

Article

Study on Synergistic Characteristics of Accumulation Landslides Supported by Arbor Species

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Abstract: Vegetation slope protection is widely used in slope support engineering as an ecologically friendly support method. There has been a lot of research on herbs and shrubs slope protection, but less on arbor slope protection. Using accumulation landslides as a research subject, a series of physical model tests of arbor slope protection were conducted, using a combination of various monitoring technologies and 3D printing technology that can produce realistic root models. The slope protection effect of arbors and the synergistic characteristics of accumulation landslides were explored using a preliminary analysis. We found that, with the support of arbor roots, (1) the peak-start stage, second peak stage, variable attenuation stage, and linear attenuation stage were the four stages of the anti-sliding force curve. The peak value of anti-sliding force on a slope with root protection increased, and the time it took to reach the peak value increased dramatically. Furthermore, after attaining the peak value, the degree of anti-sliding force attenuation was diminished. (2) The slope displacement showed a downward trend. Moreover, the coefficient of variation of displacement curves in different parts decreased, and slope integrity was enhanced. (3) The degree of slope crack growth diminished, resulting in an arch stress area and improved anti-sliding capacity. (4) There was an apparent “synergetic” tendency in the evolution process of accumulation landslides. Furthermore, the anti-sliding force and displacement curves in different parts had a good correspondence.

Keywords: accumulation landslides; arbor species; physical model experiment; anti-sliding force; displacement; synergistic characteristics



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1. Introduction

Landslides are a very common type of natural disaster. A large percentage of these landslides are accumulation landslides, which pose a significant threat to global economic and social development [1–4]. Soil cohesiveness is diminished as a result of rainfall destabilization, slope foot excavation, and other causes, promoting slope instability and generating accumulation landslides [5–8]. Meanwhile, a variety of complicated ecological processes are continually changing the properties of the slope rock–soil mass, which can affect slope stability. Vegetation, which is crucial in these ecological processes, is considered a key factor in reinforcing slopes and preventing shallow landslides [9–13]. Many landslide case studies [14] and numerical simulations [15–17] have demonstrated that the occurrence of landslides increases in the first few years after tree removal, proving that tree roots can improve slope stability. With increasingly critical environmental issues, including soil erosion, vegetation slope protection is being more widely used [18].

The mechanism of vegetation slope protection has been studied extensively. Researchers presented a reinforced soil theory based on the Mohr–Coulomb strength theory to explain the mechanical effect of vegetation slope protection. When the root–soil composite

is sheared, it is assumed that all plant roots are broken at the same time, and a pioneering model of vegetation root–soil reinforcement was developed (WWM Model) [19–23]. As the WWM model overestimated the shear strength of the root–soil composite, a fiber bundle model (FBM model) was created by scholars to account for the root-by-root fracture, which further improved the mechanical mechanism of root-reinforced soil [24–26]. Ji et al. [27] proposed an energy-based fiber bundle model to predict the reinforcement effect of roots on soil, and compared the prediction results of this model with other fiber bundle models, through in situ direct shear tests of four vegetation root systems. Mao et al. [28] compared the similarities and disparities among models in the Wu and Waldron Model (WWM) family and the Fibre Bundle Model (FBM) family, clarified some misunderstandings or citation biases of these models, and put forward a model classification using a combination of these criteria. In terms of hydrological effects, roots absorb water through transpiration, causing a increase in soil dryness and matrix suction, which indirectly contributes to slope stability [29,30]. Moreover, through soil hydrological effects, the root system can provide a preferred flow for water penetration, altering slope stability [31].

Many academics have studied the effects of vegetation on slope protection in depth. Researchers have examined the root diameter and density of herbaceous plants and shrubs, as well as performing root tensile strength tests. The anchoring effect of roots on soil was discovered, and the dominant tree species in landslide-prone areas were investigated, in order to reduce the risk of landslides [32,33]. Temgoua et al. [34,35] developed a three-dimensional numerical simulation model to evaluate the effects of forest stand structure and root morphology on slope stability. The depth of the root system and the extra cohesiveness given by the root system were shown to be the most important factors in slope stability. The safety factor is most influenced by tree spacing along the slope direction. Furthermore, a rectangular forest distribution plan can greatly improve slope stability. Vergani et al. [36] analyzed the influence of European shrubs on shallow landslides from two perspectives: hydrological and mechanical. They claimed that slope stability is influenced by the physical and chemical properties of soil. Schwane et al. [37] investigated the stability of a shallow landslide in Italy that was supported by shrubs. The slope stability study was updated to include the reinforcement effect of lateral roots, and the root stress-strain behaviors of the WWM and FBM models were quantified. It was discovered that lateral roots have a significant impact on slope stability.

It should be noted that most current researches on vegetation slope protection focus on small plants, such as herbs and shrubs. In situ studies and interior model experiments are difficult to conduct due to the arbor's huge size. Moreover, present research focuses mostly on the mechanism of root–soil interactions, with a lack of systematic studies on the effect of arbor slope protection and the synergistic-evolutionary characteristics of accumulation landslides. In view of this, 3D printing technology was used in this study to finely construct roots that closely resembled natural arbor root morphology. Four sets of vegetation slope protection physical model tests were conducted, in combination with a self-designed landslide model test platform. The effect of arbor slope protection and the synergistic characteristics of accumulation landslide under arbor support were researched in depth, using a comparative analysis of anti-sliding force, slope displacement, and slope cracks, with the goal of providing a reference for vegetation slope protection projects.

2. Materials and Methods

2.1. Experimental Material

With a developed geological structure, complicated topography, and geomorphology, western Henan is situated in the transition zone between China's second and third phases of terrain. Rainfall is concentrated and occurs primarily in the summer, making the area vulnerable to landslides and other geological disasters [38]. Therefore, the soil for this study was taken from western Henan.

A liquid-plastic limit test, compaction test, grain size distribution test using the density meter method, and direct shear test were used to determine the basic physical properties of

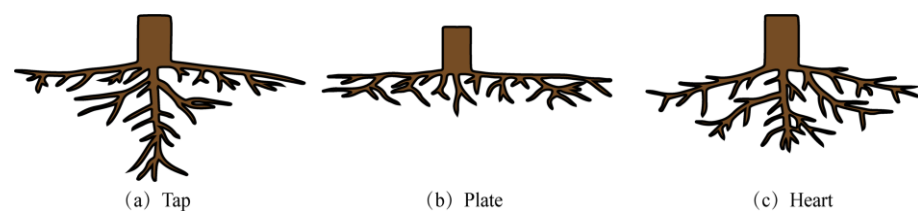
The graph illustrates the particle size distribution of the polyimide film. The Y-axis represents the Percentage pass (%), ranging from 0 to 100. The X-axis represents the Particle size in mm, on a logarithmic scale from 1.000 to 0.001. The curve shows that approximately 100% of the particles are larger than 0.100 mm, and the percentage pass drops sharply to near 0% as the particle size decreases below 0.010 mm.

Particle/mm	Percentage pass (%)
1.000	100
0.100	100
0.050	80
0.010	20
0.005	5
0.001	0

Table 1. The physical mechanics of the soil samples.

Specific Gravity, G _s	Liquid Limit, w_L (%)	Plastic Limit, w_P (%)	Plastic Index, I_P	Maximum Dry Density, ρ_d (g/cm ³)	Optimum Water Contents, w_{opt} (%)	Cohesion, c (kPa)	Internal Friction Angle, φ (°)
2.70	21.4	12.6	8.8	1.77	14.0	11.0	19.4

There are numerous different varieties of arbor species, each with its own root system morphology. As a result, there are many root system morphological classification methods. The classical root morphology classification given by Köstler was used in this study. The tap-, plate-, and heart-like morphologies of the root system are grouped into three architectural groups [39]. Tap-like root systems have longer main roots and shorter lateral roots that extend vertically downward. Plate-like root systems primarily extend horizontally and shallowly downward. Heart-like root systems mostly grow obliquely, with highly-developed lateral roots (Figure 2).



Houpoea officinalis is widely distributed in China, primarily in the forest region between mountains, at elevations of 300–1400 m. Its main root is not apparent, while its lateral roots are well developed, belonging to a heart-like root system. Most notably, *Houpoea officinalis*' bark, buds, and seeds can be employed as medicinal materials, implying a high economic worth [40]. It can also be utilized as a green decorative tree and has been employed extensively in environmental and vegetation slope protection projects. Hence, *Houpoea officinalis* was selected for this experiment. The root system of *Houpoea officinalis* is mainly distributed within 1–3 m underground. In the range of 0–1 m underground, *Houpoea*

officinalis is dominated by fibrous roots, and the slope protection effect is weak, while in the 1–3 m underground range, there are a high number of developed lateral roots, which contribute to the vast majority of slope protection effects. A quantitative scale of 1:100 was used in this experiment, with the roots within 1–3 m underground being the main focus. Three maximum vertical root lengths, 2.0 cm, 2.5 cm, and 3.0 cm, were established, with the root horizontal coverage radius equal to the maximum vertical root length. A 3D root system model was created based on the root system's natural morphology (Figure 3), and the root system used in the experiment was quickly constructed using 3D printing technology (Figure 4).

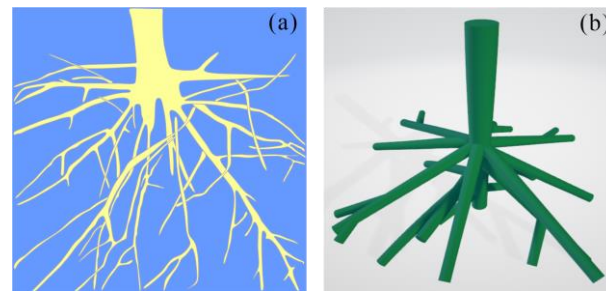


Figure 3. Root system morphology of *Houpoea officinalis* and its corresponding 3D model. (a) root system photograph, (b) 3D model.

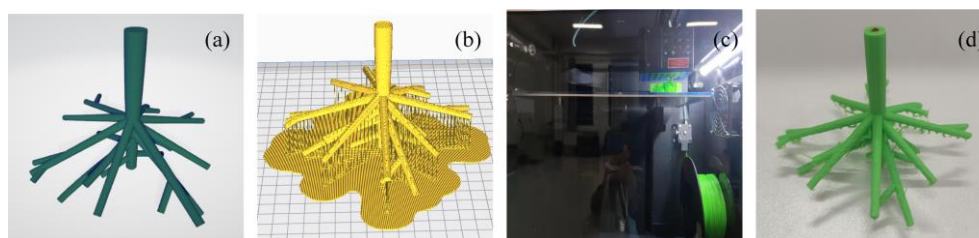


Figure 4. Printing process of 3D printer. (a) modeling, (b) slice, (c) print, (d) root system.

2.3. Physical Model Experiment System

The model test system consists of a model box, a 3D laser scanner, high-definition camera, and stress-strain data collecting system, as shown in Figure 5. The entire model box was built of steel (length 120 cm, width 50 cm, height 80 cm), with plexiglass on both sides. Pulling the sliding surface of the traction motor positioned on the leading edge of the model box triggers the landslide, and the traction motor's driving shaft moves at 0.14 mm/min. The tension sensor at the front of the model box measures the anti-sliding force, which is recorded by the stress-strain data collecting system. The measuring precision of the sensor is 0.01 N, with a range of −1000 N to +1000 N. Displacement monitoring points are set on the slope's surface, and the displacement of the monitoring points can be determined using a high-definition video of the entire experiment. Finally, the anti-sliding force, slope displacement, and cracks can be obtained during the deformation and failure of the slope.

2.4. Test Scheme

The experiment used a scale of 1:100, with a slope height of 35 cm and a sliding surface depth of 8 cm, which corresponds to an actual slope height of 35 m and a sliding surface depth of 8 m. Vertical root lengths of 2.0 cm, 2.5 cm, and 3.0 cm correspond to maximum root depths of 2.0 m, 2.5 m, and 3.0 m, respectively. The model experiment of rootless support was conducted first, followed by the model experiments with roots of three different lengths (Table 2). Three rows of root were laid out, with three root systems in each row spaced at equal intervals. As shown in Figure 6, let S be the horizontal root coverage diameter, with a row spacing of $2.5S$ ($\Delta m = 2.5S$) along the slope and a horizontal root system spacing of $2.0S$ ($\Delta' m = 2.0S$). The soil was evenly filled according to a 14%

moisture content after screening. A chromium-plated iron wire mesh was put on the preset sliding surface as the sliding surface. The slope angle was 30° , the soil layer thickness was 8 cm, and the lead slip surface was $16.5 \text{ cm} \times 64.5 \text{ cm}$ in size.

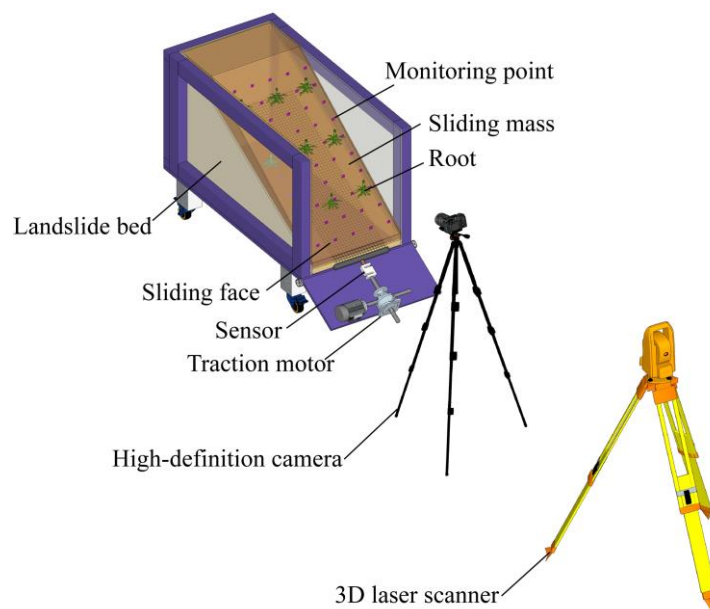


Figure 5. Schematic diagram of the physical model experiment system.

Table 2. Testing scheme.

	Root Length (cm)	Number of Roots	Δm (cm)	$\Delta' m$ (cm)
Condition 1	0	0	0	0
Condition 2	2.0	3×3	2.5S	2.0S
Condition 3	2.5	3×3	2.5S	2.0S
Condition 4	3.0	3×3	2.5S	2.0S

Note: S is the horizontal root cover diameter.

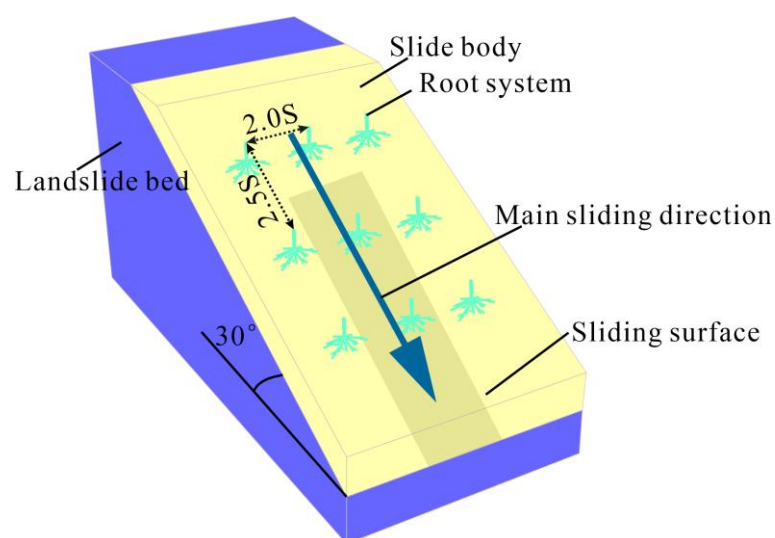


Figure 6. Schematic diagram of root arrangement.

3. Results

The anti-sliding force curve could be obtained through the sensor on the model box's front edge and the stress-strain acquisition system. The slope displacement and cracks at

different times could be studied by post-processing the photographs taken by the high-definition camera.

3.1. Analysis of Anti-Sliding Force

The four groups' anti-sliding force curves have distinct stage features, which can be split into four stages. The peak value of the sliding force in the conditions with root support was increased and the peak time was delayed, as compared to the condition without root support. Furthermore, a more prominent secondary peak was discovered, and after reaching the first peak, the degree of anti-sliding force attenuation fell under the support of the roots.

Peak-start stage (A–B), second peak stage (B–C), variable attenuation stage (C–E), and linear attenuation stage (E–F) are the four stages of the anti-sliding force curve. The variable attenuation stage (C–E) can be further separated into two stages: C–D and D–E (Figure 7). The anti-sliding force grows initially and then abruptly falls in the peak-start stage (A–B), close to a linear change. Simultaneously, the soil is continuously compacted, and the slope is in the elastic deformation stage, in which it is stable. In the second peak stage (B–C), fine cracks appeared at the trailing edge of the slope, and plastic deformation commenced; the slope was stable without large-scale sliding. The anti-sliding force reaches its second peak at this point, the soil becomes more compacted, and the energy accumulates quickly. The appearance of a more noticeable secondary peak value indicates that the root system provided effective support and could resist slope sliding. It is worth noting that the variable attenuation stage (C–E) appears to be a transitional stage in which the anti-sliding force decays slowly at first, before rapidly decaying. In the root support condition, the time of the variable attenuation stage (C–E) was longer than in the rootless support condition, showing that the transition time from stable to unstable was lengthened and that the slope stability was improved. In the linear attenuation stage (E–F), the anti-sliding force was virtually linearly attenuated.

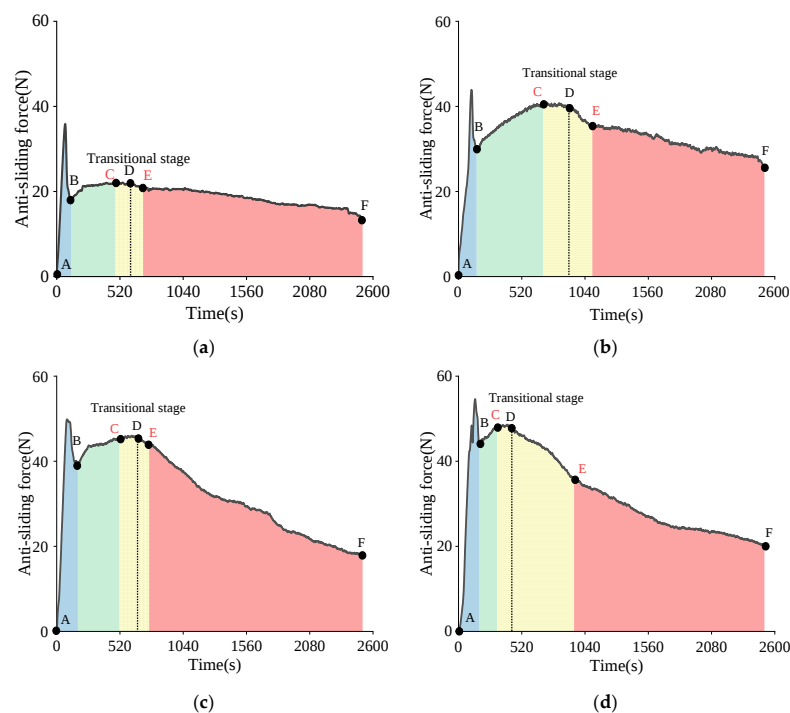


Figure 7. Stage division of anti-sliding force curve. (a) condition 1, (b) condition 2, (c) condition 3, (d) condition 4.

The peak anti-sliding force of the 2.0 cm root length, 2.5 cm root length, and 3.0 cm root length increased by 20.84%, 37.70%, and 50.44%, respectively, when compared to the rootless support condition, and the corresponding peak time was delayed by 47.92%,

18.06%, and 89.58%, respectively. Secondary peak values for the 2.0 cm root length, 2.5 cm root length, and 3.0 cm root length were 40.85 N, 45.56 N, and 48.68 N, respectively, which were much higher than the 21.84 N without root support. Furthermore, after reaching the first peak, the degree of anti-sliding force attenuation with root support was greatly reduced. After reaching the first peak, the anti-sliding force with 2.0 cm root length, 2.5 cm root length, and 3.0 cm root length support dropped to 66.64%, 78.35%, and 80.48%, respectively, while the anti-sliding force without root support dropped to 50.19% of the peak anti-sliding force (Figure 8).

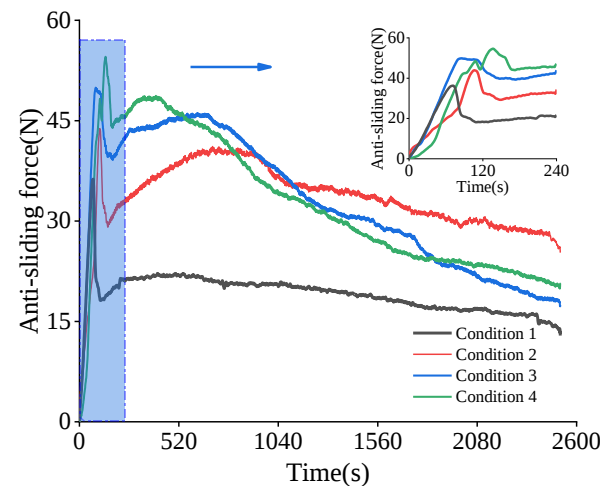


Figure 8. Anti-sliding force curve of the four conditions.

3.2. Analysis of Slope Displacement

The slope monitoring point was the large head nails with a diameter of 1 cm, and key sections of the crack development on the slope surface were chosen for the monitoring point layout (Figure 9a). The slope displacement curves under different conditions could be obtained by post-processing the photos taken with high-definition cameras (slope displacement refers to the average displacement of all monitoring points). In addition, from top to bottom, the slope surface monitoring sites were divided into four parts (Figure 9b), with the average displacement of monitoring points within each part representing the displacement of each part. The displacement curves of the four parts were obtained, and the displacement was further processed.

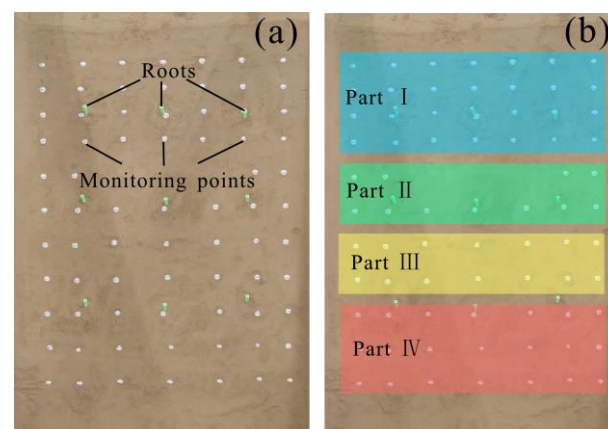


Figure 9. Control chart of slope surface displacement tracking points. (a) Layout of monitoring spots, (b) slope part division.

As shown in Figure 10, as compared to the rootless support, the slope displacement with root support generally reduced, and the slope displacement fell more noticeably as

the root length was increased. Furthermore, a coefficient of variation was introduced to characterize the discreteness of the displacement curves in different parts. The coefficient of variation (abbreviated as CV in this article) is a mathematical statistic that expresses the degree of data dispersion. It is defined as the standard deviation (σ) to mean (μ) ratio, which can eliminate the influence of measuring scales and dimensions, to objectively reflect the degree of dispersion in the data.

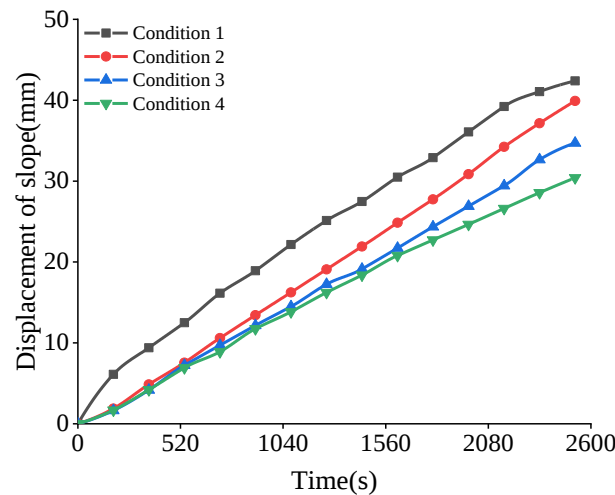


Figure 10. Slope displacement of the four conditions.

The bigger the CV, the greater the degree of data dispersion, and in this experiment, this signified that the degree of displacement dispersion in the different parts was higher, and that each part of the slope was more separated. More importantly, the coefficient of variation could better depict the slope body's synergistic process. When the coefficient of variation decreased, this indicated that the slope's degree of synergy was gradually increasing, whereas when the coefficient of variation increased, this indicated that the slope's synergy process was gradually ending and the different parts of the slope were gradually being separated.

$$CV = \frac{\sigma}{\mu} \times 100\% \quad (1)$$

We discovered that CV reduces under the support of roots (Figure 11) and it reached its minimum value later than the rootless support condition. Furthermore, CV had a long stable fluctuation time near the valley value in the case of root support, whereas it was shorter in the case of rootless support, indicating that the root system could improve the slope's integrity, delay the synergy process, and improve the ability to resist deformation and damage.

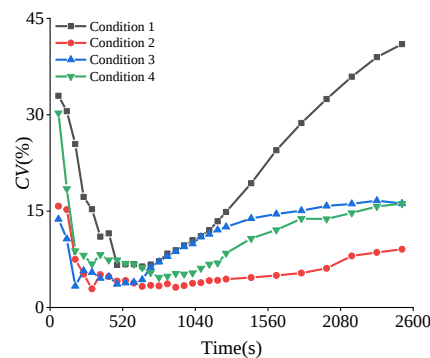


Figure 11. CV of the four conditions.

The displacement curves of the different parts under four working conditions revealed a trend of convergence, first, and then divergence, as shown in Figure 12. Additionally, the corresponding CV showed a decrease-steady-increase trend, indicating an apparent synergistic phenomenon in the accumulation landslide failure process. The soil is first compacted in the landslide evolution process, the energy accumulates quickly, and the slope integrity increases. At the same time, the CV of displacement in different parts falls, and the synergy develops. The slope is in a steady or relatively stable state without significant deformation during this process (corresponding to the anti-sliding force segment's peak-start stage and second peak stage). When the mass soil compaction reaches critical levels, the energy accumulation peaks, and the transition to the energy release stage occurs. At the same time, the CV of displacement in the different parts fluctuates near the valley value, indicating that the synergy has reached its peak. The slope is on the verge of instability during this process (matching the anti-sliding force segment's variable attenuation stage). The synergy is then completed, as deformation and failure develop, each part of the slope gradually separates, and the CV of the displacement of the different parts begins to increase monotonically, the slope instability occurs.

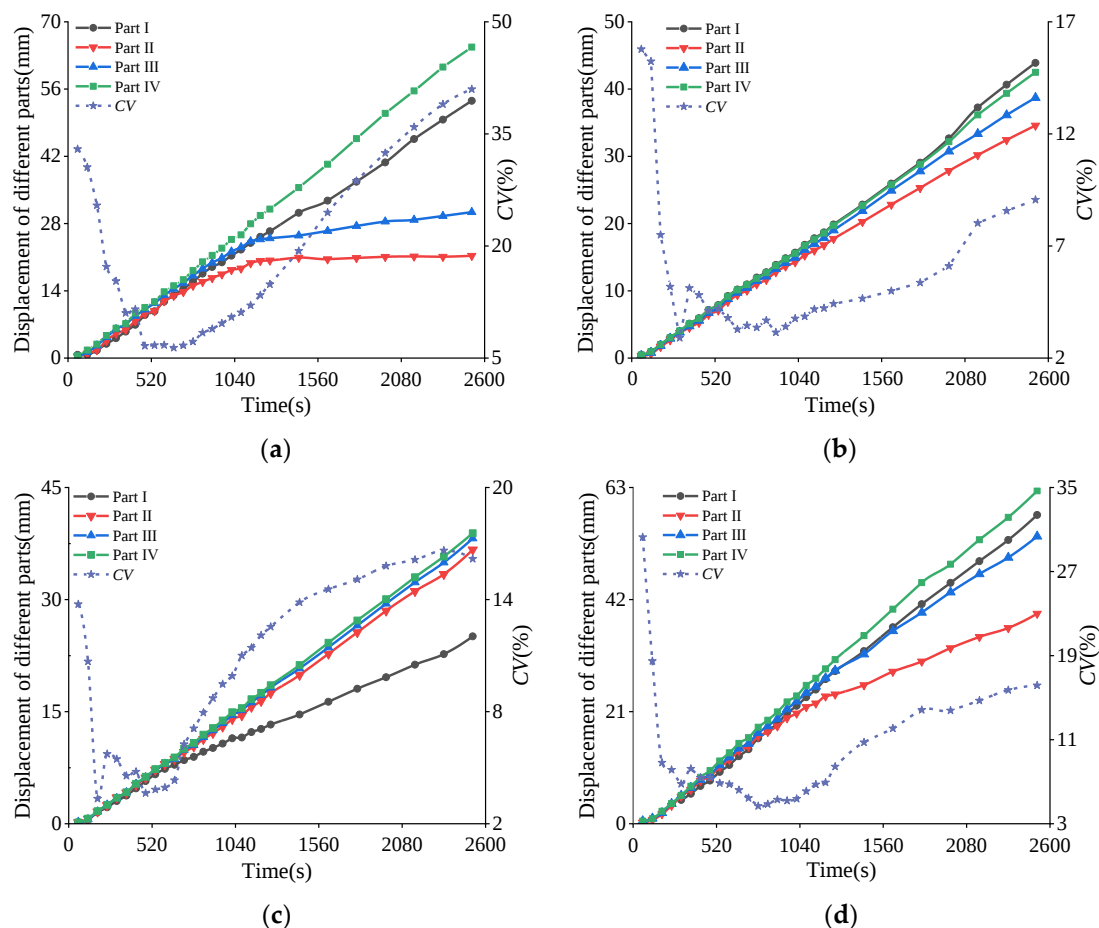


Figure 12. Displacement of different parts and coefficient of variation. (a) Condition 1, (b) condition 2, (c) condition 3, and (d) condition 4.

3.3. Crack Analysis

The formation of cracks under different conditions could be analyzed via photos taken by a high-definition camera throughout the experiments. Slope photos were taken at the start (240 s) and end (2520 s) of the experiment, to highlight cracks and analyze the effect of the root system on crack development.

Figure 13 depicts the cracks of the four working conditions at 240 s. The number of cracks in the case without root support was much higher than the number of cracks in the

case with root support. Meanwhile, in the case without root support, the cracks extended down to the middle of the slope, the trailing edge crack penetrated the model box, and the opening was larger than in the case with root support. The number of cracks with root support, on the other hand, was lower, and only the trailing edge cracks were formed, with small openings. The coverage of trailing edge cracks gradually decreased as the root system length increased. Only fine cracks were observed on the trailing edge of Condition 4, which had less coverage and a shorter downward extension. The root system could effectively prevent the progression of slope cracks and postpone the onset of a landslide.

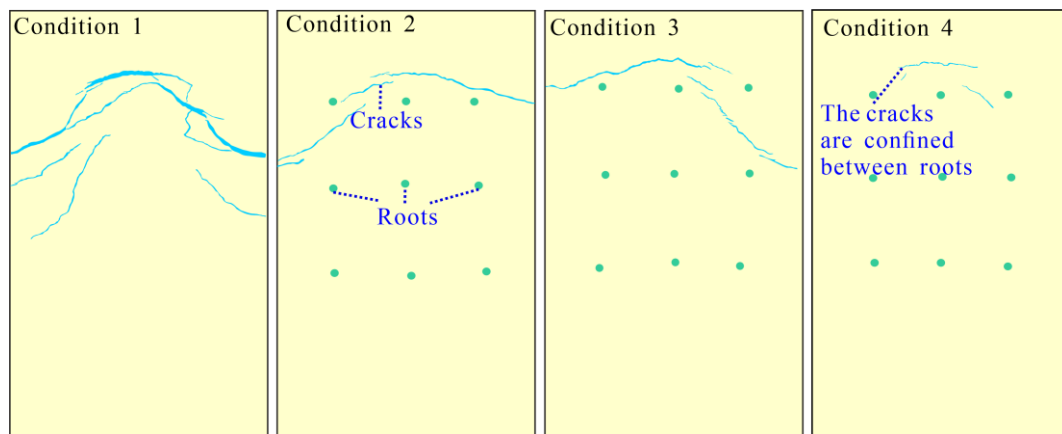


Figure 13. Cracks at 240 s of the four conditions.

Figure 14 shows the cracks in the four working conditions at 2520 s. The trailing edge cracks penetrated the whole model box, and two through cracks with large openings formed along the slope direction in the absence of root support, causing the slope to be severely cut. The trailing edge fractured with root support; however, it did not pass through the model box, and the trailing edge cracks in condition 4 were confined between the roots, with no apparent through cracks along the slope direction. The envelope area of cracks fell dramatically under the support of roots, as did the sliding area of the slope. It is worth noting that under the root support, there were arch shaped cracks in the upper part of the slope. The root–soil composite is thought to have a similar effect to arch support, and an arch stress zone was formed above the upper half of the slope, producing an effect similar to soil arching. In light of this occurrence, the model size will be increased in the future, and an additional study and verification will be conducted through large-scale model testing for natural vegetation planting.

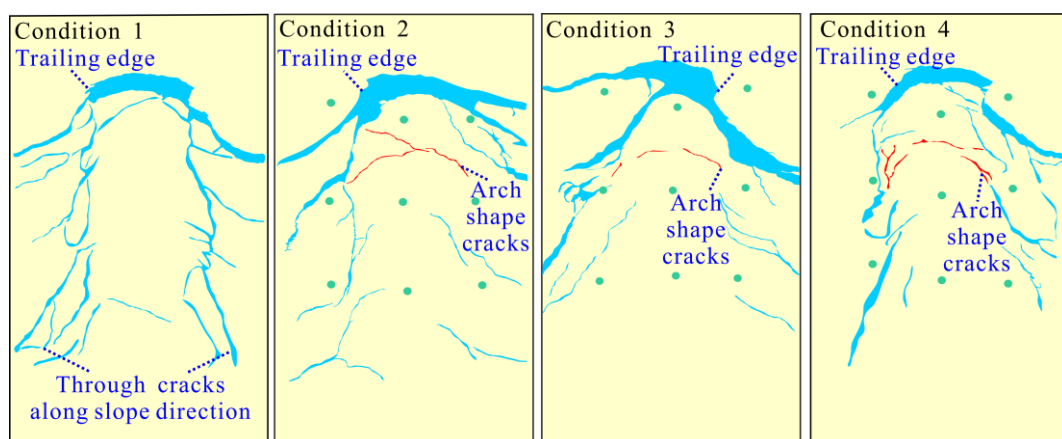


Figure 14. Cracks at 2520s of the four conditions.

4. Discussion

4.1. Coefficient of Variation of Displacement

As a commonly used statistic to express the degree of data dispersion, the coefficient of variation has been preliminarily applied in geotechnical engineering. Jiang et al. [41] applied the coefficient of variation to synthetic aperture radar (SAR) to describe construction land, generated a change indicator of the built-up land through the coefficient of variation statistics, and evaluated the potential of the coefficient of variation statistics in the detection of changes to the built-up land. Li et al. [42] combined the variation coefficient method with the entropy weight method, to construct a comprehensive weighted model for the evaluation of floor water inrush, which more accurately predicted the location of the actual water inrush point. Cao et al. [43] applied the coefficient of variation to a reliability analysis of foundation bearing capacity, and put forward a reliability and risk analysis method for foundation bearing capacity based on a comprehensive coefficient of variation. Ren et al. [44] determined mine slope parameters based on the coefficient of variation method and compared different mining schemes. While predecessors mostly used the coefficient of variation to determine the weight of each index in the decision-making scheme, this paper used the coefficient of variation as a parameter to directly characterize the degree of dispersion between the different parts of the slope. By dividing the slope into four parts, and with the mean value of displacement of the monitoring points within each part representing the displacement of this part, the coefficient of variation of the displacement curve of each part was processed. The larger the coefficient of variation, the stronger the dispersion of the displacement curves in different parts, and the farther the distance between the different parts of the slope. If the coefficient of variation decreases, this indicates that the different parts of the slope are close to each other, and vice versa; this indicates that the different parts of the slope are far away from each other, which can reflect the movement state of the slope to a certain extent. However, in this study, the movement state of the landslide could only be judged from the change trend of the coefficient of variation. In subsequent studies, we will improve this on the basis of the coefficient of variation and propose a quantitative index to consider further characterization of the evolution law of the landslide, from the perspective of quantitative analysis.

4.2. Synergistic Evolutionary Analysis of Landslides

Synergy theory was founded by the German scientist Hermann Haken in the 1970s, to study the synergistic laws among subsystems during the evolution of nonlinear systems [45]. Synergy theory has been widely used in many fields, and many scholars have applied the principle of synergetics to the study of geological disaster evolution processes. Huang et al. [46] established a synergistic-bifurcation nonlinear theoretical model for slope instability prediction, which reflects the synergistic effect and bifurcation phenomenon between various factors in the evolution process of a slope. Zhuo et al. [47] defined a synergy coefficient to study the instability sliding phenomenon of faults, and found that in the process of fault sliding, the synergy is constantly enhanced and the synergy coefficient continues to decline. Ren et al. [48] studied the dislocation process of a fault through a cooled thermal infrared imaging system, and found that the short temporary section of stress, from a stable decline to rapid decline, was accompanied by the synergistic phenomenon of multiple physical fields, such as strain, displacement, and temperature. A landslide and its constituent geotechnical bodies are in an open and complex nonlinear system, and its evolution is a gradual and continuous process, in which the internal and external environment are in change dynamically, which makes the evolution process of a landslide show obvious uncertainty [49,50]. Isolated analysis of anti-sliding force or displacement makes it difficult to obtain comprehensive information on landslide evolution. In this paper, by introducing the coefficient of variation, the anti-sliding force and displacement were combined to study their synergistic evolutionary characteristics, which provided a new concept for studying the evolution characteristics of an accumulation landslide. In subsequent research, multi-physical fields, such as temperature, stress, displacement, and

vibration will be analyzed synergistically, by combining various monitoring methods to further reveal the evolution law of accumulation landslides.

4.3. Landslide Evolution Stage and Forecast

The division of landslide's evolution stage and the prediction of its failure time are difficult, yet important, tasks, and which are crucial to mitigate the loss of life and property caused by landslides, and scholars have spent a lot of effort in this regard [51]. Satio [52] described the damage process of slopes using a classical three-stage creep model, which divided the displacement–time curve during slope damage into three stages, the first being primary (or decelerating) creep, with decreasing strain rate; followed by secondary (or steady-state) creep, with a constant strain rate; and finally tertiary (or accelerating) creep, with an increasing strain rate, and they predicted landslides from changes in strain rate. Xu et al. [53] further improved the Saito model and used the tangential angle of the creep curve to predict a landslide. It is considered that when the tangential angle $> 45^\circ$, it enters the tertiary stage, and this stage can be further subdivided into three stages: initial acceleration ($45\text{--}80^\circ$), medium acceleration ($80\text{--}85^\circ$), and high acceleration ($>85^\circ$). The closer the tangential angle is to 90° , the closer the landslide is to occurring. In addition, based on renormalization group theory, Qin et al. [54] proposed two exponential laws for critical displacement of a landslide disaster for a locked slope controlled by a locked segment. It was considered that the critical displacement of slope instability was related to the displacement of the onset point of accelerating creep and the number of locked segments. Before the damage of the locking segment evolves to its volume expansion point, slope instability will not occur, and when the damage of the locking segment evolves to its peak strength point, the slope will become unstable [55]. The previous classification of the evolutionary stages of landslides is still mainly based on stress-strain curves, and landslides are predicted from the perspective of displacement. In this paper, the anti-sliding force and displacement were synergistically analyzed, and the evolution stages of a landslide were divided from the perspective of energy.

Figure 15 shows the anti-sliding force–displacement synergy curve of the four working conditions. It can be seen that the anti-sliding force and the coefficient of variation of displacement have a strong corresponding relationship. At the peak-start stage (A–B) and the second peak stage (B–C) of the anti-sliding force curve, the displacement curves of different parts are more concentrated, and the corresponding coefficient of variation generally shows a downward trend. This shows that, in these two stages, the slope is in the process of energy accumulation, the soil is constantly compacted, and the synergistic effect of the slope is gradually enhanced. In the variable attenuation stage (C–E), transitional stage) of the anti-sliding force curve, the anti-sliding force first decays slowly and then decays rapidly. The dispersion degree of the partition displacement curve increases, but it is not obviously divergent, and the corresponding coefficient of variation is maintained at a relatively stable level, and then increases slowly. This shows that in the variable attenuation stage (C–E), the energy accumulation of the slope reaches a high point, and the soil is gradually separated. The synergistic effect reaches its highest point in the A–B section and then tends to be completed. The slope reaches a critical state, and the slope begins to produce more obvious lateral cracks, indicating that severe deformation and failure are coming. In the linear attenuation stage (E–F) of the anti-sliding force curve, the anti-sliding force is close to linear attenuation. At the same time, the displacement curve is obviously divergent, and the degree of dispersion increases continuously, while the corresponding coefficient of variation increases monotonously. This shows that, at this stage, the energy of the slope is released violently, the soil in different areas of the landslide is separated, the slope is severely deformed and destroyed, and unstable sliding occurs.

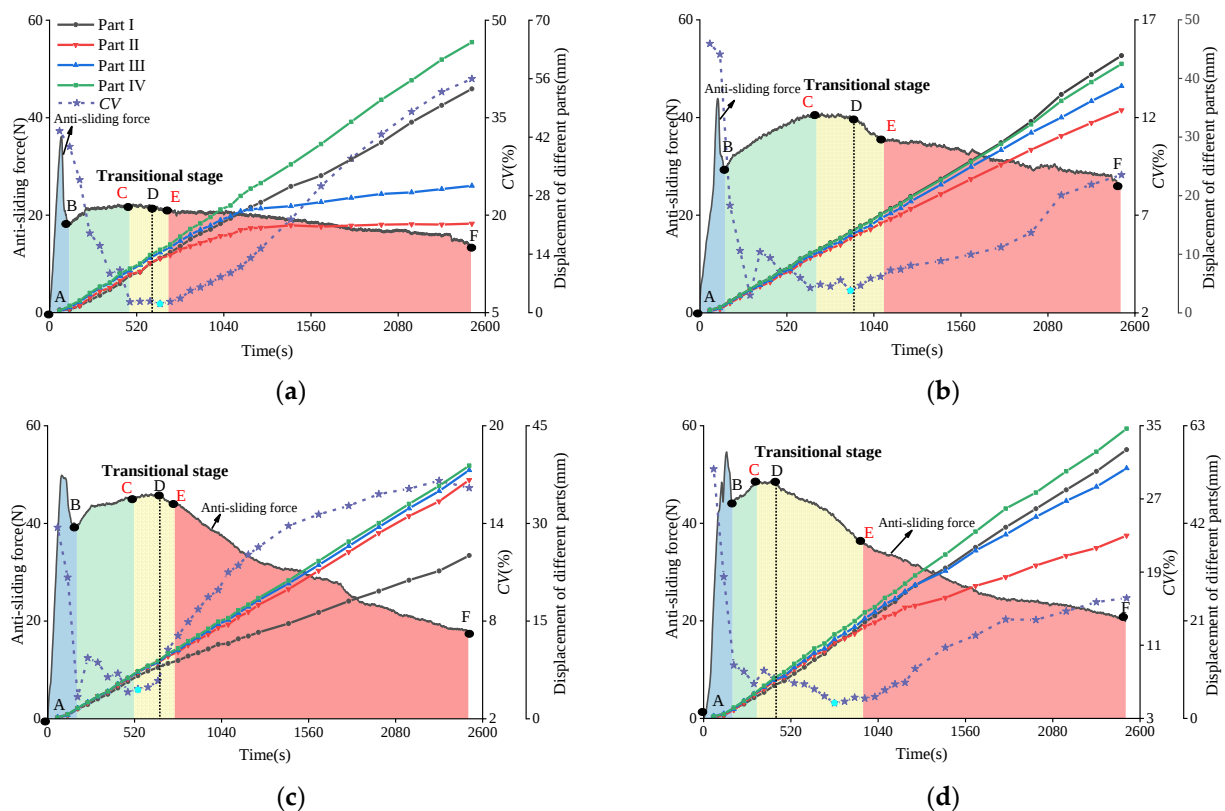


Figure 15. Synergistic evolution law of anti-sliding force and displacement of different parts. (a) condition 1, (b) condition 2, (c) condition 3, (d) condition 4.

It is worth noting that in the variable attenuation stage (C–E), the corresponding anti-sliding force curve first stabilizes, and then decreases, indicating that the energy accumulation stage transitions to an energy release stage at this stage. In addition, before the obvious divergence of the slope displacement curve, the coefficient of variation has a stable stage for a certain time, and the time when the coefficient of variation begins to increase monotonously is before the linear attenuation stage (E–F). In-depth analysis and research on this phenomenon may provide a new method for the prediction of accumulation landslides, and further experimental research will be carried out on this point.

5. Conclusions

Arbor roots were constructed through 3D printing technology, and a series of physical model experiments for slope protection were performed using a self-designed physical model test platform. We evaluated the effects of slope protection without root support and with three different root lengths support. Additionally, the synergistic evolution law of accumulation landslides was studied by incorporating a synergistic analysis of anti-sliding force and displacement.

Compared with the condition without root support, the peak value of the anti-sliding force of slope with root support increased, and the time to reach the peak value of anti-sliding force was considerably delayed. Meanwhile, after attaining the peak value, the degree of anti-sliding force attenuation diminished. The peak-start stage, second peak stage, variable attenuation stage, and linear attenuation stage are the four stages of the anti-sliding force curve. The variable attenuation stage is the transitional stage, which can be further divided into two stages.

With increasing root length, the slope displacement showed a declining trend. Furthermore, the displacement curves of different slope parts converged and then diverged, with a decreasing-stable-increasing trend in the corresponding CV. The dispersion degree of displacement curves in different sections of the slope decreased under root support, and

the corresponding CV was substantially smaller than under non-root support, implying that the slope's integrity was improved.

The development of cracks was effectively limited, and the generation time of cracks was slowed with roots. Furthermore, the coverage range of cracks at the slope's trailing edge rapidly decreased. Under the support of roots, no large-scale through cracks emerged.

The anti-sliding force and displacement in the accumulation landslide evolution process showed a clear synergistic phenomenon. The synergistic effect was steadily improved, and the slope integrity was enhanced during the peak-start and second peak stages of the anti-sliding force. Energy accumulates to its peak point in the variable attenuation stage, before transitioning to the energy release stage, where the synergistic effect is completed and the slope reaches the critical state. The slope energy is released violently in the linear attenuation stage, the integrity declines continually, and severe deformation and failure ensue. In the variable attenuation stage, the characteristic whereby the CV of displacement initially stabilizes and subsequently increases may be helpful in predicting accumulation landslides.

The reinforcement effect of arbor roots on accumulation landslides was investigated in this work, as well as the deformation and evolution process of accumulation landslides. There are certain important discoveries that can be used to guide the building of vegetation slope protection engineering. However, the impact of root spacing, root morphology, and other variables on the reinforcing effect, as well as how to fully utilize the accumulation landslide's near-slip information for landslide prediction, have not been adequately investigated. In the future, further experimental investigations on these issues will be conducted.

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