

Displacement vector angle derived from deep displacement three-dimensional measurement sensor characterize landslide deformation evolution

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**Displacement vector angle derived from deep displacement three-dimensional measurement sensor
characterize landslide deformation evolution**

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Abstract

Accurately characterizing the internal deformation evolution of landslides is crucial for early landslide warning. However, traditional deep displacement monitoring mainly relies on displacement in a single direction and its derivative, which is insufficient to reflect the evolution of landslide deformation direction. Therefore, this paper proposes the displacement vector angle, a parameter calculated from the horizontal and vertical displacements simultaneously acquired by distributed deep displacement three-dimensional measurement sensor, used to characterize the evolution of the internal deformation direction of landslides. To verify the usability of this parameter, a 51-hour landslide model experiment was conducted using a self-built landslide simulation experimental platform, and the displacement vector angle was compared and analyzed with traditional kinematic parameters such as displacement, displacement velocity, and displacement acceleration. The results show that in the main deformation zone, the displacement vector angle can respond earlier to the evolution of landslides from compression deformation to accelerated creep. Based on the evolution law of the displacement vector angle, a preliminary four-stage landslide warning framework was established. Overall, the displacement vector angle can continuously characterize the evolution of the internal deformation direction of landslides from vertical compression to horizontal sliding, providing a new indicator with clear physical meaning and engineering application potential for early landslide warning.

Key words: landslide warning; deep displacement monitoring; deep displacement three-dimensional measurement sensor; displacement vector angle; deformation evolution

1. INTRODUCTION

Landslide is one of the world's major natural disasters, typically triggered by rainfall, earthquakes, and human engineering activities, posing a serious threat to the lives of residents and infrastructure in mountainous areas(Nadim et al. 2006; Prasad et al. 2016; Jaafari 2024). With the increasing frequency of extreme rainfall events globally, the probability of landslide disasters is constantly rising, making the establishment of accurate and reliable landslide monitoring and early warning methods a crucial topic in current geological disaster prevention research(Alcántara-Ayala 2025). Landslide instability is a gradual evolutionary process(An et al. 2026), usually accompanied by a series of precursory phenomena such as internal deformation, crack propagation, and slip surface formation before final failure (Ding et al. 2025). Therefore, timely acquisition of information on the internal deformation of landslides is of great significance for improving early warning capabilities.

Landslide monitoring parameters include stress, displacement, rainfall, and groundwater (Pecoraro et al. 2019), among which displacement directly reflects the slope deformation process and is currently the most widely used monitoring indicator (Alam et al. 2024). Depending on the monitoring location, displacement monitoring is mainly divided into surface displacement monitoring and deep displacement monitoring (Shentu et al. 2011). Currently, surface monitoring technologies such as GNSS (Yasyukevich et al. 2024), 3D laser scanning(Bi et al. 2021), and InSAR (Osmanoğlu et al. 2016)are relatively mature, offering advantages such as high measurement accuracy and automation. However, because surface displacement usually lags behind internal slope deformation, its monitoring results often fail to reflect the internal failure process during the landslide's incubation stage in a timely manner(Wei et al. 2026). In contrast, deep displacement can directly reflect the internal shear deformation and slip surface development process of a landslide, allowing for earlier detection of landslide instability precursors, and has therefore received widespread attention in recent years(Alonso 2021; Ma et al. 2023) .

Currently used methods for deep displacement monitoring include borehole inclinometers (Ha et al. 2018), time-domain reflectometry (TDR) (Cho et al. 2024; Lee et al. 2024), and fiber optic grating sensing (Yang and Xu 2023; Theodosiou 2024). However, these methods still have certain limitations: most monitoring methods mainly acquire displacement information in a single direction (usually the horizontal direction), making it difficult to simultaneously acquire the three-dimensional deformation process of landslides; furthermore, they still have shortcomings in terms of measurement range, long-term stability, installation and maintenance, and engineering adaptability, making it difficult to meet the needs of long-term continuous monitoring of complex landslides (Zangerl et al. 2009). To address these issues, our research team previously developed a distributed deep displacement three-dimensional measurement sensor based on the dual-mutual-inductance equivalent voltage method (Shentu et al. 2023). This sensor adopts a mechanically unconstrained series structure, which can simultaneously acquire information such as horizontal displacement, vertical displacement, and tilt angle at different depths of the landslide, providing a data foundation for three-dimensional deformation monitoring.

However, improving measurement capabilities alone cannot guarantee effective early warning; multidimensional data must also be transformed into interpretable response indicators. Existing methods typically use displacement, displacement velocity, and displacement acceleration, which describe the magnitude and rate of change of deformation, but provide limited information on changes in deformation direction (Pang et al. 2024; Strnad et al. 2025). During the transition from compression-dominated deformation to downslope sliding, the relative contributions of horizontal and vertical displacements can change. Furthermore, displacement amplitude varies with landslide type, burial depth, and monitoring location, complicating the conversion of amplitude-based thresholds across different sites. Therefore, response parameters describing the relative relationship between horizontal and vertical deformation can

complement traditional kinematic parameters (Lv et al. 2026).

To address the aforementioned issues, this study proposes displacement vector angle as an indicator, calculated from the horizontal and vertical displacements measured by a distributed deep displacement three-dimensional measurement sensor. The displacement vector angle can be used to describe changes in deformation direction and stage. This study conducted experiments using an artificially constructed landslide simulation test site, comparing the displacement vector angle with displacement, displacement velocity, and displacement acceleration, and establishing a preliminary four-stage early warning framework for specific tests. In addition, the angle threshold proposed in this study is not universally applicable at present; repeated simulation experiments and field verification are needed.

2. EQUIPMENT AND METHODS

2.1. Landslide Simulation System

To verify the accuracy and effectiveness of the displacement vector angle, we designed an artificial landslide simulation experimental device to simulate the landslide process. The entire device consists of three parts: a simulated rainfall and groundwater system, a sensor monitoring system, and a data acquisition system, as shown in Figure 1.

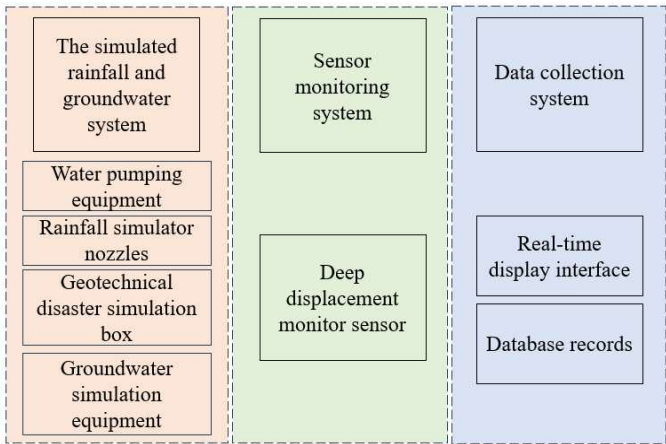


Figure 1. Schematic diagram of landslide experimental equipment frame.

As shown in Figure 2, the landslide simulation test chamber is lifted by a hydraulic support rod, and the door of the test chamber can be opened automatically by gravity. Therefore, it will not hinder the displacement of the soil and rock inside the landslide test chamber. The slope can be freely adjusted between 0° and 60°. The tilt angle in this experiment was 30°.



Figure 2. Details of the landslide simulation test chamber.

In order to induce the transition of the soil and rock mass from a stable state to an unstable state, this study employed methods such as simulated rainfall and simulated groundwater seepage, as shown in Figure 3. The rain system consists of 10 rows and 10 columns of rain nozzles, while the groundwater system consists of a 4-meter-long porous ceramic pipe that allows water to leak slowly and will not be clogged by dirt.



Figure 3. Rainfall and groundwater equipment.

Table 1 shows the settings for rainfall and groundwater flow.

Table 1 Rainfall and groundwater parameter settings

Parameter	Setting value	Explanation
Rainfall intensity	10 mm/h	Maintain high rainwater infiltration efficiency
Groundwater flow	2-5 mm/h	To prevent excessive soil loss due to subsurface runoff.

The deep displacement three-dimensional measurement sensor is then embedded in the landslide simulation experimental chamber. Figure 4 shows the sensor installation and side view of the experimental equipment.

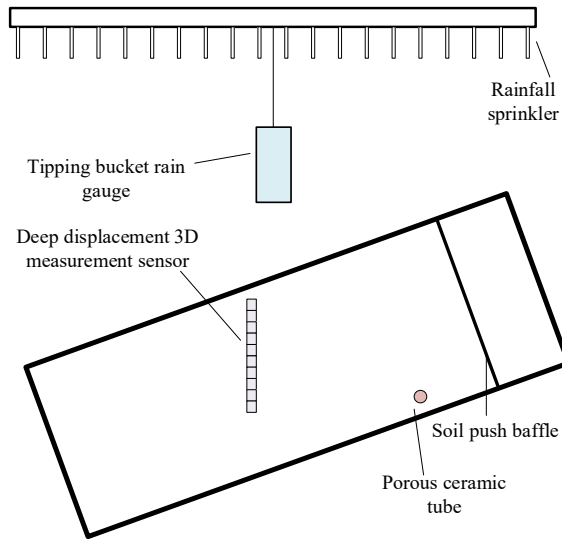


Figure 4. Side view of sensor and experimental equipment.

2.2. Introduction to Distributed Deep Displacement 3D Measurement Sensor

Figure 5 shows the distributed deep displacement three-dimensional measurement sensor independently developed by our research team. It mainly consists of a control terminal (master) and a sensor array (slave) connected in series via a power line and an RS-485 communication line. The master and slave units use a one-master-many-slave communication method. The master is responsible for sending measurement commands to slaves at different addresses and processing the data returned by the slaves using a deep displacement measurement model. Each slave is responsible for receiving measurement commands from the control terminal and executing corresponding operations. In practical engineering applications, the control terminal is located at the surface of the soil and rock mass, and the sensor array is vertically embedded into the soil and rock mass through boreholes. The sensor array consists of multiple identical sensing units, each with a completely identical structure and no mechanical constraints between them, ensuring synchronous deformation with the soil and rock mass. The working principle of the measurement system is shown in Figure 5.

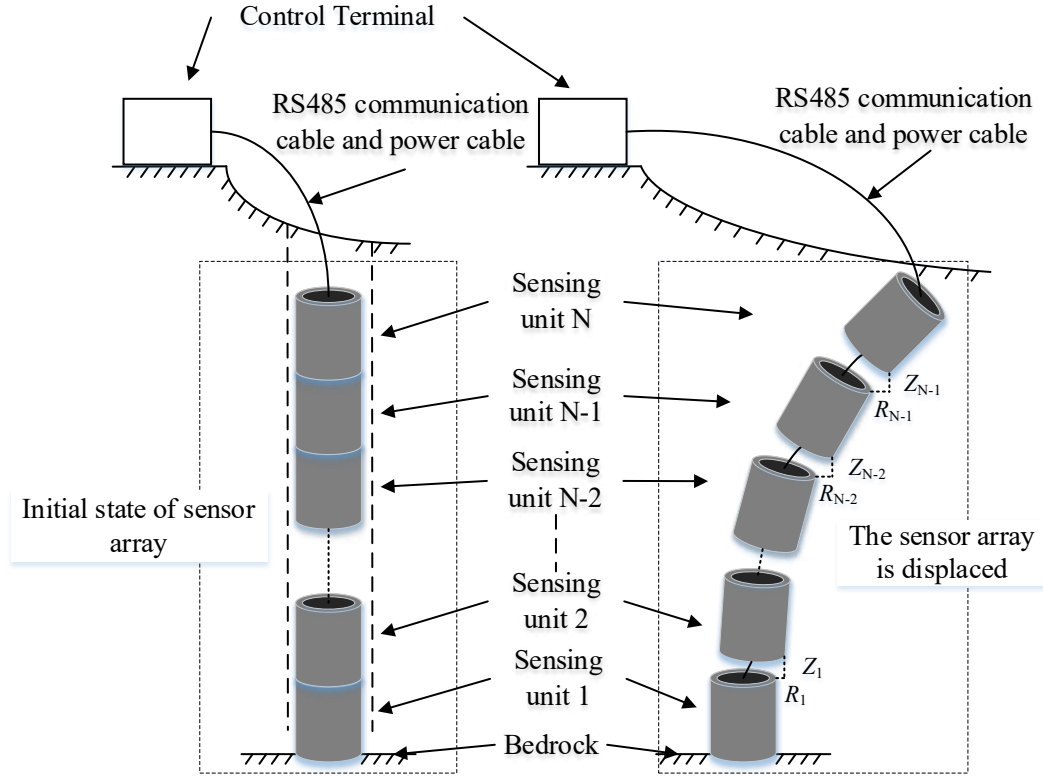


Figure 5. Measurement system working principle diagram

Any two adjacent sensing units constitute a measurement unit, and N sensing units can form $N-1$ measurement units. When the soil and rock undergo deep displacement, each sensing unit will tilt at a certain angle and relative displacement along different directions. By analyzing the collected data through the measurement model, the relative displacement distance between two adjacent sensing units can be calculated. Therefore, $N-1$ displacement measurement units can measure $N-1$ relative displacement values; by adding these values, the total displacement of the soil and rock mass can be obtained, as shown in (1).

$$\begin{cases} R = \sum_{i=1}^{N-1} \Delta R_i \\ Z = \sum_{i=1}^{N-1} \Delta Z_i \end{cases} \quad (1)$$

The sensing unit adopts a columnar structure design, consisting of a PVC tube, an air-core coil, a magnetic core coil, and a PCB board. During installation, it is necessary to ensure that the air-core coil and the magnetic core coil are coaxial. Both ends of the sensing unit are sealed with potting compound, which effectively protects the internal structure of the sensing unit from damage.

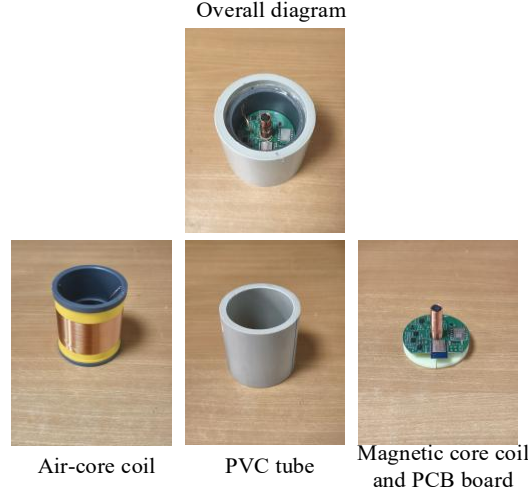


Figure 6. Physical diagram of the sensing unit structure design.

The sensor is based on the dual mutual inductance equivalent voltage method, calculating the displacement distance using the mutual inductance voltage generated by two coils with different parameters. The tilt angle and azimuth angle are measured by the internally integrated attitude sensing module. The distribution of the excitation and response ends of the measurement unit is shown in Figure 7. During measurement, sinusoidal voltage signals u_i with constant frequency and amplitude are sequentially applied to the air-core coil C_{11} and magnetic core coil C_{12} at the excitation end. According to the electromagnetic induction theory, two sinusoidal signals with the same frequency but different amplitudes, denoted as u_I and u_{II} , will be sequentially induced in the air-core coil C_{21} at the response end, corresponding to type I and type II mutual inductance voltages, respectively. When the coil impedance is sufficiently large, the mutual inductance electromotive force can be expressed as:

$$\begin{cases} u_I = \frac{u_i}{L_I} M_I \\ u_{II} = \frac{u_i}{L_{II}} M_{II} \end{cases} \quad (2)$$

Where L_I and L_{II} are the self-inductance coefficients of the air-core coil C_{11} and the magnetic core coil C_{12} , respectively. M_I and M_{II} are the mutual inductance coefficients between the air-core coil C_{11} and the air-core coil C_{21} , and between the magnetic core coil C_{12} and the air-core coil C_{21} , respectively.

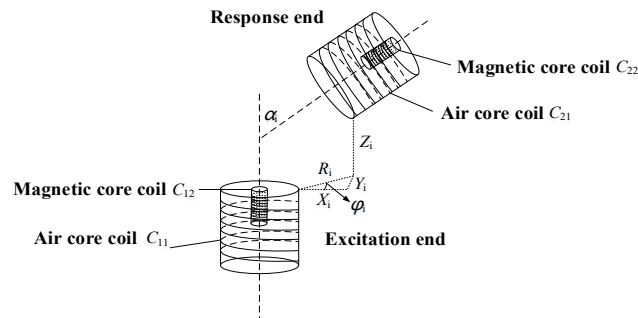


Figure 7. Schematic diagram of measurement unit principle.

u_I and u_{II} are amplified, filtered, and converted to their effective values by the mutual inductance voltage measurement module built into the sensing unit to obtain DC voltages U_I and U_{II} . Theoretical analysis and experimental results show that as the relative distance or tilt angle between two adjacent sensing units increases, the measured type I and type II mutual inductance voltages both decrease. Therefore, the entire measurement model can be transformed into the relationship between mutual inductance voltage and the relative horizontal displacement R_i , relative vertical displacement Z_i , and relative tilt angle α_i between two adjacent sensing units, as shown in (3).

$$\begin{cases} U_I = f(R_i, Z_i, \alpha_i) \\ U_{II} = f(R_i, Z_i, \alpha_i) \end{cases} \quad (3)$$

Subsequently, U_I and U_{II} were calibrated at multiple tilt angles for different horizontal and vertical displacements. After calibration, two sets of voltage surfaces were obtained, namely Type I and Type II mutual inductance voltage surfaces (A_I and A_{II}), each containing 17 surfaces corresponding to different tilt angles. Figure 8 shows the voltage surfaces at some of these tilt angles.

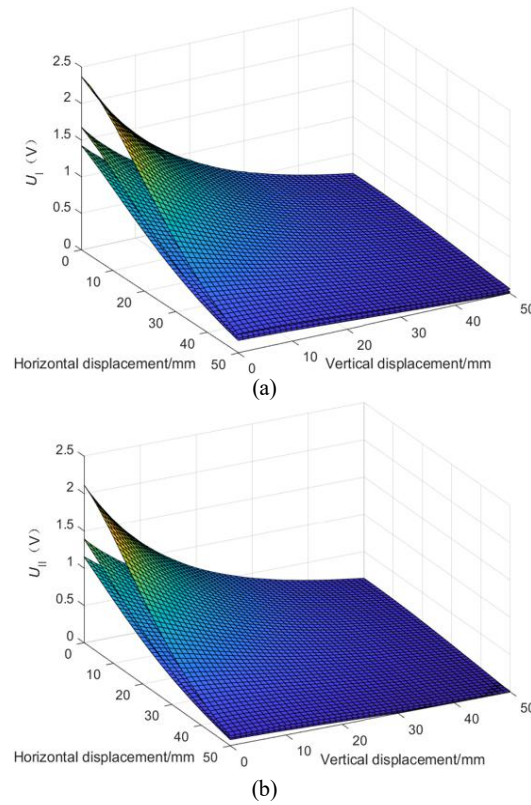


Figure 8. Three-dimensional surface diagram of double mutual inductor voltage. (a) U_I mutual inductance voltage surface- A_I . (b) U_{II} mutual inductance voltage surface- A_{II} .

In the measurement model, the voltage value at any given point may be identical to that at multiple other points. We plot these points of equal voltage yields U_I and U_{II} contour lines, as shown in Figure 9(a) and 9(b) below. Since the mutual inductance coefficients between the coils differ, the trends of the U_I and U_{II} contour lines are different. Therefore, there must be a specific displacement at which the U_I and U_{II} contour lines intersect, as shown in Figure 9(c) below. We will use a tilt angle of 15° as an example.

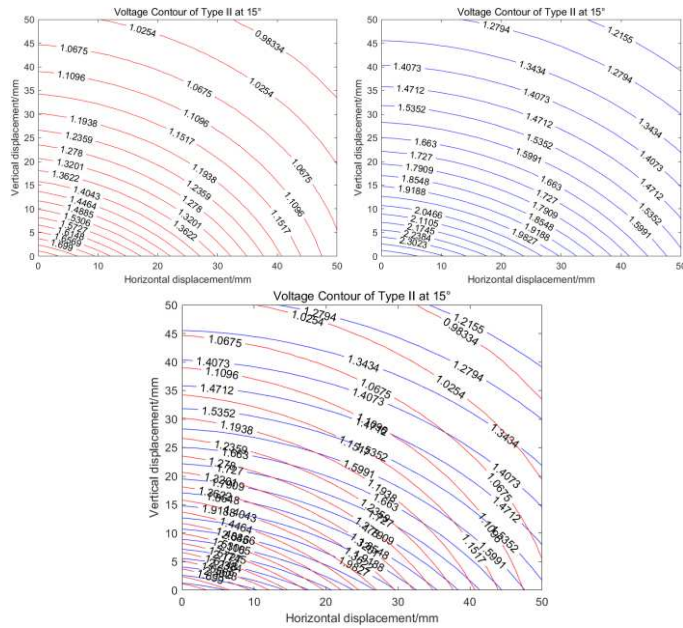
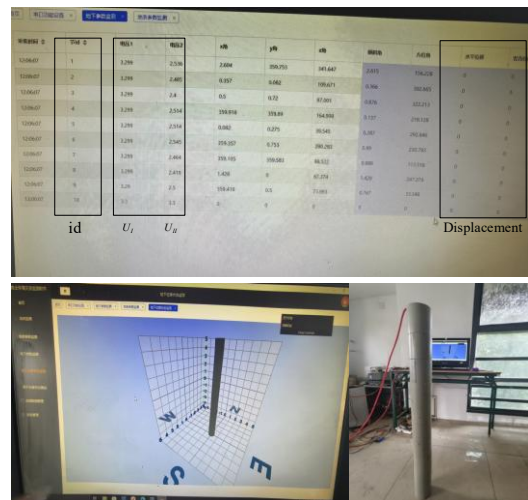


Figure 9. Type I and type II mutual inductance voltage contour at 15°. (a) Voltage Contour of Type I. (b) Voltage Contour of Type II. (c) voltage contour intersection.

Given the current tilt angle, the magnitude of the displacement can be uniquely determined by the coordinates of the intersection points of the U_I and U_{II} contour lines. In this case, the coordinates of these intersection points represent the magnitude of the relative displacement between adjacent sensing units.

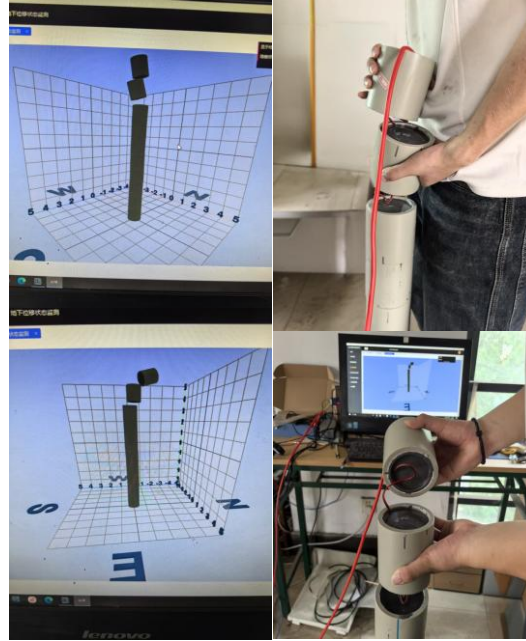
2.3. 3D Status Display of the Sensor

To verify the effectiveness of the deep displacement three-dimensional monitoring sensor in mapping soil and rock displacement, our research team conducted a verification of the mapping relationship between the sensor entity and the digital twin through a client application. As shown in Figure 10 and Figure 11, when displacement, tilting, and other motion operations are applied to different sensing units in the sensor, the corresponding digital twin in the client application can synchronously display the corresponding angle and displacement changes.



196

Figure 10. 3D status interface display when no displacement occurs.



197

198

Figure 11. 3D status interface display when displacement occurs

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2.4. Displacement Vector Angle

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Existing landslide early warning methods based on deep displacement mainly rely on deep horizontal displacement and its time derivative indices (such as displacement velocity and displacement acceleration) for instability detection. However, single deformation parameters generally suffer from problems such as response lag, sensitivity to noise, and difficulty in characterizing the deformation direction inside the landslide; at the same time, their thresholds are also difficult to apply to different working conditions.

206

To overcome the above limitations, it is necessary to construct an early warning index that can simultaneously reflect the amplitude and direction of landslide deformation and adapt to various working conditions. The displacement vector angle is synthesized from the horizontal and vertical displacement vectors, and its direction angle can characterize the deformation state of the slope. Before the landslide becomes unstable, the smaller the displacement vector angle, the more obvious the deviation between the direction of movement and the vertical direction, and the higher the degree of instability of the landslide.

213

Now assume that the three-dimensional displacements of the response end relative to the excitation end in any measurement unit are ΔX_i , ΔY_i , and ΔZ_i , respectively, where ΔX_i and ΔY_i can be expressed by equations (4) and (5), and φ_i is the azimuth angle between two adjacent sensing units. Then the displacement vector angle γ can be calculated by equation (8):

217

$$\Delta X_i = \Delta R_i \cos \varphi_i \quad (4)$$

218

$$\Delta Y_i = \Delta R_i \sin \varphi_i \quad (5)$$

$$X = \sum \Delta X_i, \quad Y = \sum \Delta Y_i, \quad Z = \sum \Delta Z_i \quad (6)$$

$$H = \sqrt{X^2 + Y^2} \quad (7)$$

$$\gamma = \arctan 2(Z, H) \quad (8)$$

When $H = Z = 0$, the displacement vector angle γ is not calculated. Therefore, the range of values for γ is defined as: $0^\circ < \gamma \leq 90^\circ$.

2.5. Physical Interpretation of Displacement Vector Angle

Figure 12 shows on-site images of the initiation, expansion, and landslide of rock and soil cracks during the experiment. Figure 13 is a schematic diagram of the evolution mechanism of displacement vector angle during landslide deformation. Figures 12 and 13 reveal the changing trend and law of displacement vector angle during the evolution of landslide disaster from experimental and theoretical perspectives, respectively. (1) In the early stage of the landslide simulation experiment, the sensing units inside the rock and soil will generate vertical displacement due to soil compression, while the horizontal displacement is almost zero, resulting in a displacement vector angle slightly less than 90° . At this time, the shear strength inside the rock and soil is relatively large, and only a small amount of soil slides due to gravity caused by the tilt of the box. The landslide is in a relatively stable stage. (2) As the experiment progresses, cracks gradually appear on the surface and inside the soil due to the influence of rainfall and groundwater. The sensing units exhibit a certain horizontal displacement, and the displacement vector angle decreases slowly. The landslide body evolves to the slow deformation stage. (3) As the cracks continue to expand and connect with each other, a potential sliding surface is formed. At this time, the cracks cause a larger area of soil to enter an accelerated creep state, and cause the buried deep displacement three-dimensional measurement sensor to generate horizontal and vertical displacements. However, the rate of increase in horizontal displacement will temporarily exceed the rate of increase in vertical displacement, so the displacement vector angle will decrease rapidly. Afterwards, as the landslide is about to become unstable, both vertical and horizontal displacements will increase significantly, resulting in a slow increase in the displacement vector angle. (4) When the crack penetrates the entire rock and soil mass, a relatively obvious sliding surface will be formed. The soil will slide along the sliding surface, which will also cause the sensor to generate large horizontal and vertical displacements. The displacement vector angle will continue to rise, indicating that the landslide has entered the stage of complete instability.

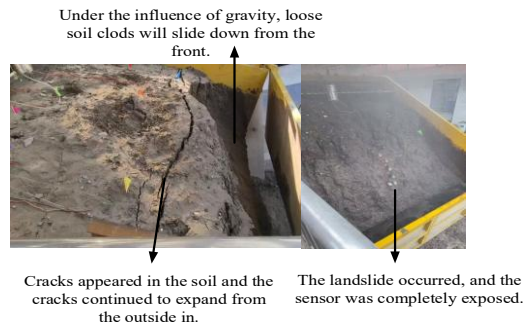
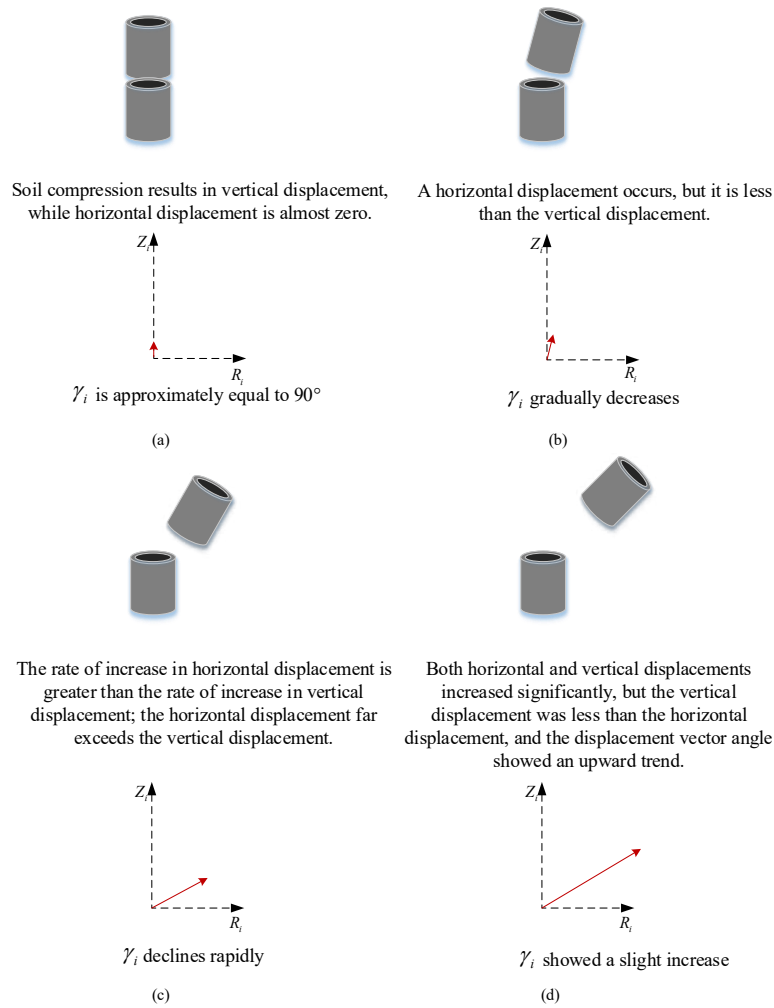


Figure 12. Visualized on-site images of the initiation and propagation of cracks in the soil and rock



252 Figure13. Mechanism of displacement vector angle evolution during landslide deformation.

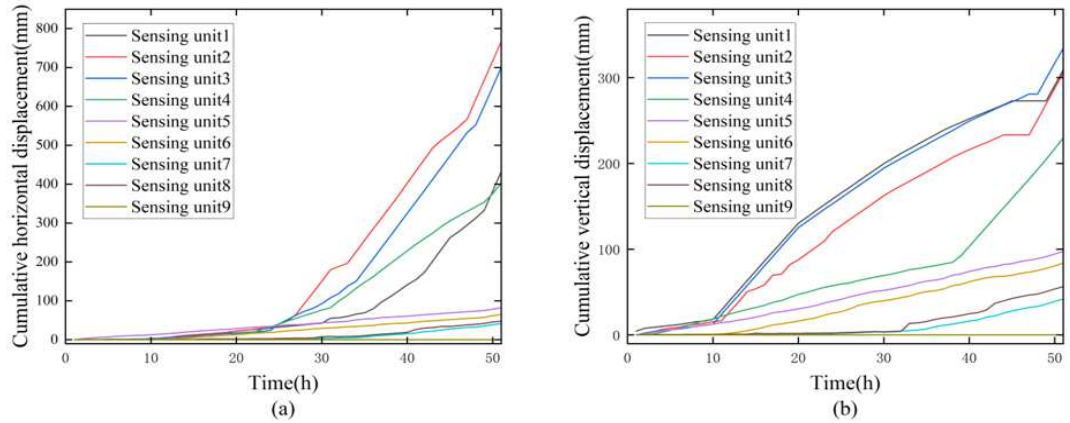
253 As can be seen from the above, this parameter has three advantages: (1) By utilizing a deep
 254 displacement three-dimensional measurement sensor that integrates bidirectional displacement
 255 information, the deformation process can be described more comprehensively; (2) Unlike displacement
 256 amplitude, displacement vector angle reflects the relative relationship between horizontal and vertical
 257 displacement, rather than the absolute displacement magnitude. Therefore, it is less affected by landslide
 258 scale, monitoring depth, and measuring point location, making it more suitable for establishing a unified
 259 early warning threshold applicable to different landslide types and working conditions; (3) By reducing
 260 the influence of inherent random errors in unidirectional measurements, signal stability and anti-
 261 interference capabilities can be improved.

262 3. RESULTS

263 3.1. Experimental Data Presentation

264 The landslide simulation experiment lasted for 51 hours. Figure 14 shows the cumulative horizontal
 265 and vertical displacements measured by the sensing units. A total of ten sensing units were used. The
 266 bottom sensing unit was only used as the excitation end and not as the response end, so no data was

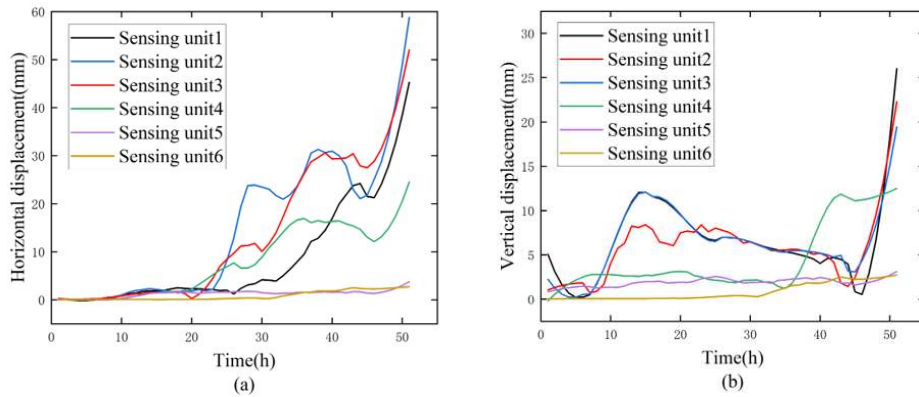
267 collected from it.



268

269 Figure 14. Cumulative deformation curves. (a) Relationship between cumulative horizontal
270 displacement and time. (b) Relationship between cumulative vertical displacement and time.

271 As shown in Figure 14, from a spatial distribution perspective, different sensing units may
272 correspond to different deformation regions. The cumulative displacement changes in the regions where
273 sensing units 1–4 are located are drastic, which can be identified as the main sliding zone or strong
274 deformation zone of the soil and rock mass; the cumulative displacement changes in the regions where
275 sensing units 7–9 are located are very small, usually less than 50 mm, belonging to a relatively stable
276 zone; sensing units 5–6 are located in the weak deformation zone. Therefore, the displacement changes
277 of sensing units 1–6 should be the focus, as shown in Figure 15.



278

279 Figure 15. Horizontal displacement and vertical displacement curves. (a) Horizontal displacement.
280 (b) Vertical displacement.

281 3.2. Displacement Vector Angle of Sensing Units 1-6

282 The figure below shows the change in displacement vector angle of sensing units 1-6, obtained from
283 the horizontal and vertical displacements of sensing units 1-6.

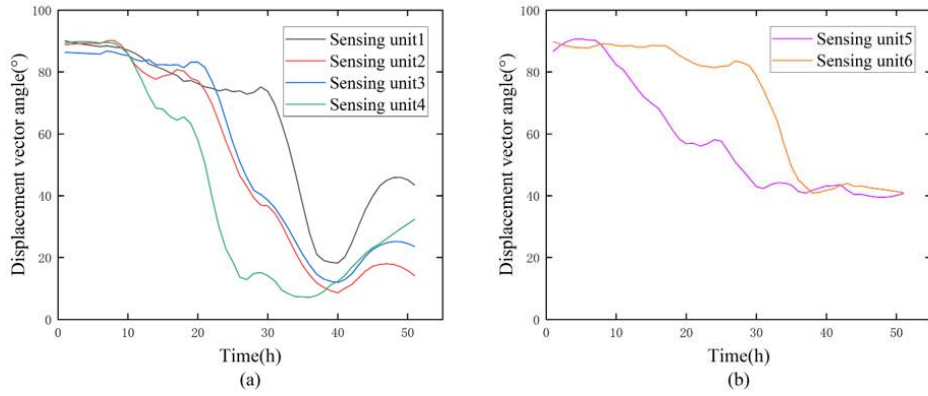


Figure 16. Displacement vector angles change curve. (a) No. 1-4 sensing unit. (b) No. 5-6 sensing unit.

As shown in Figure 16, in the main deformation zone, the displacement vector angle decreases rapidly before the overall sliding, indicating a shift in the deformation mode towards horizontal dominance. In relatively stable regions, the displacement vector angle remains relatively large, and the rate of decrease is slower. Therefore, in this experiment, the displacement vector angle can distinguish the spatial deformation behavior of the landslide.

4. DISCUSSION

4.1. Comparison with Traditional Early Warning Indicators

Displacement velocity and displacement acceleration are essentially obtained by taking the derivative of displacement data. In experimental monitoring, we usually obtain discrete displacement-time data points, so numerical differentiation is needed for approximate calculation. Here, we use the central difference method for calculation. For data sampled at equal time intervals, the central difference method is the most commonly used and highly accurate method. Its principle is to use the displacement values of a target point at two moments before and after it to calculate the instantaneous velocity or acceleration of that point. Since the noise is significantly amplified after the first and second numerical differentiations of the displacement, the Savitzky-Golay filtering method is used here to filter the differentiated result. Suppose you measure displacement s_i at time t_i , and the sampling time interval is Δt , then:

Displacement velocity:

$$v_i = \frac{s_{i+1} - s_{i-1}}{2\Delta t} \quad (9)$$

Displacement acceleration:

$$a_i = \frac{s_{i+1} - 2s_i + s_{i-1}}{(\Delta t)^2} \quad (10)$$

The central difference method requires data before and after the target point, so the first and last points of the data sequence cannot use this formula. For these two endpoints, we can use:

Displacement velocity starting point (forward difference):

$$v_1 = \frac{s_2 - s_1}{\Delta t} \quad (11)$$

Displacement velocity endpoint (backward difference):

$$v_n = \frac{s_n - s_{n-1}}{\Delta t} \quad (12)$$

Displacement acceleration starting point (forward difference):

$$a_1 = \frac{s_3 - 2s_2 + s_1}{(\Delta t)^2} \quad (13)$$

Displacement acceleration endpoint (backward difference):

$$a_n = \frac{s_n - 2s_{n-1} + s_{n-2}}{(\Delta t)^2} \quad (14)$$

Taking sensor unit 1 as an example, the displacement vector angle was compared with the horizontal and vertical displacements, the horizontal and vertical displacement velocities, and the horizontal and vertical displacement accelerations.

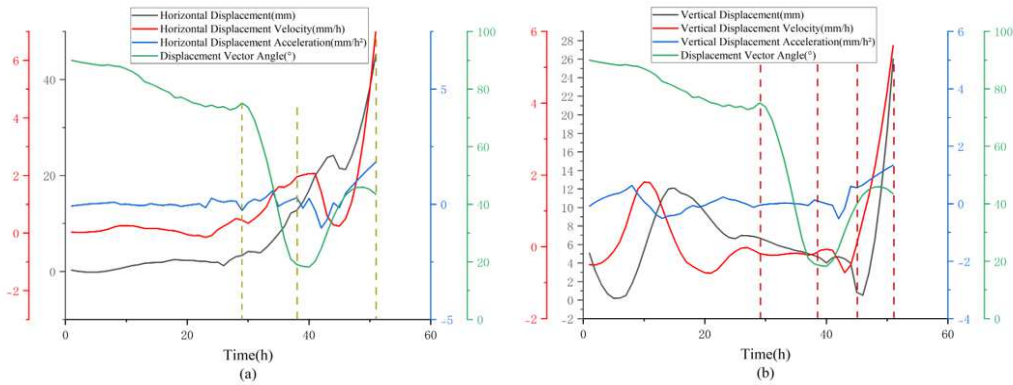


Figure 17. Comparison of results for four parameters.(a) Comparison of horizontal displacement, horizontal displacement velocity, horizontal displacement acceleration, and displacement vector angle. (b) Comparison of vertical displacement, vertical displacement velocity, vertical displacement acceleration, and displacement vector angle.

Figure 17 illustrates the evolution of displacement, displacement velocity, displacement acceleration, and displacement vector angle during landslide deformation over the same time period. Even before the other three kinematic parameters show a significant response to landslide deformation, the displacement vector angle is sufficient to capture the information that horizontal displacement is gradually becoming dominant, quickly identifying changes in the landslide state. We can then use this change to provide early warning of landslide.

4.2. Landslide Warning Level Classification

Based on the above exploration and simulation of displacement vector angle and landslide dynamics evolution, we can roughly divide landslides into four stages, as shown in the figure below.

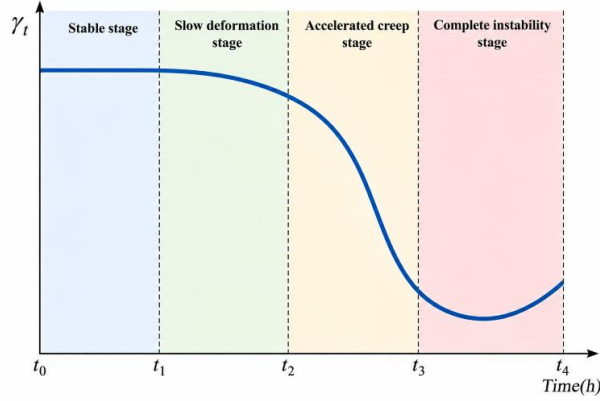


Figure 18. Schematic diagram of landslide deformation stages based on displacement vector angle.

The proposed classification method considers both the value of the displacement vector angle and its time trend. In a relatively stable phase, the value of the displacement vector angle fluctuates within a range of approximately 5° . In the slow deformation phase, the value of the displacement vector angle gradually decreases and typically remains above 70° . In the accelerated creep phase, the value of the displacement vector angle decreases rapidly, reaching a minimum value close to 10° in this experiment. After sliding begins, large-scale horizontal and vertical displacements occur, and the value of the displacement vector angle increases. As the displacement continues to rise, it may reach the upper limit of sensor measurement, at which point the horizontal displacement equals the vertical displacement, and γ is 45° . The boundary values of 85° , 70° , 10° , and 45° in Table 2 are all from this experiment; therefore, they should be considered as preliminary standards for specific experiments, rather than general warning thresholds. Since the same value of γ can occur in both the rising and falling phases, we introduce $\gamma \uparrow$ to represent the rising phase and $\gamma \downarrow$ to represent the falling phase, in order to eliminate ambiguity in phase identification.

Table 2. Landslide warning level classification

Alert Level	Level I: Normal	Level II: Advisory	Level III: Warning	Level IV: Alarm
γ range	$90^\circ > \gamma > 85^\circ$	$85^\circ \geq \gamma > 70^\circ$	$70^\circ \geq \gamma \downarrow > 10^\circ$	$10^\circ \leq \gamma \uparrow \leq 45^\circ$
Landslide movement direction	It mainly moves in the vertical direction.	Gradually deviating from the vertical direction	Increasingly horizontal deformation	Landslide occurs, direction not determined
Stage division	Relatively stable stage	Slow deformation stage	Accelerated creep stage	Complete instability stage
Typical characteristics	Soil compression, vertical movement	Surface cracking, slight displacement	Interconnected cracks, potential slip surface	Continuous slip surface, large-scale sliding

Note: These angle boundaries and trend conditions are derived from a simulation experiment and are preliminary, experiment-specific standards, not general warning thresholds.

4.3. Limitations

This study still has certain limitations. The proposed stage boundaries are based on artificial simulation experiments, they cannot be considered universal indicators until verified with actual field

data. Subsequent studies will be conducted under different slopes, rainfall and groundwater conditions, and soil properties to evaluate their robustness and generalizability.

5. CONCLUSIONS

(1) This paper proposes a landslide response parameter based on a distributed deep displacement three-dimensional measurement sensor—the displacement vector angle. This parameter is calculated from both horizontal and vertical displacements, reflecting not only the deformation amplitude within the landslide but also the evolution of the deformation direction within the landslide.

(2) Based on a self-built landslide simulation experimental platform, a distributed sensor consisting of ten sensing units was continuously monitored for 51 hours. The experimental results show that as the landslide gradually evolves from soil compression to crack propagation, accelerated creep, and overall sliding stages, the displacement vector angle exhibits an evolutionary pattern of "slow decrease—rapid decrease—slow recovery." This change corresponds to the transformation of the landslide's internal deformation mechanism from vertical compression to horizontal shear sliding, and has clear physical significance.

(3) Compared with traditional kinematic parameters such as displacement, displacement velocity, and displacement acceleration, the displacement vector angle can more continuously describe the evolution of the deformation direction within the landslide and exhibits more obvious response characteristics during the accelerated creep stage. This is because the displacement vector angle reflects the change in the relative contribution of horizontal and vertical displacements, while traditional parameters mainly describe the deformation amplitude and its rate of change. Therefore, the displacement vector angle can more effectively reveal the transformation of the deformation mechanism within a landslide.

(4) Based on the evolution law of the displacement vector angle, this paper establishes a four-stage landslide early warning framework, providing a new approach for landslide stage identification and early warning threshold determination. Currently, the relevant thresholds are mainly derived from indoor landslide simulation experiments. Further verification and optimization of the evolution law of the displacement vector angle and the early warning threshold will be conducted using long-term monitoring data from 200 deep displacement three-dimensional measurement sensors deployed in Fuxian County, Yan'an City, Shaanxi Province, to improve its engineering applicability and universality.

In general, the displacement vector angle is not a displacement amplitude index in the traditional sense, but a novel response parameter reflecting the evolution of the deformation direction within a landslide. It can reveal the development process of a landslide from vertical compression to horizontal sliding from the perspective of deformation mechanism, providing a new approach with clear physical meaning for deep displacement monitoring and early landslide warning.

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Author contributions: N.S. provided guidance and conceptualization for this study. Z.S. conceived the research, built the simulation experimental platform, and conducted the experiments. Data processing and analysis, and chart creation were then performed. Q.L., G.Q. and R.T. participated in experimental

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