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Study on the Influence of Rainfall Intensity on the Response of Shallow Soil Moisture to Rainfall in Loess High-Fill Slope

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Abstract. Rainfall-induced soil moisture dynamic is a key factor that can trigger slope failures and geological disasters on the Loess Plateau. According to long-term, multi-point, and multi-depth on-site monitoring, this study conducts time series analysis to explore the response of soil moisture to rainfall events in loess high-fill slope and the influence of topographic conditions and rainfall intensity on soil moisture dynamics. The findings reveal that topographic conditions significantly influence soil moisture variability. The coefficient of variation (CV) follows a decreasing order as slope surface > slope step > flat terrain. The spatial variability of soil moisture has a negative correlation with depth in the vertical direction. Besides, under similar rainfall amounts, higher rainfall intensity can reduce the optimal lag time by about 50% at all positions except the slope step. The findings of this study can provide valuable insights into the soil moisture dynamics on high-fill slopes and offer a scientific basis for optimizing the soil-water relationship.

Keywords: Loess high-fill slope; rainfall; soil moisture; time series analysis; topographic conditions; rainfall intensity.

1. Introduction

Loess is one of the most widely distributed soil types in northwestern China, covering an area of 640,000 km2 [1]. In recent years, many land remediation projects, such as Gully Land Consolidation, have been conducted to solve the land usage problems on the Loess Plateau. During the remediation process, numerous high-fill slopes have been constructed. These loess high-fill slopes are susceptible to landslides, soil erosion, and other degradation due to internal and external factors [2,3]. Studies indicate that soil moisture dynamics are crucial in surface runoff, erosion, and slope failure [2]. As a result, exploring the soil moisture dynamics of loess high-fill slope is important to understand the soil moisture evolution and optimize the soil-water relationship.

Soil moisture is the crucial link between atmospheric precipitation, surface water, and groundwater. Various factors influence its variability, including topographic conditions and rainfall characteristics [4]. Topographic conditions alter the spatial distribution of soil moisture through slope gradients and position [5]. Lower slope positions often retain higher moisture content due to lateral supply from upslope areas [6]. Rainfall has a direct influence on soil moisture dynamics through its intensity [7]. The amplitude of soil moisture response is positively correlated with rainfall intensity and negatively correlated with soil depth [8,9]. Although considerable advancements have been made in soil moisture dynamics on natural slopes of the Loess Plateau, further research is needed to explore the moisture distribution characteristics of high-fill slopes.

There are various methods for investigating soil moisture characteristics. Compared to the time-consuming and labor-intensive manual sampling, in situ monitoring, remote sensing inversion, and numerical simulation offer broader spatial coverage and higher data accuracy. At the slope scale, soil moisture sensors are extensively used for long-term field monitoring. The primary advantage of this method is its capacity to continuously monitor soil moisture dynamics [10] and accurately capture the complicated moisture variation. However, because of monitoring range constraints, in situ measurement data are difficult to utilize on larger scales [10]. The remote sensing method estimates soil moisture content based on surface reflectance and radiative energy. Despite its efficiency, the detection depth is limited to surface layers [1]. Additionally, interpreting remote sensing inputs is a complicated process, and the reliability of inversion requires further validation [11]. Numerical simulation utilizes limited data to depict hydrological processes on

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different temporal and spatial scales. However, due to model simplifications and parameter uncertainties, it cannot accurately reflect the true soil layer characteristics of loess high-fill slopes, resulting in discrepancies between simulation results and real conditions [12]. In summary, while each method has its unique advantages and limits, in situ monitoring is more suitable for accessing soil moisture dynamics on loess high-fill slopes. It provides accurate time-series data and directly reveals the spatial distribution characteristics of soil moisture.

Theoretical approaches used to understand soil moisture dynamics mainly include classical statistical methods, wavelet coherence analysis, and time series analysis. Classical statistical methods analyze the spatial variability of soil moisture by statistical parameters [13]. However, this approach assumes that soil hydrological properties are independent within a certain spatial range. In contrast, wavelet coherence analysis calculates wavelet coefficients and cross-wavelet spectra to investigate the connection between two sequences [14]. This method is useful for dealing with non-stationary time series. But issues like scale selection, threshold denoising, and wavelet decomposition are still to be solved [15]. Time series analysis is an effective method for studying soil moisture dynamics at the slope scale. For two time-synchronous sequences, the cross-correlation coefficient (CCF) can be used to describe their correlation regardless of their variability [16]. Thus, it can quantitatively reveal the response characteristics of soil moisture to rainfall events. For loess high-fill slopes, time series analysis based on monitoring data can effectively capture the soil moisture characteristics at different positions across the slope.

In the view above, the high-fill slopes on the Loess Plateau change the original surface morphology and soil hydrological processes. To explore the special soil moisture dynamics on the loess high-fill slopes, this study investigates the real response process of soil moisture under rainfall conditions by in situ monitoring and time series analysis. The results are of great significance for understanding the soil moisture dynamics and refining the soil-water relationship on loess high-fill slopes.

2. Materials and Methods

2.1 Study Area

The study area is situated in Nangou Village, Yan'an City, China, within the central region of the Loess Plateau. The region is characterized by a typical semi-arid monsoon climate, with an average annual temperature ranging from 7.7°C to 10.6°C. The precipitation is mainly concentrated from July to September.

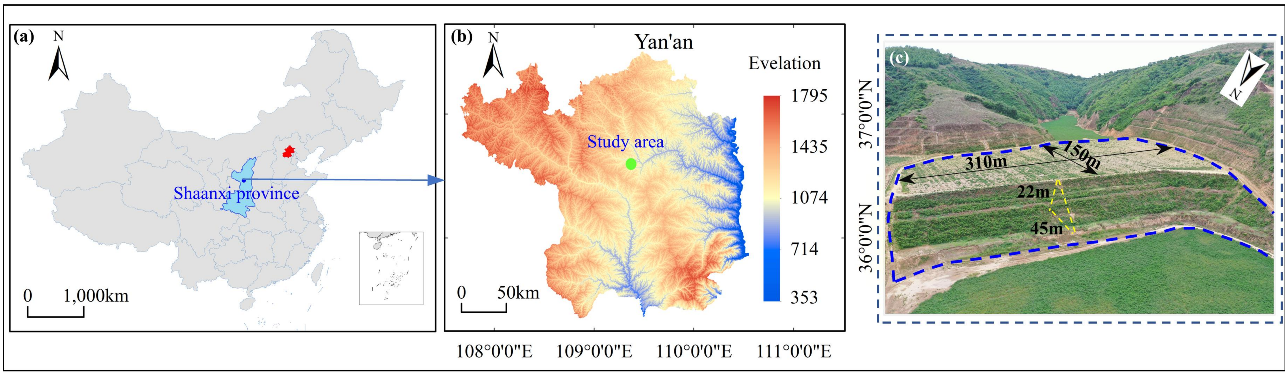

Fig. 1 Overview of study area (a) Map showing the study area location; (b) information of the study area; (c) dimensions of the slope

The high-fill slope investigated in this study was constructed in 2015, and its original topography was a natural ditch. The fill body was designed as four steps, extending about 310 m in the east-west direction and 150 m in the north-south direction, with an elevation of roughly 22m. The slope has a projected length of around 45 meters and a gradient of approximately 28° (Fig. 1). The

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filling soil was sourced from nearby mountains and compacted by basic mechanical methods, with a total filling volume of approximately 7 × 105 m3. The basic properties of the filling soil are shown in Table 1. Additionally, black wolfberry and purple Robinia are planted on the top platform and slope respectively.

Table 1 Basic properties of the filling soil

Depth (cm)	Dry Density (g/cm3)	Void ratio	Hydraulic Conductivity (10-3cm/s)	Plastic Limit (%)	Plastic Index	Particle Size Distribution		
						Clay (%)	Silt (%)	Sand (%)
10	1.42	0.87	0.39	16.59	12.98	12.62	77.41	9.97
50	1.60	0.69	0.09					

2.2 Research Method

2.2.1 In situ monitoring

This research arranged 3 monitoring points (M1-M3) along the central line on the slope to monitor the real-time moisture dynamics, as shown in Fig. 2 (a). The monitoring points M1-M3 are located at the top platform, third step, and second slope respectively.

In the vertical direction, volumetric soil moisture sensors were installed at depths of 10 cm, 20 cm, 30 cm, 50 cm, 100 cm, and 200 cm. The monitoring data were collected every 10 min. A tipping bucket rain gauge was placed at the slope top, with an increment of 0.2 mm. The detailed layout of the monitoring points is shown in Figure 2.

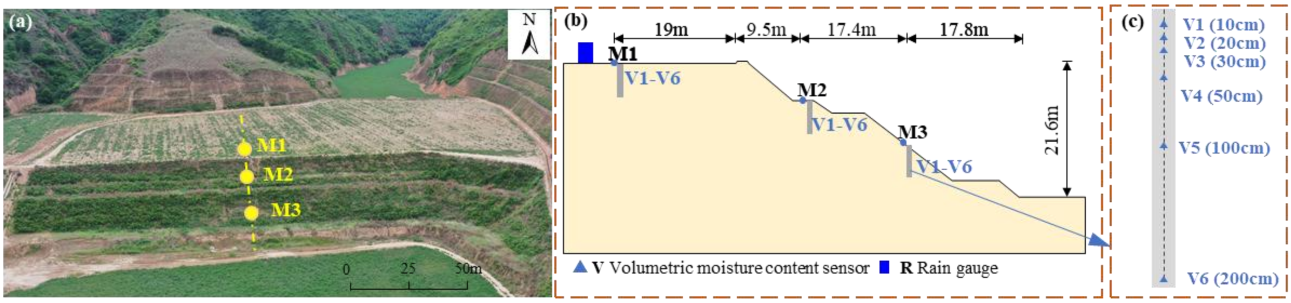

Fig. 2 Monitoring point locations and sensors layout (a) Locations of monitoring points; (b) monitoring layout along the central line; (c) detailed sensors arrangements in the vertical direction

2.2.2 Principle of time series analysis

For two time series x and y with consistent sampling intervals, the equation for CCF calculation is:

$$CCF = \frac{S_{xy}(h)}{\sqrt{S_{xx}(0)S_{yy}(0)}} = \frac{S_{xy}(h)}{\delta_x \delta_y} \quad (1)$$

Where *CCF* represents the cross-correlation coefficient between two sequences *x* and *y* at lag time *h*; S_{xy} (*h*) represents covariance between *x* and *y* at lag time *h*; $S_{xx}(0)$ and $S_{yy}(0)$represent variances of *x* and *y*; δ_x and δ_y represent standard deviations of *x* and *y*; *h* is the lag time. In this study, *h* is set to 1 hour.

For the time series (x_1, y_1), (x_2, y_2), (x_3, y_3) ···, (x_n, y_n), the covariance S_{xy} (*h*) at a time lag *h* can be calculated using the following formula:

$$S_{xy} = \frac{1}{n}\sum_{i=1}^{n-1}(x_i - \bar{x})(y_{i+h} - \bar{y}) \quad h=0, 1, 2\ldots\ldots, n \quad (2)$$

Where $\bar{x}$ and $\bar{y}$ are the mean values of the time series samples *x* and *y*, respectively.

Combining the two equations above, CCF at the lag time *h* can be calculated, along with the double standard deviation of the sequence. When CCF=0, the two sequences are significantly uncorrelated; when CCF exceeds twice the standard deviation, the two sequences are uncorrelated. Conversely, if CCF is less than twice the standard deviation, the sequences are deemed uncorrelated.

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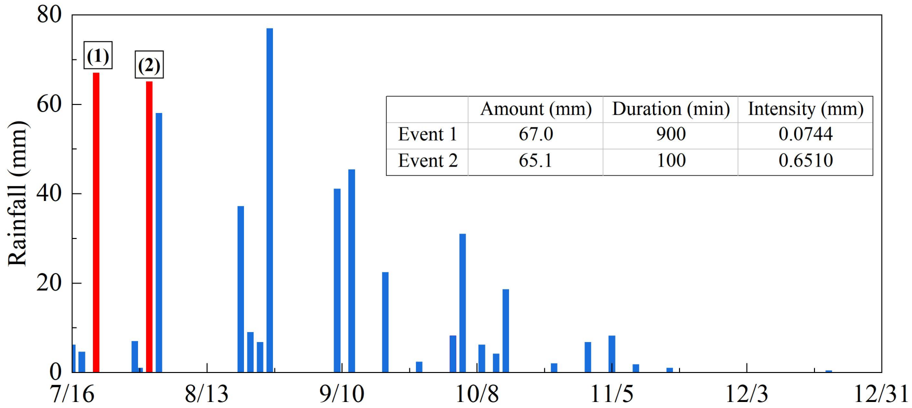
3. Results

3.1 Rainfall Events and Soil Moisture Dynamics

The monitoring data from July 16, 2019, to December 31, 2019 is used for analysis. Independent rainfall events were identified based on the criterion that no other rainfall occurred the day before or after the event. Accoring to the monitoring rainfall data, 27 rainfall events directly influenced the soil moisture at a depth of 10 cm, with a total amounts of 539 mm. Two distinctive rainfall events were selected to analyze the impact of rainfall intensity on the soil moisture dynamic, as shown in Fig. 3. Among them, Events 1 and 2 were short-duration rainstorms with differing rainfall intensities.



	Amount (mm)	Duration (min)	Intensity (mm)
Event 1	67.0	900	0.0744
Event 2	65.1	100	0.6510

Fig. 3 Rainfall events during the research period and characteristics of two selected events

Table 2 summarizes a statistical analysis of soil moisture throughout the study period. Soil moisture content at monitoring locations varied from 17.13 to 50.46 cm^3/cm^3. CV ranged from 1.35% to 30.36%, which indicates weak variability (CV < 10.00%) and moderate variability (10% ≤ CV < 100%). CV exhibited a declining trend in the vertical direction, suggesting a negative correlation between CV and soil depth. Shallow soil moisture is more susceptible to rainfall, temperature, and evapotranspiration, and the water movement is most active.

Table 2 Statistical characteristics of moisture content

M1						
Depth (cm)	10	20	30	50	100	200
Average (cm^3/cm^3)	19.52	23.29	27.48	28.49	46.16	46.29
CV (%)	25.87	11.90	5.35	3.84	7.83	1.35
M2						
Depth (cm)	10	20	30	50	100	200
Average (cm^3/cm^3)	21.76	17.42	25.48	27.49	27.30	25.56
CV (%)	28.05	23.38	11.25	5.56	4.08	2.60
M3						
Depth (cm)	10	20	30	50	100	200
Average (cm^3/cm^3)	20.42	25.00	24.80	20.07	17.11	31.60
CV (%)	30.36	26.72	19.69	16.45	10.16	1.47

3.2 Analysis of the Correlation Between Rainfall and Soil Moisture

Figure 4 depicts the autocorrelation of rainfall and soil moisture sequences based on Eq (1). The rainfall sequence exhibits high randomness, implying that rainfall events are independent, with no correlation between previous and subsequent rainfall events, as illustrated in Fig. 4(a). Figure 4(b) - 4(d) show the autocorrelation of soil moisture at hourly scale. The previous soil moisture content at various depths significantly influences the subsequent soil moisture content.

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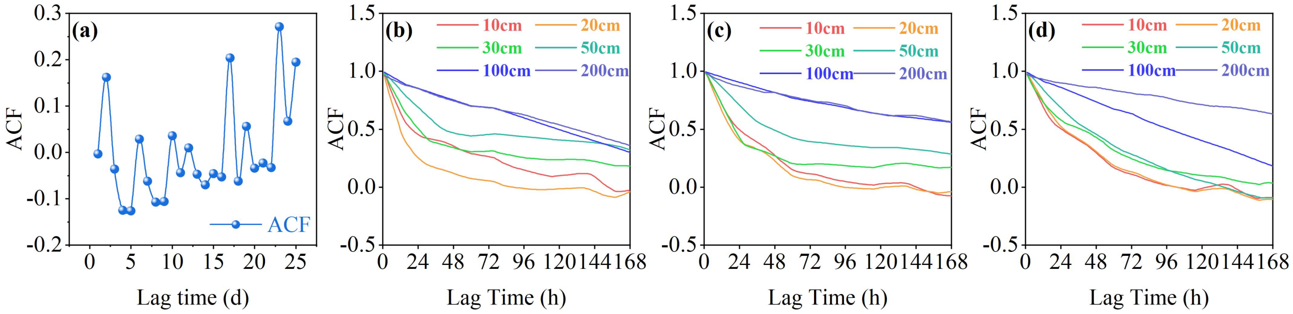

Fig. 4 Autocorrelation analysis of rainfall events and soil moisture at different positions. (a) rainfall; (b)-(d) are soil moisture at M1, M2, M3, respectively

According to Eq (1) and (2), cross-correlation analysis was performed on the rainfall and soil moisture time series, as shown in Figure 5. The cross-correlation dynamics between rainfall and soil moisture reveal clear stratification. Soil moisture at depths of 10-30 cm has a CCF value greater than twice the standard deviation in most situations, showing a considerable association in response to rainfall events. At 50-200 cm, soil moisture occasionally responds to rainfall but with lower CCF values, reflecting a weaker correlation. As a result, soil moisture in the shallow layers is more susceptible to rainfall events and shows a higher sensitivity in response.

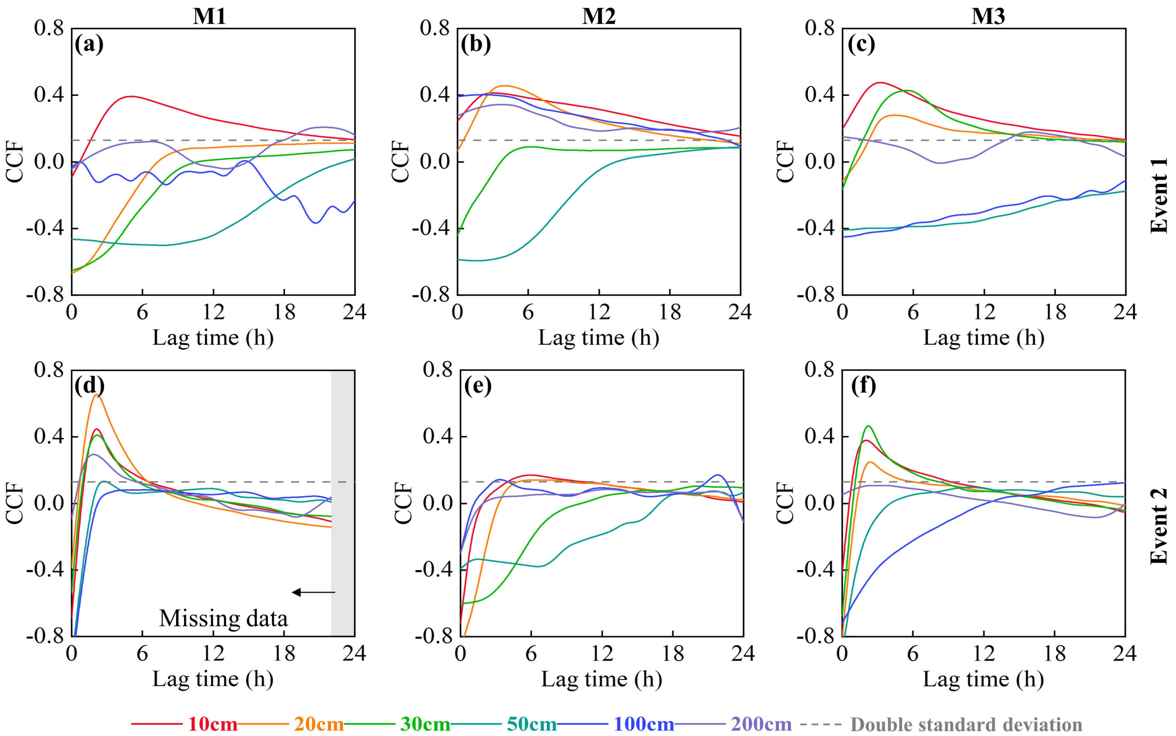

Fig. 5 Cross-correlation analysis of rainfall and soil moisture. Each column represents a monitoring location, and each row represents a selected rainfall event. For example, Fig. b shows the CCF between soil moisture and rainfall at different depths of M2 in Event 1

When rainfall events occur, soil moisture at a depth of 10 to 30 cm usually reaches a single peak CCF. Since the rainfall response of soil moisture is concentrated within this range, the optimal lag time is defined as the duration between the peak CCF moment and the start of rainfall. The results are summarized in Table 3. The data indicate that the optimal lag time also shows a declining trend with depth, and varies across different slope positions. Therefore, when choosing the observation time for soil moisture after rainfall, depth and slope position are crucial factors that should be taken into account.

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Table 3 Statistics of optimal lag time for selected rainfall events at 10–30 cm depth (unit: h)

	Depth (cm)	M1	M2	M3
Event 1	10	5.2	2.8	3.4
	20	/	3.8	4.6
	30	/	/	5.8
Event 2	10	1.9	5.5	1.8
	20	2	5.6	2.3
	30	2.1	/	2.2

Note: / means no obvious peak CCF was observed.

4. Discussion

4.1 Influence of Topographic Conditions on Soil moisture Dynamics

The statistical analysis of soil moisture across monitoring points revealed notable variations in the spatial distribution of CV (Fig. 6). According to Fig. 6, CV for soil moisture in this study usually goes as follows: slope surface (M3) > slope step (M2) > level terrain (M1). Previous studies have shown that the lower slope position receives water not only from rainfall but also from upslope runoff, leading to higher variability of soil moisture compared to the upper slope. During rainfall events, the lower slope surface receives water through both surface and subsurface runoff [17]. The abundant supply and various water movement cause more frequent and complex moisture dynamics on the slope, which increases soil moisture variability [13]. When the slope gradient decreases, as in the case of flat terrain, soil moisture is only replenished by atmospheric precipitation, lacking the extra input from upslope runoff [16]. The soil moisture variability on flat terrain decreases accordingly. Despite being on similar flat terrain, however, the slope step can intercept water from the upper slope and reduce surface runoff [18]. This process increases the water supply to the step and prolongs the residence time of water [19], thereby increasing the variation of soil moisture compared to the top platform.

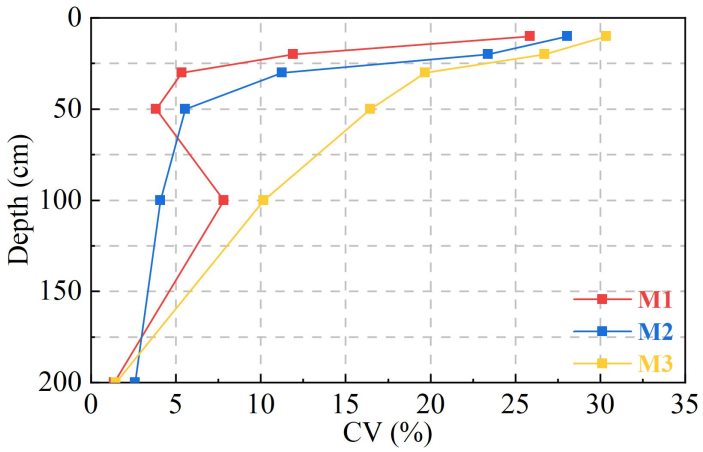

Fig. 6 Variation of CV at different positions in the vertical direction

In the vertical direction, shallower soil layers experience continuous wet-dry cycles due to surface evaporation, plant root water uptake, and canopy interception, which intensifies the spatial variability of soil moisture dynamics [20]. As depth increases, CV at different slope positions exhibits a declining trend, and the spatial heterogeneity gradually diminishes (Fig. 6). Nonetheless, some research on the Loess Plateau indicates that depth and CV are positively correlated. In these cases, the impact of topographical factors has been overwhelmed by the influence of vegetation factors [13]. Thus, influenced by slope position, the spatial variability of soil moisture follows the order: slope surface >slope step > flat terrain. As the soil depth increases, the spatial variability diminishes accordingly in the vertical direction.

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4.2 Influence of Rainfall Intensity on soil Moisture Response

Based on the observed optimal lag time, differences in rainfall intensity alter the soil moisture response to rainfall, as shown in Figure 7. Taking Event 1 (67.0mm, 0.0744mm/min) and Event 2 (65.1mm, 0.6510mm/min) as examples: the amounts of both events are comparable, but their intensities differ significantly.

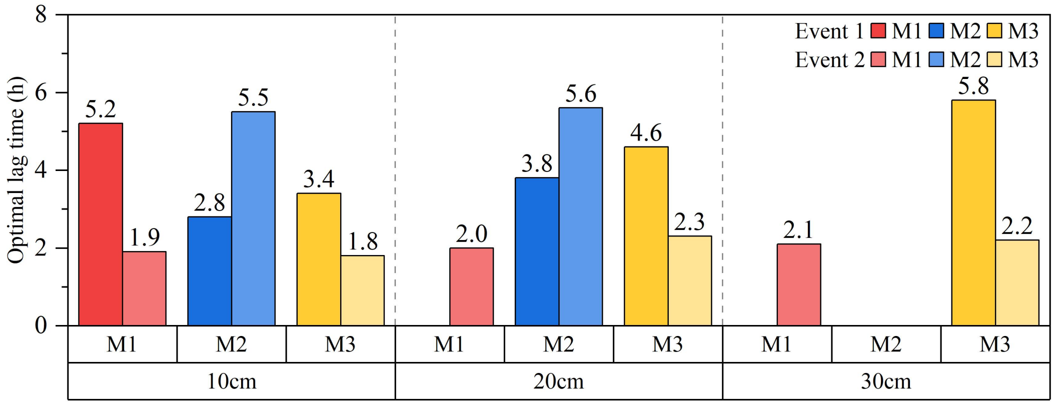

Fig. 7 Effect of rainfall intensity on the optimal lag time at different positions during selected events

Although the rainfall amounts are similar, high-intensity rainfall can supply ample water for infiltration and facilitate rapid movement into deeper soil layers [21]. As shown at the top platform and slope surface, rainfall can quickly and sufficiently supply moisture to the soils as rainfall intensity increases. The optimal lag time in Event 2 is approximately 50% shorter than that in Event 1. However, under extreme rainfall intensity, raindrops cause soil aggregates to erode and form a sealing layer on the soil surface [22], thereby decreasing the infiltration rates[4]. This process causes abundant water supply on the slope step to remain on the surface and infiltrate slowly, thus extending the optimal lag time. As a result, the optimal lag time is effectively shortened by an increase in rainfall intensity except for the slope step.

5. Conclusion

Based on long-term, multi-point, and multi-depth on-site monitoring, this research uses time series analysis to investigate the relationship between soil moisture dynamics and rainfall intensity in high-fill loess slopes on the Loess Plateau. The following conclusions were drawn:

(1) The spatial variability of soil moisture follows the relative order: slope surface > slope step > flat terrain.

(2) The variability of soil moisture in the vertical direction at different positions all exhibits a decreasing trend with increasing depth.

(3) When rainfall amount is similar, an increase in rainfall intensity can shorten the optimal lag time at all positions except the step.

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