except for the treatment with mixed application depth less than 10 cm, the n values for the other treatments increased by 1.00% to 21.09% compared to CK.

Table 3. Kostiakov model fitting results of soil cumulative infiltration under WSC addition.

Treatments		k	n	MAE	RMSE	R^2
CK		0.3706	0.5121	0.0099	0.0116	0.9999
A5		0.4532	0.5172	0.0145	0.0168	0.9999
A10		0.4580	0.5227	0.0206	0.0238	0.9999
A20		0.5603	0.5363	0.0385	0.0441	0.9998
B5		0.4648	0.5251	0.0234	0.0269	0.9999
B10		0.5099	0.5594	0.0651	0.0743	0.9994
B20	0–20 cm	0.6913	0.5943	0.2053	0.2704	0.9969
C5		0.4420	0.5222	0.0189	0.0219	0.9999
C10		0.5286	0.5553	0.0614	0.0702	0.9994
C20		0.5913	0.6184	0.1591	0.1958	0.9983
D5		0.4776	0.5216	0.0194	0.0224	0.9999
D10		0.5120	0.5706	0.0802	0.0914	0.9991
D20		0.5780	0.6201	0.1453	0.1722	0.9986

Table 3. Cont.

Treatments		k	n	MAE	RMSE	R^2
B20	0–5 cm	1.0730	0.3910	0.1152	0.1450	0.9964
	0–10 cm	1.0180	0.4559	0.2609	0.2990	0.9921
	0–15 cm	0.8598	0.5263	0.2799	0.3367	0.9936
	0–20 cm	0.6913	0.5943	0.2053	0.2704	0.9969
C20	0–5 cm	1.0000	0.4037	0.1142	0.1400	0.9967
	0–10 cm	0.9155	0.4754	0.2382	0.2747	0.9934
	0–15 cm	0.7486	0.5500	0.2165	0.2746	0.9956
	0–20 cm	0.5913	0.6184	0.1591	0.1958	0.9983

Under each particle size, increasing the addition amount simultaneously enhanced both the k and n values, with the 20% addition amount yielding the optimal effect, and the increase in k value is highly consistent with the increase in K_s . However, at each addition amount, the k and n values had no obvious change rule with particle size. Under the same treatment, the k value gradually decreased with increasing mixed application depth, while the n value continued to increase, indicating that deep mixed application sacrifices the initial cumulative infiltration advantage (smaller k) in exchange for longer infiltration sustainability (larger n).

3.3. Effects of WSC on Soil Moisture Infiltration Rate

3.3.1. Addition Amount and Particle Size

The soil moisture infiltration rates for all treatments exhibited a pattern of “rapidly decreasing and then gradually stabilizing” as the infiltration time progressed (Figure 6a). Under the same particle size, the soil infiltration rate of each treatment increased with an increase in the addition amount of WSC, especially regarding improvement in the initial soil infiltration rate during the early infiltration stage. Compared with CK, the initial soil infiltration rates for the A, B, C, and D particle sizes with the 5%, 10%, and 20% additions increased by 24.51%, 31.65%, and 62.27%; 31.92%, 56.79%, and 109.51%; 24.18%, 60.34%, and 100.10%; and 33.43%, 64.92%, and 96.71%, respectively, in each treatment. The effect of WSC particle size on infiltration rate was not significant. The infiltration rate curves for the B, C, and D particle sizes were essentially consistent, being only slightly higher than that of the A particle size under the 10% and 20% addition amounts.

The infiltration process can be divided into two stages. The first stage involves the upper mixed soil layer gradually becoming saturated. The second stage: the mixed soil layer approaches saturation, and water enters the lower unamended soil layer. The infiltration rate is closely related to soil hydraulic characteristics. When the difference in soil hydraulic characteristics between upper and lower soil layers is too large, it will lead to abrupt changes. It can be seen that the soil infiltration rates of the B20, C20, and D20 treatments showed obvious inflection points at 100 min, 110 min and 120 min, respectively, at which time the mixed soil layers of these three treatments just reached saturation.

3.3.2. Mixed Application Depth

Within 0–15 min, the mixed application depth had no significant effect on the soil infiltration rate, and the attenuation extents of the rate were basically consistent (Figure 6b,c). The initial infiltration rates for all treatments were more than double that of CK. In the middle and late stages of infiltration (30–180 min), differences appeared among the treatments. As time progressed, the infiltration rate curves of the different mixed application depth treatments began to separate, and inflection points emerged.

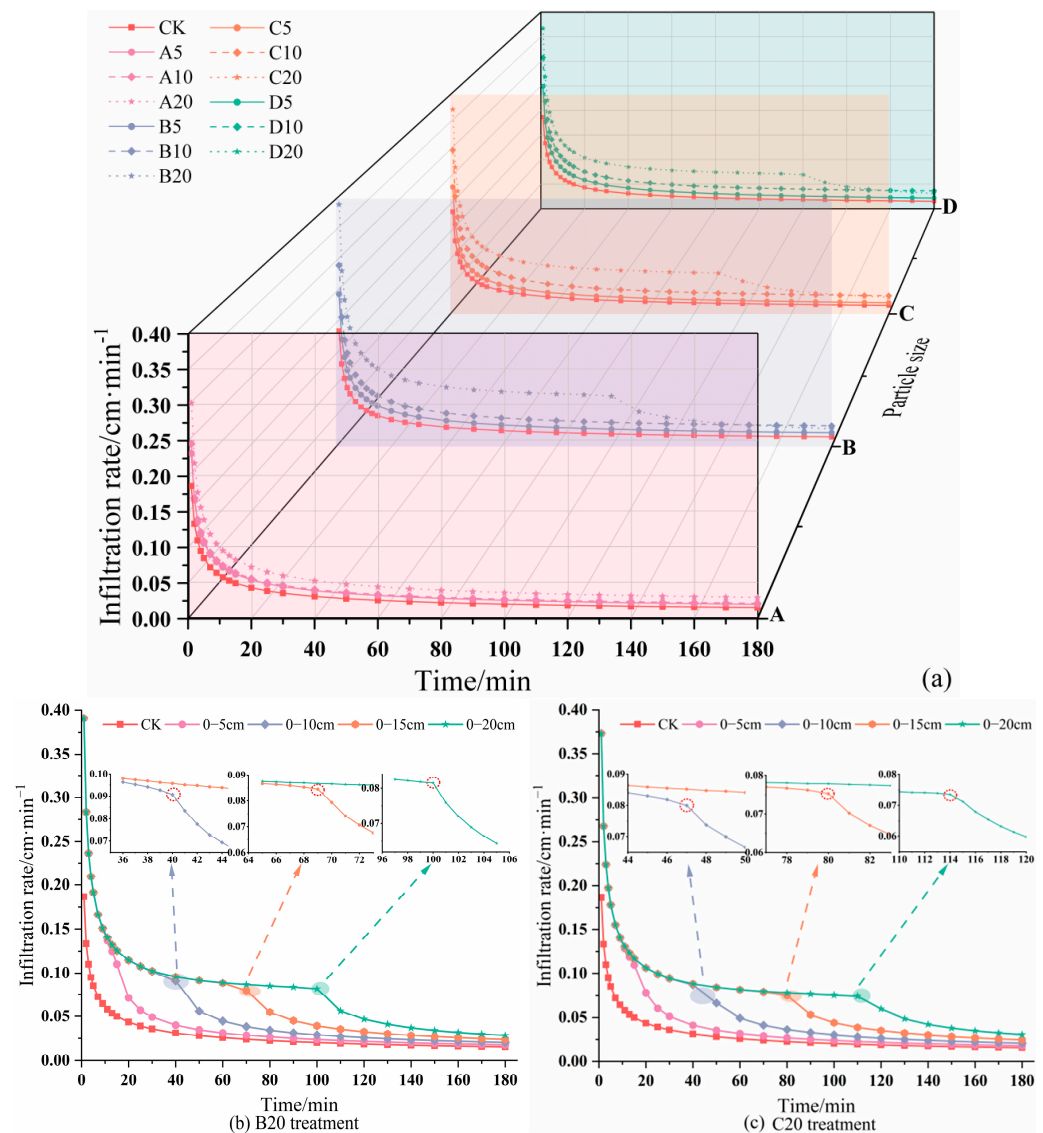


Figure 6. Effects of adding WSC on the soil moisture infiltration rate: (a) addition amount and particle size; (b) mixed application depth—B20 treatment; (c) mixed application depth—C20 treatment.

The mixed application depth determined the occurrence time and decline range of the rate decay inflection point. The B20 treatment under 0–10 cm, 0–15 cm, and 0–20 cm mixed applications showed a decline in the inflection point at 40 min, 69 min, and 100 min, respectively. The corresponding soil moisture contents at the interface between the upper and lower layers for these treatments were 52.18%, 52.15%, and 52.48%, respectively (close to saturation). Similarly, the C20 treatment under mixed applications of 0–10 cm, 0–15 cm, and 0–20 cm exhibited inflection points at 47 min, 80 min, and 114 min, respectively, with the corresponding moisture content of the mixed soil layers also approaching saturation. It can be seen that, at the same mixing depth, the inflection point of the infiltration rate curve was delayed with increasing particle size of the WSC.

3.3.3. Fitting Analysis of Soil Moisture Infiltration Rate

By taking the derivative of the Kostiakov model and simplifying it, the fitting formula for the infiltration rate can be obtained as follows:

$$f(t) = at^{-b}, \quad (13)$$

where $f(t)$ denotes the infiltration rate ($\text{cm} \cdot \text{min}^{-1}$), t denotes the infiltration time (min), a and b denote both model parameters, and a is the infiltration rate per unit time, characterizing the soil water conductivity at the initial infiltration stage. b is the attenuation index of infiltration rate, and a smaller b indicates slower attenuation of the infiltration rate.

The MAEs and RMSEs of all treatments were between 0.0003 and 0.0145, with $R^2 > 0.977$. The fitting accuracy was high, indicating that the temporal variation in soil moisture infiltration rate following the addition of WSC conforms to the Kostiakov model. As shown in Table 4, the a values of each treatment were all higher than those of CK, with an increase ranging from 23.03% to 122.22%, indicating that the addition of WSC can enhance the initial infiltration rate. Except for the A10 treatment and mixed application depth treatment of 0–5 cm, the b values under other treatments were lower than those of CK, with a reduction ranging from 0.54% to 17.76%, indicating that the addition of WSC can mitigate the attenuation of the infiltration rate. Among them, the addition amount was positively correlated with a value and negatively correlated with the b value; there was no obvious variation pattern of a and b values with particle size; the mixed application depth was negatively correlated with the a and b values.

Table 4. Kostiakov model fitting results of soil moisture infiltration rate under WSC addition.

Treatments		a	b	MAE	RMSE	R^2
CK		0.1863	0.4838	0.0003	0.0003	0.9999
A5		0.2315	0.4812	0.0005	0.0006	0.9999
A10		0.2409	0.4850	0.0013	0.0016	0.9990
A20		0.2998	0.4680	0.0017	0.0019	0.9991
B5		0.2431	0.4783	0.0011	0.0013	0.9994
B10		0.2857	0.4495	0.0029	0.0033	0.9970
B20	0–20 cm	0.3798	0.4046	0.0105	0.0124	0.9775
C5		0.2292	0.4790	0.0008	0.0010	0.9996
C10		0.2933	0.4518	0.0026	0.0030	0.9976
C20		0.3569	0.3988	0.0093	0.0107	0.9805
D5		0.2469	0.4785	0.0008	0.0009	0.9997
D10		0.2986	0.4459	0.0039	0.0046	0.9950
D20		0.3525	0.3979	0.0085	0.0097	0.9827
B20	0–5 cm	0.4140	0.5384	0.0134	0.0145	0.9771
	0–10 cm	0.4022	0.4762	0.0129	0.0139	0.9772
	0–15 cm	0.3913	0.4386	0.0107	0.0127	0.9790
	0–20 cm	0.3798	0.4046	0.0105	0.0124	0.9775
C20	0–5 cm	0.3912	0.5312	0.0112	0.0120	0.9820
	0–10 cm	0.3794	0.4718	0.0102	0.0113	0.9827
	0–15 cm	0.3678	0.4316	0.0092	0.0110	0.9819
	0–20 cm	0.3569	0.3988	0.0093	0.0107	0.9805

In summary, increasing the addition amount and particle size can enhance the initial infiltration rate and delay the infiltration attenuation. Although the increase in mixed application depth slightly reduces the initial infiltration rate, it makes the infiltration process last longer.

3.4. Effects of WSC on Soil Profile Moisture Distribution

3.4.1. Addition Amount and Particle Size

As shown in Figure 7a, at the same particle size, the soil profile moisture content increased with the increase in the addition amount of WSC, and the wetting range of the soil also expanded; the higher the addition amount, the more obvious the aggregation effect of moisture in the surface layer. After infiltration, the soil moisture of each treatment was mainly distributed in the 0–10 cm soil layer, and the soil moisture content in this area was almost saturated. Compared with CK, the average soil water content in the 0–10 cm soil layer for the A, B, C, and D particle sizes with 5%, 10%, and 20% additions increased by 6.26%, 11.17%, and 16.24%; 9.78%, 15.11%, and 19.51%; 7.97%, 15.87%, and 21.46%; and 9.50%, 18.78%, and 22.64%, respectively, in each treatment.

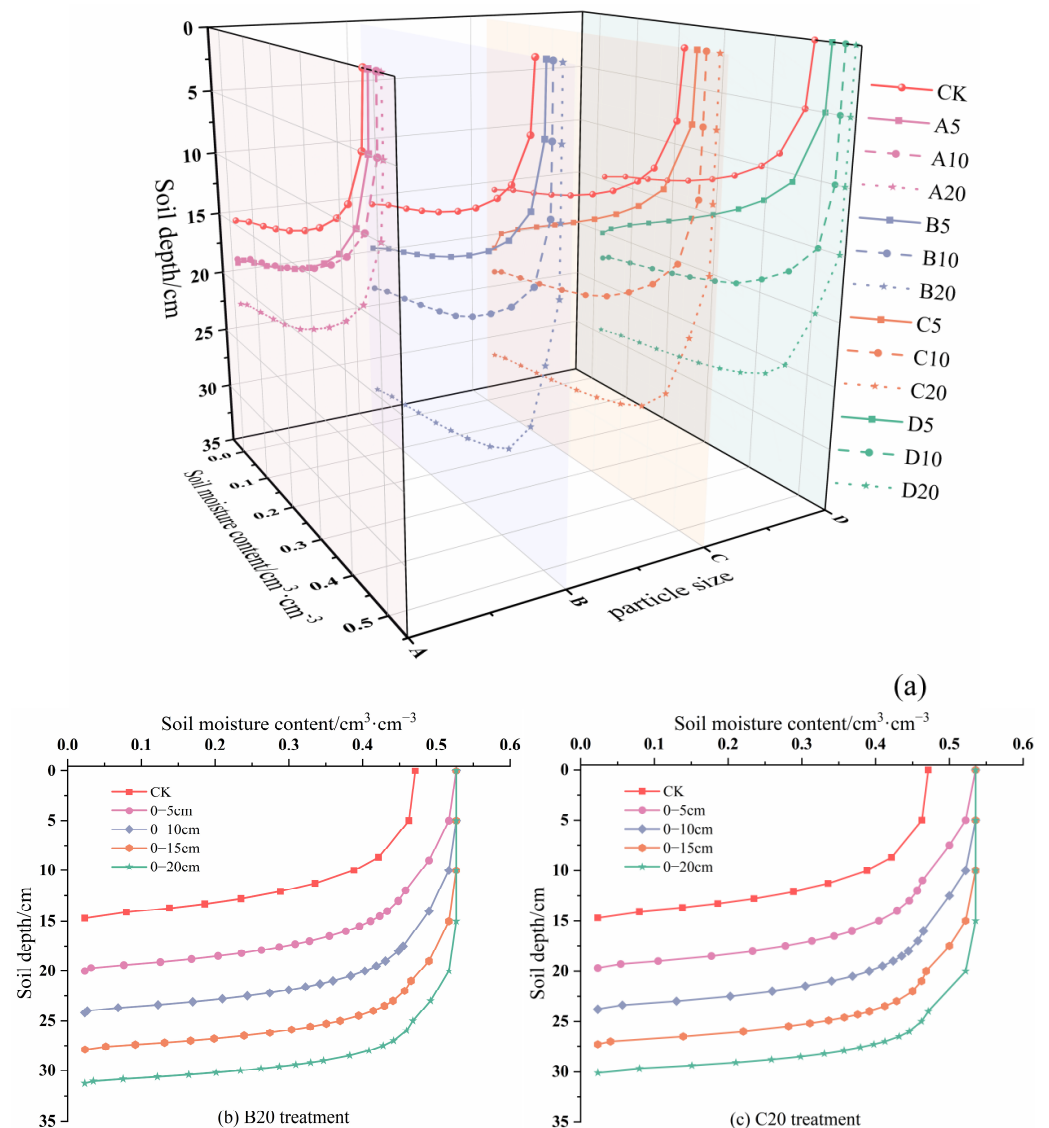


Figure 7. Effects of adding WSC on the soil profile moisture infiltration distribution at 180 min: (a) addition amount and particle size; (b) mixed application depth—B20 treatment; (c) mixed application depth—C20 treatment.

With an increasing addition amount, the effect of particle size on soil profile moisture distribution gradually became significant, exhibiting an overall trend of “larger particle sizes being superior to smaller ones”. At a 5% addition amount, the soil profile moisture content curves of the four particle size treatments basically coincided, and the increase was

all within 3.31% compared with CK (0–10 cm soil layer). At 10% and 20% addition amounts, pronounced differentiation emerged: the profile moisture contents of B, C, and D particle size treatments were significantly higher than that of the A particle size, with an increase ranging from 2.81% to 6.86%. The differences among the three were relatively small.

3.4.2. Mixed Application Depth

With increasing mixed application depth, the overall moisture content of the soil profile gradually increased, the wetting range of the soil expanded, and the depth of the near-saturated soil layer also increased. In the 0–15 cm soil layer, the average moisture content of the B20 treatment under 0–5 cm, 0–10 cm, 0–15 cm, and 0–20 cm mixed applications increased by 68.21%, 87.00%, 90.34% and 91.25%, respectively, compared with CK; the C20 treatment increased by 70.43%, 85.69%, 93.15%, and 94.37%, respectively. In conclusion, WSC can not only improve soil moisture infiltration capacity, but it can also enhance soil water-holding capacity (Figure 7b,c).

3.5. Comprehensive Evaluation of Improvement Effect of WSC

To determine the optimal application mode of WSC, this study employed the entropy weight (EWM) method and TOPSIS to comprehensively evaluate the wetting front migration distance (180 min), cumulative infiltration (180 min), initial infiltration rate, and surface soil moisture content (0–10 cm) under different treatments. In this method, entropy weight is first used to determine the weight of each indicator. Then, the TOPSIS model is applied to calculate the distances between each treatment and the optimal/worst treatments, thereby obtaining the relative closeness of each treatment to the optimal treatment, which serves as the basis for performance evaluation.

Using the EWM to assign weights to the four indicators, the weight proportions of wetting front migration distance, cumulative infiltration, initial infiltration rate, and surface soil moisture content were determined to be 26.24%, 34.19%, 23.61%, and 15.96%, respectively. The TOPSIS evaluation results for different treatments are shown in Table 5. The optimal application method was the B20 treatment (20 cm mixed application depth), followed by the C20 and D20 treatments, while the CK treatment had the lowest comprehensive score.

Table 5. The TOPSIS evaluation results of each treatment.

Treatments	Positive Ideal Solution Distance	Negative Ideal Solution Distance	Composite Score Index	Ranking
CK	1.000	0.000	0.000	13
A5	0.793	0.216	0.214	12
A10	0.746	0.289	0.279	10
A20	0.509	0.518	0.504	6
B5	0.734	0.285	0.280	9
B10	0.505	0.509	0.502	7
B20	0.053	0.980	0.949	1
C5	0.756	0.264	0.259	11
C10	0.485	0.531	0.523	5
C20	0.060	0.945	0.940	2
D5	0.705	0.311	0.306	8
D10	0.441	0.589	0.572	4
D20	0.079	0.934	0.922	3

4. Discussion

4.1. Analysis of Model Applicability, Reliability, and Application Advantages

The addition of soil amendments will alter the soil structure and its hydraulic characteristics [9,30], making the upper and lower soil layers heterogeneous. Numerous studies have shown that Hydrus-1D not only performs well in homogeneous soils [31,32] but can also effectively simulate moisture movement under different layered soils [33,34]. Ibrahim et al. [13] demonstrated that the Hydrus-1D model accurately simulated the effects of adding clinoptilolite on the moisture content and soil moisture storage in loamy sandy soil under specified initial and boundary conditions ($R^2 = 0.73\text{--}0.93$, $\text{RMSE} = 0.023\text{--}0.033$). By calibrating the soil hydraulic parameters using the reverse modeling program in Hydrus-1D, Soudejani et al. [21] successfully simulated the effects of compost amended with natural and magnesium-modified zeolites on soil moisture distribution ($R^2 = 0.57\text{--}0.92$, $\text{NRMSE} = 0.07\text{--}0.19$).

The Hydrus-1D model constructed in this study was based on measured soil hydraulic characteristic parameters, and the authenticity of the input parameters laid a solid foundation for simulation reliability. Verified by the soil column experiment of D20 treatment, the simulated values of soil wetting front migration, cumulative infiltration, and profile moisture content were highly consistent with the measured values, with R^2 values all exceeding 0.988, MAE and RMSE values below 0.700, and T-test correlation coefficients ranging from 0.994 to 0.999, indicating no significant differences. These results fully demonstrate that the model can accurately simulate the vertical migration process of soil moisture after adding WSC.

Such high accuracy and reliability, combined with the inherent efficiency and flexibility of numerical simulation, endow it with significant potential to replace or partially replace conventional infiltration experiments [35,36]. The established model can not only simulate various scenarios (different particle sizes, addition amounts, and mixed application depths) but it can also continuously and non-invasively output dynamic moisture data at any spatio-temporal node (e.g., moisture content at specific depths). This overcomes the limitations of conventional experiments, including limited sampling points and soil disturbance, and is more favorable for mechanistic analysis.

4.2. Effects of Addition Amount and Particle Size on Soil Moisture Movement

The simulation results showed that the addition of WSC significantly altered the moisture movement of silty loam (Figures 4–7). With an increasing amount of WSC, the soil wetting front migration distance, cumulative infiltration, infiltration rate, and profile moisture distribution all increased, and the enhancement effects became pronounced over time, which were 21.77–112.24%, 25.70–172.23%, 24.18–109.51%, and 6.26–22.64% higher than CK, respectively. This can be attributed to the following factors: as a porous material, WSC has a well-developed pore structure; the incorporation of WSC into the soil alters the soil structure, resulting in increased soil porosity and reduced bulk density. As reported by Liu et al. [29], the addition of WSC increased the soil pore volume content by 4.84–13.60% compared with CK, particularly for fissure pores ($>500\text{ }\mu\text{m}$), and the enhancement effect increased with an increasing addition amount or particle size. As shown in the SEM results (Figure 1), WSC exhibited a macropores–micropores multi-level pore structure, in which macropores primarily facilitate soil moisture infiltration, whereas micropores dominate soil moisture retention. Biochar, a porous soil amendment, can also reduce soil bulk density and increase soil porosity upon application [7]. As Omondi [37] summarized from previous studies, the addition of biochar could reduce the average value of bulk density by approximately 7.6% and increase soil porosity by 8.4%. Secondly, WSC contains abundant mullite crystallites, whose crystal structure is composed of $[\text{AlO}_6]$ octahedral chains and $[(\text{Al,Si})\text{O}_4]$

tetrahedra [38], indicating that these materials are strongly hydrophilic. Moreover, the parallel arrangement of mullite crystallites forms numerous intercrystalline capillary pores between pore walls, endowing WSC with the capacity for rapid water absorption and slow water release (Table S1) [17]. As shown in Table 1, the addition of WSC increased soil saturated hydraulic conductivity by 50–1133.33% compared with CK, with the B20 treatment exhibiting the most significant enhancement effect. Therefore, the addition of WSC enhances the soil's moisture conductivity, thereby promoting downward moisture movement and resulting in increased cumulative infiltration and infiltration rate. The increase in soil porosity and the unique internal pore structure of the WSC also improve the soil's water-holding capacity. Moreover, as the addition amount increases, the soil structure becomes looser and the water-conducting capacity becomes stronger, rendering these improvements even more pronounced. These results further supported our previously proposed hypothesis that the improvement effect increases with an increasing addition amount.

The effect of particle size of WSC on moisture movement varied with the addition amount. There was no significant difference among all particle sizes at a 5% addition amount, and the effect of particle size at 10% and 20% addition amounts exhibited pronounced polarization: no significant differences existed among the B, C, and D particle sizes, but all were significantly higher than the A particle size. This phenomenon may be related to the regulatory effect of particle size on soil pore structure. Similarly, Zou et al. [39] investigated the effects of a biochar addition amount and particle size on moisture infiltration and found that the addition amount and particle size affected soil porosity through an interactive effect, with the addition amount showing a more significant influence on soil porosity. A higher addition amount led to a more pronounced effect on moisture infiltration. In this study, the A particle size WSC was close to the soil particle size and contained relatively few large pores itself. When mixed with the soil, it was difficult to form a pronounced macropore structure, resulting in a limited improvement in water conductivity. In contrast, the B, C, and D particle sizes were considerably larger than the soil particles and were capable of effectively constructing a stable macropore network, thereby significantly enhancing water conductivity [34]. Among them, for WSC of particle size A, a 5% addition amount slightly optimized the pore structure; at a 10% addition amount, excessive fine particles filled and blocked the soil macropores, weakening infiltration, thus treatment A10 was slightly lower than A5. At a 20% addition amount, the WSC reconstructed the pore structure, and the infiltration was greatly improved. This phenomenon reflects the interactive effect between particle size and the addition amount. This further indicates that at medium- and high-addition amounts, the effect of particle size difference on soil moisture migration is mainly achieved by regulating pore structure. Based on the EWM-TOPSIS comprehensive evaluation, it was determined that the B20 treatment exhibited the optimal improvement effect on soil infiltration and storage capacity. The effect of particle size differed from our hypothesis, but similar variation trends had been reported in biochar amendment studies [39], indicating that the change in soil infiltration was not caused by particle size or addition amount individually, but by their coupled interaction.

However, in contrast, studies on the effects of biochar amendments—which are also characterized by lightweight and porous properties—on soil infiltration had generally shown opposing trends. For example, Wang et al. [40] investigated the effects of biochar application on the moisture infiltration process and soil profile moisture distribution in sandy loam soil and found that biochar treatment prolonged the infiltration duration and reduced the wetting front migration distance and infiltration rate. Results from Sun et al. [41] also demonstrated that compared with unamended clay soil, biochar addition increased the wetting front migration time by 10.2–257.9% and reduced cumulative infiltration by 14.1–62.4%.

Zou et al. [39] studied the effects of mixed-based biochar on moisture infiltration in aeolian sandy soil and found that biochar treatments reduced the cumulative soil water infiltration compared with CK, and a higher addition amount and finer particle size led to slower wetting front migration velocities. As an inorganic porous material, zeolite applied to loam soil in the study by Ibrahim et al. [13] was found to enhance soil water retention capacity, increasing available water and soil water storage by 3.6–14.7% and 6.8–10.5%, respectively. Moreover, zeolite with a smaller particle size reduced the infiltration rate and hydraulic conductivity by 25.6% and 19.3%, respectively, compared with CK. These inconsistencies may be caused by differences in the raw materials, internal structure, physicochemical properties, and experimental conditions of the soil amendments. Therefore, it is necessary to select appropriate soil amendments according to the actual problems to be solved in order to avoid negative effects, such as deeper leakage loss and groundwater pollution.

4.3. Effects of Mixed Application Depth on Soil Moisture Movement

The application method of WSC has an important impact on its improvement effect, among which the mixed application depth is the key factor in determining its distribution in the soil profile and functional performance [9]. In practical agricultural applications, the application depth of amendments is often affected by tillage methods, crop root distribution, etc. Therefore, determining the optimal mixed application depth of WSC not only contributes to the in-depth analysis of the theoretical mechanism but also provides a scientific basis for precise application in the field [21,39]. As shown in Figures 4–7, all mixed application treatments enhanced the wetting front migration distance, cumulative infiltration, infiltration rate, and soil profile moisture distribution, and these improvements increased with increasing mixed application depth. This is because the mixed layer, due to the addition of WSC, exhibits higher water conductivity and water-holding capacity than the underlying silty loam layer. The greater the mixed application depth, the thicker the high water conductivity and high water-holding layer becomes, facilitating easier downward moisture movement while also retaining more moisture. These findings were consistent with our hypothesis; however, it can be observed that the magnitude of the improvement effect decreased with increasing mixing depth. The conventional tillage depth in the Loess Plateau is usually 0–20 cm, and the active root zone of major crops (e.g., maize and wheat) is also mostly within 0–30 cm [42,43]. The 20 cm mixed application exactly covers the main water absorption area of the root system. Considering diminishing marginal benefits and field operations, the optimal mixed application depth was determined to be 20 cm.

The simulation results also revealed that obvious inflection points occurred in wetting front migration and infiltration rates under different mixed application depths and high-addition treatments. This is because the upper and lower soil layers are distinct heterogeneous soils, with significant differences in soil hydraulic characteristics. An interface resistance effect exists at the boundary, generating a certain degree of resistance that alters moisture movement, thereby producing characteristic inflection points. Berdouki et al. [44] specifically investigated the effects of two-layered soil combinations (sandy loam/clay loam and clay loam/sandy loam) on the infiltration rate via laboratory soil column experiments and found that obvious inflection points occurred in the infiltration rate at the interface between soil layers. Liu et al. [45] reported that due to the difference in permeability between adjacent soil layers, abrupt changes in suction stress occurred at most soil layer interfaces, and such abrupt changes directly led to the appearance of inflection points in the infiltration process. Both this study and previous investigations on infiltration in soils with different textures indicate that during the infiltration process of soil isomers (either by adding amendments or consisting of different soil textures in the upper and lower layers),

the existence of the isomer interface inevitably results in inflection points in the infiltration rate curve.

4.4. Limitations and Future Research Directions

Through laboratory experiments and Hydrus-1D numerical simulation, this study systematically revealed the influence mechanism of WSC on vertical moisture transport in silt loam on the Loess Plateau; however, there were still some limitations. First, this study only employed single-texture soil (silt loam), and its generalizability to soils with other textures requires further verification. Second, the infiltration condition was set as constant-head, without considering real field hydrothermal processes such as natural rainfall, soil evaporation, and crop root water uptake. Moreover, the preferential flow effect induced by root channels and the influence of root water uptake on soil water redistribution were not accounted for, and field-scale validation was lacking.

The application of WSC promotes water infiltration and retention, improves soil water availability (reducing irrigation demand), and enhances the resilience of rain-fed agriculture on the Loess Plateau, thereby providing a practical and feasible pathway to achieve more sustainable crop production and long-term land use. Future research should address the above limitations by extending the investigations to a wider range of soil textures, incorporating coupled rainfall–evaporation boundary conditions [46,47], conducting root–water–amendment interaction studies, and establishing long-term in situ field observations to evaluate the practical application effectiveness of WSC. Meanwhile, it is suggested to combine economic cost–benefit analysis to determine the optimal application schemes under different objectives (e.g., drought resistance and soil moisture conservation, runoff, and sediment reduction).

5. Conclusions

This study, through both indoor experiments and Hydrus-1D numerical simulation, elucidated the influence mechanism of WSC on moisture movement in silt loam soil of the Loess Plateau. The D20 treatment soil column experiment confirmed that the constructed model could accurately simulate the vertical soil moisture movement process following the incorporation of WSC. The results showed that WSC effectively enhanced moisture infiltration and soil water retention by improving soil porosity and reducing soil bulk density. These improvement effects were synergistically regulated by the addition amount and particle size; increasing the mixed application depth further enhanced soil moisture infiltration and storage capacity, however, the magnitude of improvement gradually diminished with increasing depth. The relationship between wetting front migration distance and infiltration time was a power function ($R^2 > 0.998$), and the relationships of cumulative infiltration and infiltration rate with time conformed to the Kostiakov model ($R^2 > 0.977$).

This study provides a low-cost and eco-friendly approach for soil and water loss control and establishes a scientifically sound numerical simulation framework for the large-scale application of porous inorganic soil amendments. Our findings are applicable not only to the Loess Plateau, but they also provide a technical reference for soil and water conservation and drought mitigation in loess-covered regions worldwide. Subsequent work should include field validation and cost–benefit analysis to formulate site-specific application schemes for different regions.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su18147093/s1>, Table S1: The basic composition of WSC.

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References

1. Wang, R.; Shen, L.; Sun, J.; Hou, J.; Geng, G.; Wang, L. Effects of Biodegradable Mulch and Organic Amendments on Maize Root Characteristics and Soil Stabilization Capacity in the Hilly Region of the Loess Plateau. *Sustainability* **2026**, *18*, 2587. [\[CrossRef\]](#)
2. Fenn, K.; Stevens, T.; Bird, A.; Limonta, M.; Rittner, M.; Vermeesch, P.; Andò, S.; Garzanti, E.; Lu, H.; Zhang, H.; et al. Insights into the provenance of the Chinese Loess Plateau from joint zircon U-Pb and garnet geochemical analysis of last glacial loess. *Quat. Res. Interdiscip. J.* **2018**, *89*, 645–659. [\[CrossRef\]](#)
3. Zhang, X.; Song, J.; Wang, Y.; Deng, W.; Liu, Y. Effects of land use on slope runoff and soil loss in the Loess Plateau of China: A meta-analysis. *Sci. Total Environ.* **2020**, *755*, 142418. [\[CrossRef\]](#) [\[PubMed\]](#)
4. Zhao, G.; Ji, Y.; Zhang, T.; Ming, J.; Huang, W.; Gao, L. Characteristics of spatial and temporal variability in the distribution of biological soil crusts on the Loess Plateau, China. *Ying Yong Sheng Tai Xue Bao J. Appl. Ecol.* **2024**, *35*, 739–748. [\[CrossRef\]](#) [\[PubMed\]](#)
5. Huang, Y.; Wei, W.; Chen, S. Effect of Terraces and Rainfall on Water and Soil Loss in Pinus tabulaeformis Plantations in the Semiarid Loess Hilly Region of China. *Ecohydrology* **2024**, *17*, e2720. [\[CrossRef\]](#)
6. Li, Q.; Li, D.; Wang, S.; Wang, J.; Wang, R.; Fu, G.; Yuan, Y.; Zheng, Z. Spatiotemporal patterns and driving factors of soil protection in the wind-water erosion area of Chinese Loess Plateau. *J. Arid Land* **2024**, *16*, 1522–1540. [\[CrossRef\]](#)
7. Ahmad Bhat, S.; Kuriqi, A.; Dar, M.U.D.; Bhat, O.; Sammen, S.S.; Towfiqul Islam, A.R.M.; Elbeltagi, A.; Shah, O.; AI-Ansari, N.; Ali, R.; et al. Application of Biochar for Improving Physical, Chemical, and Hydrological Soil Properties: A Systematic Review. *Sustainability* **2022**, *14*, 11104. [\[CrossRef\]](#)
8. Ghassemi-Golezani, K.; Farhangi-Abri, S. Improving plant available water holding capacity of soil by solid and chemically modified biochars. *Rhizosphere* **2022**, *21*, 100469. [\[CrossRef\]](#)
9. Jia, A.; Song, X.; Li, S.; Liu, Z.; Liu, X.; Han, Z.; Gao, H.; Gao, Q.; Zha, Y.; Liu, Y.; et al. Biochar enhances soil hydrological function by improving the pore structure of saline soil. *Agric. Water Manag.* **2024**, *306*, 109170. [\[CrossRef\]](#)
10. Ma, R.; Tian, Z.; Wang, M.; Zhu, X.; He, Y.; Shi, X.; Liang, Y. Effects of organic amendments on soil hydraulic characteristics in the Mollisols of Northeast China. *Land Degrad. Dev.* **2023**, *34*, 5401–5415. [\[CrossRef\]](#)
11. Wang, S.; Tian, Z.; Ma, R.; Wang, M.; Zhao, Y.; Liang, Y. Effects of composite soil amendments on soil hydraulic characteristics in the Mollisols of Northeast China. *Soil Adv.* **2025**, *3*, 100056. [\[CrossRef\]](#)
12. Wang, H.; Bai, W.; Peng, X.; Han, W.; He, J.; Song, J.; Lv, G. Effect of super absorbent polymer sodium polyacrylate on the bacterial community and associated chemistry of loessial soil. *Arch. Agron. Soil Sci.* **2020**, *66*, 70–82. [\[CrossRef\]](#)
13. Ibrahim, H.; Alghamdi, A. Effect of the Particle Size of Clinoptilolite Zeolite on Water Content and Soil Water Storage in a Loamy Sand Soil. *Water* **2021**, *13*, 607. [\[CrossRef\]](#)
14. Cai, J.; Gao, Y.; Zhou, Y.; Xu, G.; Tian, Q.; Shen, W.; Zhang, M.; Diao, Y.; Zhang, Z. Porous ceramsite from construction muck and wheat straw for wastewater treatment. *Proc. Inst. Civ. Eng. Water Manag.* **2025**, *178*, 198–209. [\[CrossRef\]](#)
15. Zhao, Y.; Liu, H.; Wei, G.; Zhu, Y.; Zhang, S.; Liu, Z.; Wang, X. Effect of sewage sludge separation pretreatment on the performance of sludge-based porous ceramsite. *Constr. Build. Mater.* **2025**, *466*, 140343. [\[CrossRef\]](#)

16. Zheng, W.; Li, Y.; Zhu, Y.; Wang, F.; Zhao, D.; Yang, Y.; Li, H. Preparation of a Novel Structure-Designed Porous Ceramsite for Water Retention. *ACS Appl. Mater. Interfaces* **2023**, *15*, 42753–42763. [[CrossRef](#)] [[PubMed](#)]
17. Chang, Y.; Ma, J.; Sun, X.; Zheng, L.; Guo, X. Effect of Overlying Water Storage Clay Layer on Soil Water Infiltration and Evaporation on the Loess Plateau. *J. Soil. Water Conserv.* **2022**, *36*, 101–109. [[CrossRef](#)]
18. Šimůnek, J.; Genuchten, M.T.V.; Šejna, M. Development and Applications of the HYDRUS and STANMOD Software Packages and Related Codes. *Vadose Zone J.* **2008**, *7*, 587–600. [[CrossRef](#)]
19. Yang, Y.; Chen, Y.; Chen, J.; Zhang, Z.; Li, Y.; Du, Y. The applicability of HYDRUS-1D to infiltration of water-repellent soil at different depths. *Eur. J. Soil. Sci.* **2021**, *72*, 2020–2032. [[CrossRef](#)]
20. Liu, X.; Yang, Y.; Lin, Y. Simulation of organic acid migration and transformation in Mangrove soils based on soil column experiments. *Sci. Rep.* **2025**, *15*, 8354. [[CrossRef](#)] [[PubMed](#)]
21. Soudejani, H.T.; Shayannejad, M.; Kazemian, H.; Heidarpour, M.; Rutherford, M. Effect of co-composting municipal solid waste with Mg-modified zeolite on soil water balance components using HYDRUS-1D. *Comput. Electron. Agric.* **2020**, *176*, 105637. [[CrossRef](#)]
22. Wang, X.; Huang, Z.; Qin, H.; Dai, F. Sensitivity analysis of VG model parameters for infiltration in undisturbed loess under ponding conditions using the HYDRUS-1D model. *Sci. Rep.* **2025**, *15*, 25204. [[CrossRef](#)] [[PubMed](#)]
23. Chen, Y.; Zhang, J.; Wang, Z.; Li, H.; Chen, R.; Zhao, Y.; Huang, T.; Luo, P. Influence of Long-Term Mulched Drip Irrigation on Upward Capillary Water Movement Characteristics in the Saline–Sodic Region of Northwest China. *Agronomy* **2024**, *14*, 1300. [[CrossRef](#)]
24. Gee, G.; Bauder, J.W. Particle-size analysis. *Methods Soil Anal.* **1986**, *5*, 383–411. [[CrossRef](#)]
25. Li, Y.; Sun, Q.; Fu, Y.; Wei, J. Solving the Richards infiltration equation by coupling physics-informed neural networks with Hydrus-1D. *Sci. Rep.* **2025**, *15*, 18649. [[CrossRef](#)] [[PubMed](#)]
26. Nascimento, Í.; Assis, R.; Araújo, J.; de Alencar, T.L.; Freire, A.G.; Lobato, M.G.R.; da Silva, C.P.; Mota, J.C.A.; Nascimento, C.D. Estimation of van Genuchten Equation Parameters in Laboratory and through Inverse Modeling with Hydrus-1D. *J. Agric. Sci.* **2018**, *10*, 102. [[CrossRef](#)]
27. Ngo, V.; Latifi, M.; Simonnot, M. Estimability Analysis and Optimisation of Soil Hydraulic Parameters from Field Lysimeter Data. *Transp. Porous Med.* **2013**, *98*, 485–504. [[CrossRef](#)]
28. Zhang, S.; Lövdahl, L.; Grip, H.; Tong, Y. Soil hydraulic properties of two loess soils in China measured by various field-scale and laboratory methods. *CATENA* **2007**, *69*, 264–273. [[CrossRef](#)]
29. Liu, Y.; Zhou, D.; Sun, X.; Wang, Q.; Ma, J.; Zheng, L. The Influence of Application of Water-Storage Clay on the Hydraulic Properties of Soil on the Loess Plateau. *J. Soil Water Conserv.* **2025**, *39*, 154–162. [[CrossRef](#)]
30. Chen, X.; Duan, M.; Zhou, B.; Cui, L. Effects of biochar nanoparticles as a soil amendment on the structure and hydraulic characteristics of a sandy loam soil. *Soil Use Manag.* **2021**, *38*, 836–849. [[CrossRef](#)]
31. Mohammadzadeh-Habili, J.; Heidarpour, M. Application of the Green–Ampt model for infiltration into layered soils. *J. Hydrol.* **2015**, *527*, 824–832. [[CrossRef](#)]
32. Qin, H.; Peng, Y.; Tang, Q.; Yu, S. A HYDRUS model for irrigation management of green roofs with a water storage layer. *Ecol. Eng.* **2016**, *95*, 399–408. [[CrossRef](#)]
33. Wang, J.; Garg, A.; Huang, S.; Wu, Z.; Wang, T.; Mei, G. An experimental and numerical investigation of the mechanism of improving the rainwater retention of green roofs with layered soil. *Environ. Sci. Pollut. Res.* **2022**, *29*, 10482–10494. [[CrossRef](#)] [[PubMed](#)]
34. Wang, X.; Li, Y.; Si, B.; Ren, X.; Chen, J. Simulation of Water Movement in Layered Water-Repellent Soils using HYDRUS-1D. *Soil Sci. Soc. Am. J.* **2018**, *82*, 1101–1112. [[CrossRef](#)]
35. Zahra, A.; Amir, V. Modeling root water uptake of landscape groundcovers with HYDRUS-1D and particle swarm optimization. *Agric. Water Manag.* **2025**, *322*, 109972. [[CrossRef](#)]
36. Ishmeet, K.; Afua, A.; Mante, R.; Francis, Z.; Kayla, M.; Kurt, G.; Taras, L. Estimation of soil hydraulic parameters for fine-textured soils using HYDRUS-1D coupled with PEST. *Agric. Water Manag.* **2025**, *322*, 109947. [[CrossRef](#)]
37. Omondi, M. Quantification of biochar effects on soil hydrological properties using meta-analysis of literature data. *Geoderma* **2016**, *274*, 28–34. [[CrossRef](#)]
38. Schneider, H.; Fischer, R.; Schreuer, J. Mullite: Crystal Structure and Related Properties. *J. Am. Ceram. Soc.* **2015**, *98*, 2948–2967. [[CrossRef](#)]
39. Zou, Y.; Zhang, S.; Shi, Z.; Zhou, H.; Zheng, H.; Hu, J.; Mei, J.; Bai, L.; Jia, J. Effects of mixed-based biochar on water infiltration and evaporation in aeolian sand soil. *J. Arid Land Issue* **2022**, *14*, 374–389. [[CrossRef](#)]
40. Wang, J.; Shi, D.; Li, Y.; Chen, A.; Feng, S.; Liu, C. A Study on Infiltration Characteristics and One-Dimensional Algebraic Model Simulation in Reclaimed Soil with Biochar. *Water* **2023**, *15*, 2985. [[CrossRef](#)]
41. Sun, Y.; Wang, X.; Wu, Q.; Zong, T.; Xin, X.; Xie, J.; Yang, J. Use of rice straw nano-biochar to slow down water infiltration and reduce nitrogen leaching in a clayey soil. *Sci. Total Environ.* **2024**, *20*, 174956. [[CrossRef](#)] [[PubMed](#)]

42. Thidar, M.; Gong, D.; Mei, X.; Gao, L.; Li, H.; Hao, W.; Gu, F. Mulching improved soil water, root distribution and yield of maize in the Loess Plateau of Northwest China. *Agric. Water Manag.* **2020**, *241*, 106340. [[CrossRef](#)]
43. Wang, B.; Zheng, L.; Ma, J.; Sun, X.; Guo, X.; Guo, F. Effective root depth and water uptake ability of winter wheat by using water stable isotopes in the Loess Plateau of China. *Int. J. Agric. Biol. Eng.* **2016**, *9*, 27–35. [[CrossRef](#)]
44. Berdouki, A.; Besharat, S.; Zeinalzadeh, K.; Cruz, C. The effect of soil texture, layering and water head on the infiltration rate and infiltration model accuracy. *Irrig. Drain.* **2024**, *73*, 846–865. [[CrossRef](#)]
45. Liu, S.; Yuan, Z.; Xiao, Y.; Fang, Q.; Liu, H. Profiles of suction stress of layered soils under infiltration conditions and its applications. *Eur. J. Environ. Civ. Eng.* **2024**, *29*, 64–88. [[CrossRef](#)]
46. Zheng, H.; Bai, J.; Niu, P.; Peng, T.; Jin, Z.; Bao, H.; Naqvi, S.A.F.; Guan, Y. Soil water balance in response to rainfall variability over a dammed valley farmland in the Chinese Loess Plateau. *Ecol. Indic.* **2025**, *175*, 113594. [[CrossRef](#)]
47. Garbanzo, G.; Cameira, M.; Paredes, P.; Temudo, M.; Ramos, T. Modeling soil water and salinity dynamics in mangrove swamp rice production system of Guinea Bissau, West Africa. *Agric. Water Manag.* **2025**, *313*, 109494. [[CrossRef](#)]

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