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Review

Factors Affecting the Stability of Loess Landslides: A Review

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Abstract: The stability of loess landslides affects the production and livelihood of the people in its vicinity. The stability of loess landslides is influenced by various factors, including internal structure, collapsibility, water content, and shear strength. The landslide stability of loesses can be analyzed by several geophysical methods, such as seismic refraction tomography (SRT), electrical resistivity tomography (ERT), micro-seismic technology, and ground penetrating radar (GPR). Geotechnical tests (compression and shear tests) and remote sensing techniques (Global Navigation Satellite System (GNSS), Interferometric Synthetic Aperture Radar (InSAR) and airborne 3D laser technology) are used for studying the landslide stability of loesses as well. Some of the methods above can measure parameters (e.g., fractures, water content, shear strength, creep) which influence the stability of loess landslides, while other methods qualitatively indicate the influencing factors. Integrating parameters measured by different methods, minimizing disturbances to landslides, and assessing landslide stability are important steps in studying landslide hazards. This paper comprehensively introduces the methods used in recent studies on the landslide stability of loesses and summarizes the factors which affect the landslide stability. Furthermore, the relationships between different parameters and methods are examined. This paper enhances comprehension of the underlying mechanisms of the stability of loess landslides to diminish disastrous consequences.

Keywords: landslide stability; loess; geophysical methods; geotechnical test

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1. Introduction

Loess landslides are common in the northwestern, northern, and northeastern regions of China, mainly due to the distinctive climatic and environmental conditions in these regions [1]. Landslides have been a primary topic in the prevention of geological hazards for a long time. Geological hazards are triggered by the release of energy within the earth, external environmental changes, and other factors. They are characterized by their sudden occurrence and destructive consequences which result in significant losses and disruptions to human society. Although the annual geological hazards in China have been declining from 2013 to 2021, the total number of hazards still reached 4761 in 2021 and landslides accounted for about 49% of these. Thus, the warning and prevention of landslides are important.

Numerous research studies have been conducted to measure parameters affecting landslides' stability. Many studies have explored the relationship between internal structure and topography, the effects of short-term continuous heavy rain, and the influence of irrigation, human activities, and earthquakes in landslide-prone areas [1,2]. Specialized instruments and equipment (e.g., SRT, ERT, GPR) can measure some parameters accurately, to provide valuable insights into the internal mechanism of landslides. Additionally, some methods can indicate external factors that affect landslides' stability. Some studies have extensively utilized seismic, magnetic, electrical, and drilling analysis methods for determining the volume, internal structure, resistivity, irrigation, and water content of landslides [3–12]. Alternatively, slope stability has been evaluated by examining the relationship between the changes in water content, loess particles, porosity, and peak shear strength [13–15]. Water infiltration along fractures increases soil water content, leading to reduced effective stress and reduced shear strength [16–20]. Vertical liquefaction during landslide shearing is a major cause of landslides according to Coulomb mechanics [21–23].

Remote sensing satellite technology is a valuable tool for monitoring landslide characteristics. There are some studies that have utilized topographic maps, remote sensing data, and InSAR technology to obtain varying information. High-resolution optical satellite data can be used for landslide monitoring and hazard assessment. Global Positioning Systems (GPSs) can visualize the location and speed of deformation. Robotic velocimeters facilitate remote monitoring [24]. In China, practical satellite remote sensing technology is being used for the monitoring of loess landslides. Restoration of the deformation baseline and cyclic monitoring are carried out by real-time monitoring using real-time kinematic (RTK), precise point positioning (PPP), and static baseline technologies supported by the Beidou positioning system and GPS [25]. Based on Sentinel-1A satellite images, Zhu et al. [26] used hotspot analysis to cluster the average line-of-sight deformation rate of hills along the Lanzhou–Urumqi high-speed railroad line between 2017 and 2022 and proposed a framework for the early identification and monitoring of landslides.

It is still a big challenge to utilize some parameters that impact landslide stability indirectly. Some progress has been made despite the limited attention given to these parameters. A series of intermediate parameters are used to obtain indirectly measured parameters. These intermediate parameters can be measured directly by the instrument. They can then be derived, transformed, modeled, and inverted to obtain the indirectly measured parameters. Several indirectly measured parameters such as shear strength, matrix suction, and pore water pressure have been identified in China. The collapsibility of loesses is influenced by their granular structure, which can be categorized as self-weight collapsibility and non-self-weight collapsibility under internal and external loads [1,27]. Matrix suction is correlated with water content, initial dry density, and the hydrodynamic properties of loess samples. This provides valuable information for landslide stability [28,29]. Changes in pore water pressure, particularly in terms of permeability, strain, and static liquefaction, caused by loess landslides are key factors contributing to the damage caused by loess landslides [13,29,30].

In the formation of landslides, the unique volumetric properties of the loess are critical [4]. General experiments often lead to multiple interpretations of the results, ignoring the complexity of the actual situation. Because of complex geological settings, using one geophysical survey may lead to less trustworthy results and interpretation errors [3,31]. Target properties can be acquired by assuming certain conditions. However, these properties may only reflect certain characteristics. They cannot reflect all scenarios in a dynamic environment. All possible scenarios must therefore be considered. Currently, using a single method cannot provide comprehensive understanding of subsurface properties. For example, electrical resistivity tomography (ERT) can determine the type and composition of the landslide by analyzing resistivity anomalies. However, it cannot specifically reflect the mechanical properties of loess landslides [32]. Many studies have focused on the parameters that impact the stability of loess landslides. Some studies argue that direct testing of parameters under specific conditions does not adequately determine their impact. The need for further research is highlighted by the lack of definitive evidence. For example, an increase in resistivity cannot always be explained by a decrease in the water content of the soil matrix. Moreover, resistivity raised by cracking exceeds that only resulting from a decrease in soil water content [33].

This paper provides a systematic review on the studies of loess landslides from 1980 to 2023, with a specific focus on studies in China in the last 9 years. The stability of landslides is influenced by many parameters and factors, and some of them can be derived by geophysical methods, while others only be acquired by multidisciplinary and integrated approaches. This paper also provides a comprehensive overview of recent research on the monitoring and prevention of loess landslide hazards. Additionally, the paper highlights the significant challenges of data processing and improving equipment based on previous studies. It also presents visual representations of the data and findings through graphs and diagrams. This work can provide a foundation for future research and improve the methods and techniques for monitoring loess landslides.

2. Relevant Measured Parameters

Considerable research into the various parameters influencing the stability of loess landslides has been carried out in recent years. Particularly in the areas of resistivity, water influence, and mechanics, this research has produced important results. Several aspects have been considered when studying resistivity including medium composition, saturation, metal ions, and compaction. Wet trapping, irrigation, rainfall, and spatial and temporal variations in moisture content have been considered in relation to the effect of water. The role of mechanics has been compared in terms of shear strength, matrix suction, pore water pressure, and strength and deformation. Several methods have been used to analyze loess landslides, either individually or in combination. In general, similar conclusions have been reached for the main influencing parameters. However, each analysis method has unique characteristics. It remains a challenge to deal with the wide range of parameters and to reduce the complexity of the solution. In addition, certain parameters have been overlooked and are in need of further investigation by subsequent researchers.

2.1. Parameters of Landslide Structures

The internal structure of loess landslides has been investigated and validated using a variety of methods. These include porosity analysis [34–37], fracture structure assessment [8,15,38–40], landslide geometry evaluation [4,8,36], and investigation of subsurface geological conditions [8,15,17,22,23]. The techniques used include electrical testing [8,20,23,30,34,36], seismic testing [35,41–53], mechanical testing [13–15,18,19,22,37,38], and borehole data analysis [9,31,43,47,53,54]. Figure 1 shows the vertical and lateral structure of landslides in the Heifangtai terrace [55]. Geological hazards, such as landslides, avalanches, and collapses, can occur due to the presence of joints in loesses [4,38]. Volume contraction, or the tendency of the soil to contract under different stress paths due to the destruction of the loess structure, has been suggested as a mechanism for the stress-induced failure of loess landslides [56]. It has been found that clustering occurs as a result of the inherent structure of loesses, summarizing the general characteristics of landslides on the Loess Plateau. In particular, it is susceptible to collapse under high pressure due to its loose composition and high porosity. The volume, length, width, and thickness of the deposit, vertical difference, sliding direction, slope angle, and dip of the strata are of great importance in landslide structures [57].

Seismic methods have been extensively investigated by academic researchers in various countries, including the use of seismic refraction tomography (SRT) for the determination of stratigraphic thickness variations in landslides [41,43,45,47,48,51,52,58], seismic scatter imaging (SSI) to characterize the interior of landslides [47,58], horizontal-to-vertical spectral ratio (HVSR), and multichannel analysis of surface waves (MASW) to analyze the spatial distribution of subsurface structures [43,49,50]. In addition, the use of ERT for the determination of water content distribution within the landslide and the geometry of the landslide surface [43–50,52,58] and ground penetrating radar (GPR) for the analysis of the spatial stratigraphy of the landslide [3,31,44] are commonly used in electrical methods. To provide a thorough understanding of the complexity of the subsurface, these methods are often calibrated using borehole data. This approach allows the investigation of fracture systems in loess landslides, reconstruction of landslide topography and geometry, study of fracture–water interactions, analysis of complex subsurface geological conditions, mapping of landslide surfaces and failure surfaces, assessment of changes in landslide thickness, and identification of paleochannels, landslides, and failures [8,9]. It also assists in the confirmation of changes in the internal structure of landslides, the identification of the depths of major landslide surfaces, the analysis of landslide evolution, and the development of hydrogeological models for landslide events [41–53]. It can also be used to differentiate loess landslides, as shown in Figure 2 regarding the differentiation of rock landslides by wave velocity. The surface mapping of landslides and avalanches and the identification of paleochannels, landslides, and avalanches can also be achieved using geophysical methods (SRT, SSI, and ERT) and their integrated methods [58].

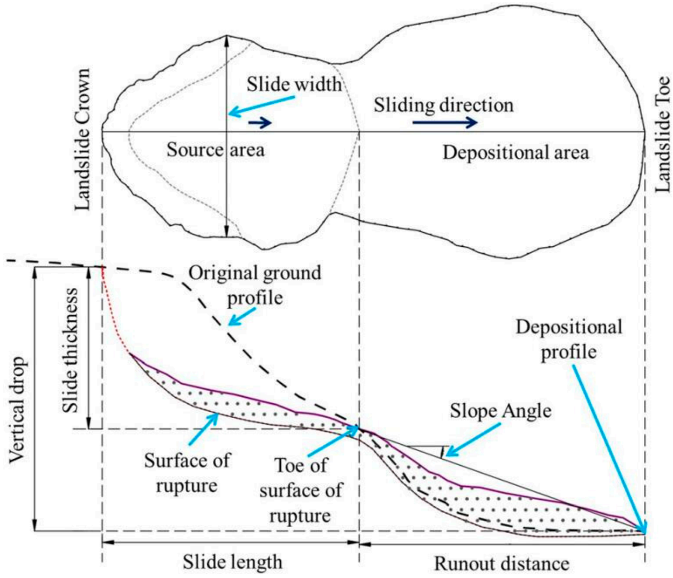

Figure 1. Vertical and lateral structure of landslides in Heifangtai terrace. Reprinted/adapted with permission from Ref. [54]. 2017, Springer Nature.

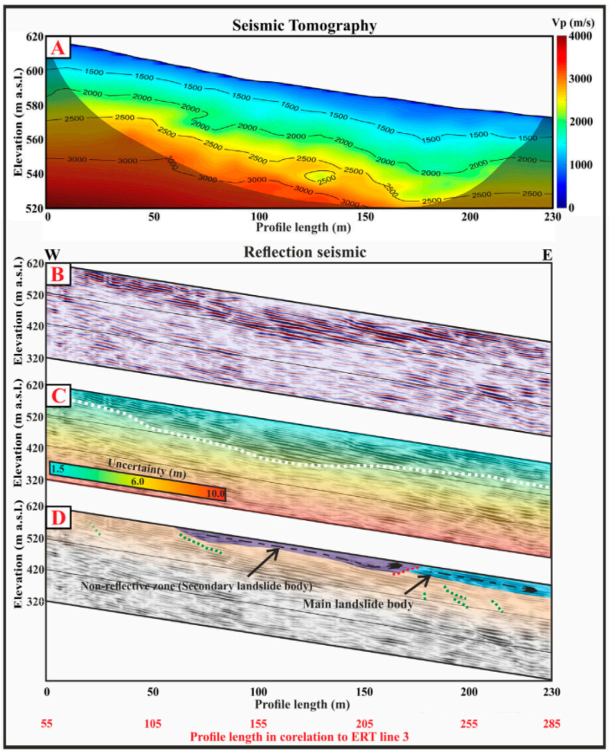

Figure 2. Differentiation of rocky landslides according to wave velocity on the northeast slope below Czerwieńska Grapa mountain, southwest Poland. (**A**) Results of the smooth ray-based tomography. (**B**) Depth section. (**C**) Uncertain depth of the seismic imaging. The white dotted line marks 4 m depth uncertainty. (**D**) Two active landslide bodies. Green and red dashed line marks discontinuities. Reprinted/adapted with permission from Ref. [49]. 2021, Elsevier.

2.2. Resistivity

Numerous scientific studies have shown that the resistivity of a soil is mainly influenced by its water content. It decreases with increasing water content. In this particular order, soil resistivity is determined by water content, pore water conductivity, saturation, and soil type [59]. Water content has a strong effect on the salinity, gravel content and compactness of soils, and sandy soils [60]. A large decrease in resistivity can occur at a moisture content of 2%. The resistivity of all gravel is slightly higher than that of 50% gravel content. The resistivity of sand decreases with increasing bulk density for the same water content. Clearer results are obtained by measuring the resistivity of loess landslide layers in different environments using a modified probe electrode device and a digital DC exciter [61]. Drilling and trench probing techniques can be costly and cause some damage to the landslide. However, they can help to validate the accuracy of the results. It is necessary to determine the rock physical properties of the medium before directly converting soil volumetric conductivity to solute concentration using ERT and time-domain reflectometer (TDR) equipment. However, it is difficult to apply this method to certain conditions [5]. With increasing water content, temperature, metal ion content, compaction, and contaminant concentration, the resistivity of compacted loesses, contaminated loesses, and unsaturated soils increases [62–64]. Calibration of soil physical properties can effectively demonstrate the range of water content [65]. Figure 3 shows the resistivity distribution of the slopes in the Cuiying area. It can be seen that the surface resistivity is significantly higher than the subsurface resistivity. It also indicates the approximate area of low resistivity distributed underground. The characteristics of resistivity include low resistance for soil landslides, medium to high resistance for rock landslides, and high resistance for fractured rock landslides [32]. Nevertheless, resistivity shows a reverse pattern of change in laboratory model tests of moisture migration in remolded loesses under rainfall conditions, with infiltration fronts showing a "Y" shape in light rain and a "D" or "Λ" shape in heavy rain [66]. Changes in both soil water content and suction can be observed using four-dimensional electrical resistivity tomography data, which track temporal and spatial differences in electrical resistivity [10]. There is an exponential relationship between loess resistivity and water content. Hysteresis, with higher resistivity during moisture absorption and desorption at equivalent water content levels, is also observed [67].

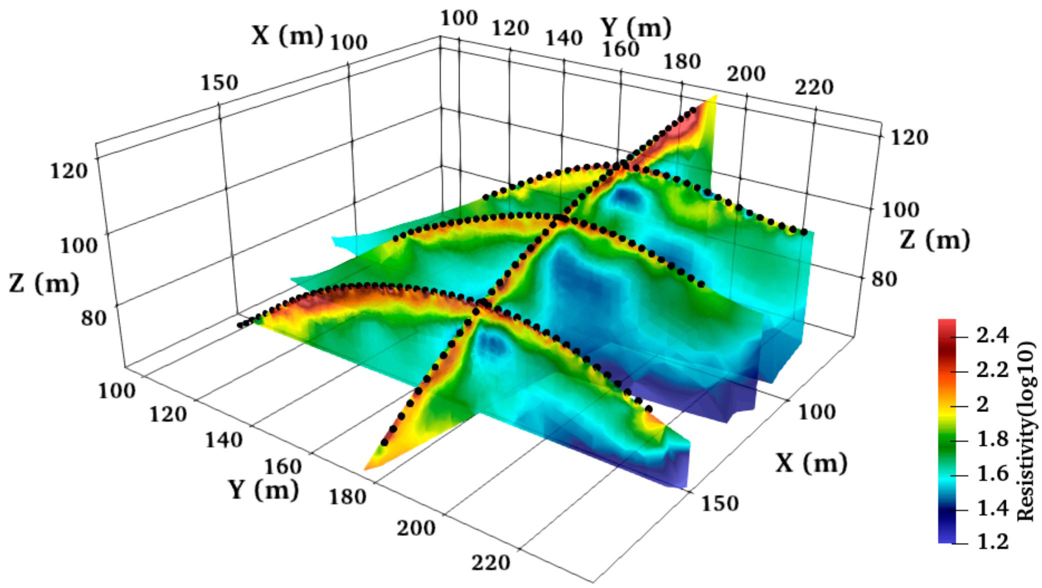

Figure 3. Resistivity model of the Cuiying Mountain region, Lanzhou, China.

2.3. The Effect of Water

Researchers have also studied the effects of water on landslides in loesses, including changes in water content that affect factors such as water table and liquefaction, as well as changes in water content due to rainfall and spatial and temporal variations of water. Researchers generally agree that irrigation has a significant impact on landslides. Erosion of the sliding surfaces and layers, water table fluctuations, cracks formation, liquefaction under static conditions, effects on the shear strength, and changes in the morphology of landslides have been the main focus of research into the damage caused by irrigation-induced loess landslides. These effects are all interrelated, and variations in different parameters have a direct or indirect effect on the stability of loess slopes. Improper irrigation and drainage practices can exacerbate the damage to loess slopes and become important factors in triggering loess landslides [4,22]. Irrigation can cause static liquefaction, leading to the formation of localized slip surfaces which then lead to landslide movement [68,69]. The resistivity of the soil body shows a slow decreasing trend with increasing water content when the water content of the soil body is greater than its optimum water content [59]. Compared to rainfall, diffuse irrigation has a greater effect on loess water content and, consequently, groundwater [70]. As soil moisture increases and diffuse irrigation raises the water table, the shear strength of the loess decreases. In addition, concave slopes are more susceptible to irrigation-induced soil moisture. Landslides are more likely to occur in gullies or on the backs of landslides [71]. Finally, the detrimental effects of irrigation-induced high-speed landslides in remote areas of loesses are also worth mentioning [72].

Rainfall has been extensively studied as an important factor in triggering loess landslides. Previous studies have demonstrated the significant influence of rainfall on landslides by extensively investigating the effects of natural rainfall and the use of artificial rainfall for controlled purposes. Chen et al. [73] concluded that the strength of loesses is more sensitive to variations in water content than other soil types, based on artificial rainfall experiments conducted on natural loess landslides. An increase in water content results in a significant reduction in the strength of the loess, which in turn triggers landslides in loesses [37]. Furthermore, the time taken for water migration in the sample to reach an essentially steady state under rainfall conditions gradually increases as the compaction of the loess sample increases [66]. Hydraulic equilibrium disturbance of a loess landslide was modelled by Hou et al. [74]. As shown in Figure 4, the model indirectly changes irrigation location by the changing of landslide geometry. Rainfall intensity has a relatively small effect on the collapse mode, although it influences slope deformation and landslide development in the long term [30]. Consequently, sustained rainfall is the main trigger for landslide formation [20].

ERT is mainly used to study the spatial and temporal dynamics of water. The spatial and temporal distribution of water movement within loess slopes can be visualized using this technique. ERT is an invaluable tool for assessing landslide stability as there is currently no alternative method that provides the same insights into the temporal distribution of subsurface moisture. In areas of unsaturated loesses, shallow infiltration depths can cause soil liquefaction. As water content increases, drainage at the base of a slope can be impeded, leading to landslides [75]. The maximum value of the slope in the apparent resistivity curve, together with the portion of the ERT curve, provides an accurate estimate of the maximum variation in water content within the loess layer, particularly near the water table boundary [76]. The temporal and spatial dynamics of surface soil moisture change over time and wetting fronts during extreme rainfall events can be captured by time-lapse electrical resistivity tomography [12]. ERT is proving to be an effective method for mapping and monitoring the spatial and temporal changes in soil water content [12,77,78].

Inappropriate irrigation is often identified as an important factor when studying the damage caused by water to loess landslides. Many scientists have proposed a reduction in agricultural irrigation on loess slopes and the improvement of irrigation methods, such as the use of drip irrigation or the extraction of groundwater for well irrigation, in order to effectively control and prevent landslides [68–70,74]. However, large-scale implementation of these measures may not currently be feasible in certain regions due to the influence of geographical conditions, economic constraints, political considerations, and operational challenges. Under certain conditions, however, demonstration studies can be carried out.

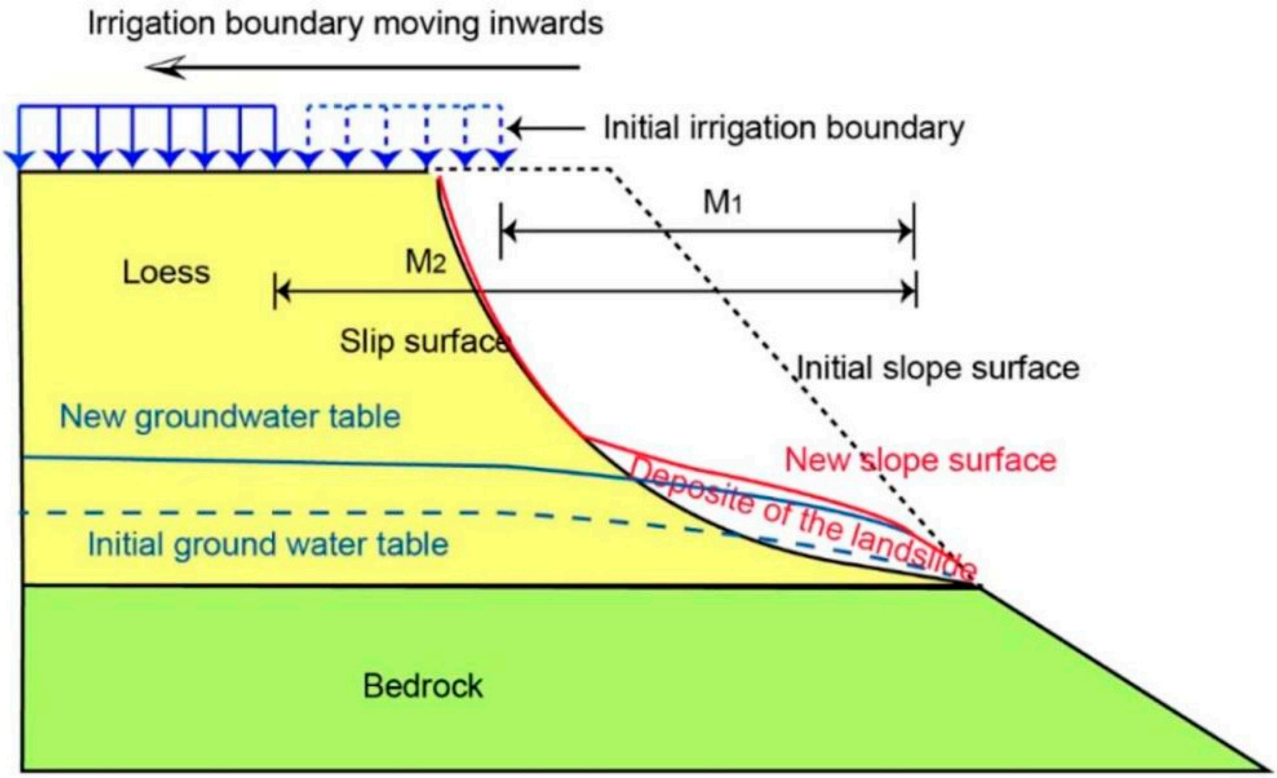

Figure 4. Mechanism of recurring irrigation-induced loess landslides in Heifangtai loess highland, Gansu, China. The disruption of the hydraulic equilibrium of a loess landslide indirectly changes the irrigation location by directly altering its geometry through the first landslide. Reprinted/adapted with permission from Ref. [74]. 2018, Elsevier.

2.4. Matrix Suction

Several interdependent parameters influence the stability of loess slopes, and by manipulating related parameters, it is possible to establish a basis for analyzing their stability. Certain factors that have received limited attention in previous studies have been increasingly emphasized by researchers, including the factor of matrix suction. Unsaturated zones located above the water table can generate matrix suction that improves soil shear strength and, consequently, slope stability. The suction stresses of the loess samples show different characteristics. The magnitude of suction stress is approximately linearly related to matrix suction in the high saturation range [28]. The failure of the slope occurs when the volumetric water content and the matrix suction reach their maximum and minimum values, respectively [29]. Both the magnitude and rate of reduced substrate suction increase with rainfall intensity [30]. By installing water content sensors and matrix suction sensors connected to data loggers and integrating them with data processing software, it is possible to quantitatively characterize slope deformation and damage [79]. Short-term irrigation reduces topsoil matrix suction, while prolonged low-intensity irrigation has a greater effect on slope stability than a single high-intensity irrigation event [70]. In addition, loess volume damage and shear deformation due to wetting are determined by matrix suction, stress levels, and hydraulic pathways [80].

2.5. Deformation Damage and Monitoring

Scientists use integrated geophysical and satellite remote sensing techniques to monitor the geomorphology, deformation, and damage of landslides. It is possible to identify the location where the most significant change in geophysical response occurs by using time-lapse and hierarchical stability analysis methods to interpret landslide data [81]. Geophysical methods such as SRT, ERT, MASW, and HVSR can be used to visualize and monitor the site, constrain the hydrological model based on morphology, and determine the relevant rock stratigraphy and damage surface geometry. In addition, borehole samples can be used in combination with these methods to improve the accuracy of interpretation [48,82,83]. In recent years, a major focus in the study of landslide deformation, failure, and monitoring has been on geophysical data, including precise topography from GPS and DTMs from ground laser scanning. These data provide more accurate estimates of the near-surface velocity field, as well as more accurate models of the spatial variability and area of landslides [50].

Some scientists have conducted extensive research on landslide deformation, damage, and monitoring. They have been able to infer the processes of landslide deformation and damage by performing sensitivity analyses on the results of model back-calculations [84]. The prediction of landslide travel distances is possible from geometric datasets of shallow loess landslides and loess–rock landslides [54]. Landslide hazard monitoring and prediction can be improved by the application of seismological basement theory, which uses the mechanical properties of earthquake faults comparable to landslide slip surfaces [85].

Satellite remote sensing technology, with its ability to provide rapid, real-time, and high-resolution data, plays an important role in the monitoring of geological hazards. This technology is particularly useful in situations where it is impractical or time-consuming for humans to intervene. To date, this technology has been successfully used to create slope databases, remotely monitor landslide deformation in real time, and predict slope stability, among other applications. For example, Zhang et al. [86] used Google Earth high-resolution remote sensing imagery to conduct a preliminary investigation of the geomorphologic types in the landslide distribution area, identifying 609 landslide sites and performing a landslide hazard assessment using the weight-of-evidence method. Putro et al. [87] investigated the stability of the slope geomorphology calculated from Landsat 8 imagery and used the Selby model for slope stability analysis in terms of deformation monitoring and modelling. Zhou et al. [88] analyzed the capability of ground-based GNSS technology for integrated monitoring of shallow loess landslide hazards. GNSSs can monitor changes in soil moisture around the station while providing highly accurate deformation time series features. In addition, using high-precision Beidou and displacement meter monitoring data, Li et al. [89] developed a high-precision prediction model for loess landslide displacement. They went on to comprehensively analyze the predictive performance of the various models used. Guo et al. [72] presented a comprehensive study of the sliding characteristics during the development of loess landslides by combining remote sensing, 3D laser scanning, and additional monitoring information. Based on geological investigations, it is possible to analyze the surface geomorphology, sliding stages, and movement patterns of loess landslides by combining remote sensing, 3D laser scanning and other comprehensive techniques. It has been proposed that the steepness of the terrain serves as a fundamental factor that contributes to the occurrence of high-speed landslides in remote areas.

However, satellite remote sensing technology can only measure the surface. It does not capture the characteristics of subsurface changes at depth, which are typically analyzed retrospectively. This approach is suitable for predicting landslides that are undergoing deformation. However, it cannot accurately predict landslides that are small and rapidly deforming. For comprehensive analysis and monitoring, it is therefore essential to use surface monitoring data and interdisciplinary techniques and tools. For subsurface monitoring methods such as GPR, seismic and electromagnetic surveys can be used [24]. As shown in Figure 5, the variation of slope stresses and instability damage with the increase in seismic ground motion.

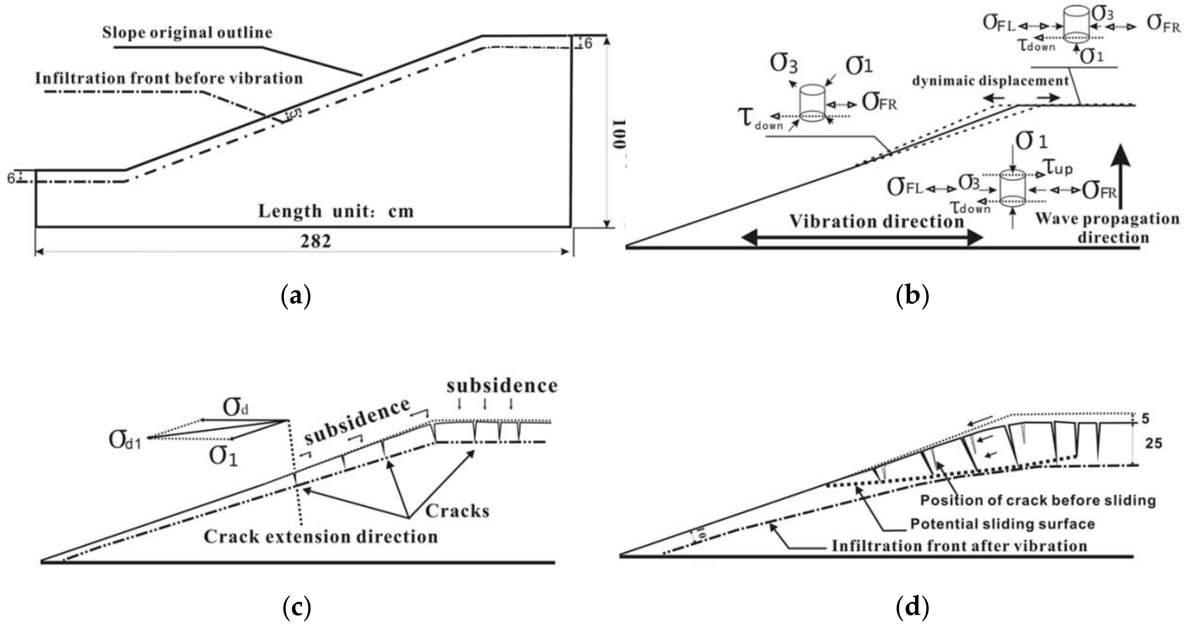

Figure 5. Schematic diagram of stress and instability failure of the slope under seismic ground motion in Lanzhou New District, China. (**a**) The infiltration zone before vibration; (**b**) the tensile (compressive) stress from adjacent soil elements on the left and right sides of the soil elements in the slope as earthquake wave transmitted; (**c**) the soil microstructure is gradually damaged and leads to residual deformation under the continuous tensile and shear action of the dynamic stress with the increase in the ground motion; (**d**) the sliding displacement decreases gradually from the surface to inside. Reprinted/adapted with permission from Ref. [90]. 2020, Springer Nature.

2.6. Shear Strength

The determination of slip surface shear strength parameters is key to landslide stability assessment and engineering design. Previous limitations in accounting for the randomness and uncertainty associated with geotechnical parameters are overcome using inverse analysis to determine slip surface shear strength parameters [91]. The angle of inclination of the fracture surface determines the strength and deformation characteristics of a loess. A larger angle of inclination results in higher tensile stress and tensile strength [38]. Under seismic loading, super-porous pressure accumulates and plastic deformation develops rapidly in the shear zone. This leads to liquefaction of the loess and a reduction in shear strength [92]. Rapid slope failure may not result from shear expansion and consolidation caused by intermittent or prolonged rainfall. Loess landslides may suffer from shear dilatation during acceleration of slope movement, leading to a reduction in pore water pressure and landslide deceleration [73]. The accuracy of prediction and monitoring in moisture-induced landslide environments may be improved by combining groundwater mapping with modulus distributions [93]. Strain-softening behavior observed in direct shear tests of these media has been linked to sudden collapse events in loess landslides [94]. Figure 6 shows the relationship between shear strength parameters and water content for different slip zone soils. Mechanical parameters such as cohesion, angle of internal friction, and deformation have been shown to vary in a quasi-linear fashion with water content [95]. Horizontal tensile stresses within landslides predominantly occur in the upper and middle sections, while vertical tensile stresses are concentrated near the sliding surface. Intense rainfall conditions lead to the expansion of the plastic shear strain zone along the entire sliding surface, triggering landslides [40].

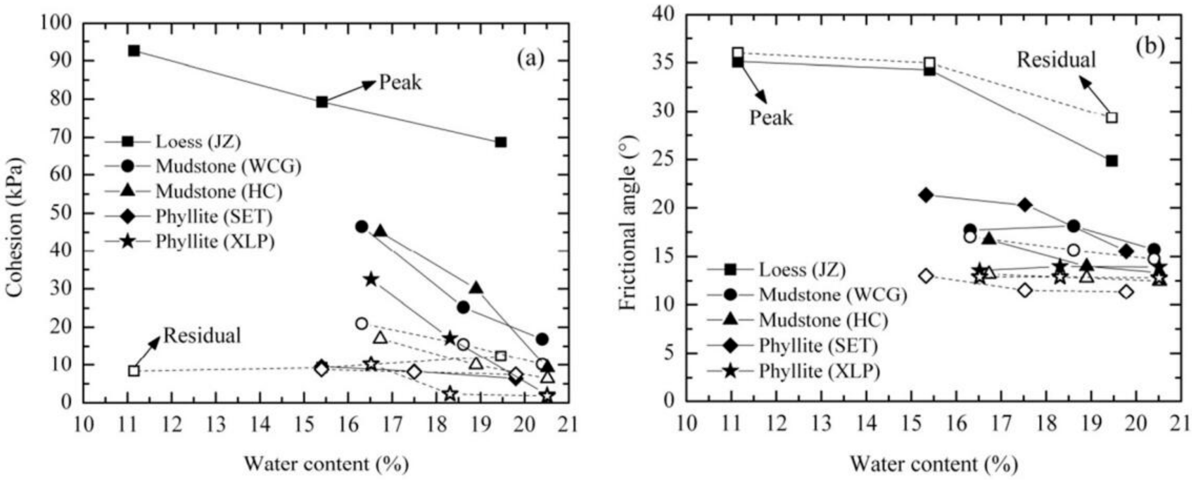

Figure 6. Relationships between shear strength parameters and moisture content for different slip zone soils of five sampling points in Lanzhou, China. (Black solid symbol represents the peak state, and white hollow symbol belongs to residual state). (**a**) Peak cohesions of slip zone soils decrease continuously with increasing moisture, while residuals appear insensitive to moisture; (**b**) the variations of peak and residual internal friction angles with moisture content for slip zone soil. Reprinted/adapted with permission from Ref. [94]. 2021, Springer Nature.

2.7. Pore Water Pressure

The stress–strain behavior and liquefaction of loess slopes is significantly influenced by pore water pressure. Due to the high pore water pressure resulting from low permeability, fine-grained loesses are prone to rapid movement after damage [13]. With increasing pore water pressure, saturated loesses exhibit pronounced strain softening and static liquefaction [96]. Given the limited contribution of suction strength to shear strength, its attenuation cannot determine the stability of homogeneous loess slopes without preferential infiltration channels. Therefore, the key determinant of slope failure may be the increase in positive pore water pressure at the potential slip surface [30]. The influence of pore water pressure on the morphological characteristics of landslides is significant. It should not be underestimated. However, further investigation is required as there are few studies in this area.

2.8. Creep

While landslide creep has been studied extensively, there is a lack of specific investigations on creep in loess landslides, primarily due to the complex nature of the landslide medium, which includes expansive soils, red clay fills, variations in rock composition, and more. The combination of creep action and external factors increases the likelihood of failure. To determine the long-term strength of loess landslide specimens under creep conditions, Wang et al. [80] proposed the steady-state creep rate slope method (SCRSM). At constant moisture content, the deformation at the steady-state creep stage increases dramatically with the increasing deviatoric stress. In addition, to describe the accelerated creep behavior in the loess medium, an improved Burgers model was introduced. Higher moisture content reduces the preload required for creep damage to occur, while higher axial strain increases the time required for each load [97]. Precipitation is the most important catalyst for the acceleration of creep in landslides [26]. However, the need for further research is highlighted by the paucity of studies investigating the effect of creep on the stability and formation mechanism of loess landslides. To describe the creep properties of rocks and soils prior to accelerated creep, the Burgers model is well suited. The creep equation of the Burgers model can be expressed as follows [80]:

$$\varepsilon(t) = \frac{q}{E_1} + \frac{q}{E_2}\left(1 - e^{-\frac{E_2}{\eta_1}t}\right) + \frac{q}{\eta_2}t \quad (1)$$

where ε is the total strain; E_1 is the instantaneous modulus of elasticity; E_2 is the viscoelastic modulus; and η_1 and η_2 are the viscoelastic coefficients.

Different approaches have been used to study loess landslides, especially in the Loess Plateau region. In order to find a more appropriate method for studying loess landslides, a comparison of different landslide research methods will be made. These methods include the use of different geophysical instruments, the development of inversion-based models, and the study of the influence of changes in water content. However, these methods have limitations. Specific conditions are required for accurate interpretation of the results. The methods used to obtain measured parameters for landslide stability analysis are summarized in Table 1. In this case, analytical factors are those that relate to the specific situation we want to analyze. They are mainly qualitative. The measured parameters are those that we can obtain by some means. They are mainly quantitative. The measured parameters include those mentioned above. They are obtained by direct and indirect measurements. The directly measured parameters refer to the data measured by instruments. Indirectly measured parameters have to be inferred, converted, modeled, and inverted by intermediate parameters. And it is these intermediate parameters that can be measured directly by the instrument. For example, water content is an essential parameter in the analysis of the collapsibility of loesses and can be measured directly by the instrument. Similarly, to analyze the internal structure of a landslide, the size and number of fractures must be considered, and these parameters can be inverted by seismic methods.

Table 1. Summary of methods for obtaining measured parameters for landslide stability analysis.

Analytical Factors	Measured Parameters	Methods	Application	References
thickness, volume, open stacking structure	bulk properties, subsidence, mass movements, erosion	analysis of data and artifacts	survey (loess)	[4]
fracture system	resistivity	ERT		[7]
depth, volume, angle	rainfall, coefficient of friction, static liquefaction	field investigation, geotechnical in situ testing and indoor testing		[56]
internal structure	water infiltration, physical state	penetration test, undrained triaxial test, particle analysis, scanning electron microscope test		[37]
structural strength	moisture content	double line method humidification test		[89]
landslide thickness, fracture, stratification, porosity, failure surface, saturation	seismic wave velocity, resistivity, isotope, displacement and hydrogeological parameters	ERT, SRT, mass spectrometer, Liquid Water Isotope Analyser	survey and monitor (non-loess)	[41,42,45,48,51]
subsoil complexity, sliding surface, fractures, water flow within formation	seismic wave velocity, resistivity	SRT, ERT, HVSR and MASW	survey (non-loess)	[43,46]
spatial orientation of rock layers	seismic wave velocity, permittivity	SRT, GPR, geotechnical surveys		[44]
underground geological conditions	seismic wave velocity, Bouguer gravity anomaly	SRT, ERT, Bouguer gravity anomaly modeling		[47]
landslide surfaces, paleochannels	seismic wave velocity, resistivity	SRT, ERT, SSI		[58]
structure of landslide deposition	s-wave velocity	HVSR		[11]
underground images, depth of landslide surfaces	seismic wave velocity, resistivity	ERT, MASW, SRT		[49]
spatial variability, surface area of landslides	seismic wave velocity, resistivity	ERT, MASW, SRT, and Digital Terrain Models (DTMs)		[50]
landslide geometry	seismic wave velocity, resistivity, lithology logging data	SRT, ERT, and borehole data		[52]

Table 1. *Cont.*

Analytical Factors	Measured Parameters	Methods	Application	References
resistivity	slip band, compaction, saturation, resistivity, temperature, pollution concentration, irrigation and rainfall	WDJD-1 multi-purpose numerical direct-current electricity meter modeled, boreholes, ESEU-1 resistivity equipment, voltammetry test sets, ERT	survey (loess)	[61,62,64,75]
	electrical characteristics, water content, salinity, gravel content, solidity, compaction	ERT, boreholes, resistivity tests, high-resistance measuring instruments	survey (non-loess)	[32,33,59,60,63]
irrigation	shear force, cracks, water content, infiltration of water, groundwater level	triaxial shear test, field measurements, static liquefaction test	survey and monitor (loess)	[22,68–70]
rainfall	water content, pore water pressure, cracks, landslide morphologic features, stratigraphic structure, thickness of the slide, groundwater distribution	artificial rainfall tests, model tests, moisture sensors, tensiometers, pressure sensors, drone aerial surveys, ERT	survey and monitor (loess)	[20,29,30,73]
spatial and temporal evolution	matric suction, moisture content, pore water pressure, deformation of the slope, resistivity, movement and changes of particles	physical model test, coupled monitoring system, triaxial test, four-phase electrode method, boreholes, ERT, scanning electron microscopy	survey and monitor (loess)	[29,65,67,70,77,96]
	top-soil moisture, geometry of the landslide, moisture content, elastic moduli, shear strength	TL-ERT, ERT, field experiments, lab simulations, ERT, time-lapse methods, limit analysis	survey and monitor (non-loess)	[12,82,91,93]
matrix suction	dry density, moisture content, rates of desorption, pore water pressure, cracks, rainfall intensities, saturation, irrigation infiltration, groundwater level, creep rate, stratum lithology, rainfall	analysis experiments, failure mode early warning threshold model, field experiments, numerical simulation, Transient Release and Imbibition Method, triaxial creep tests, steady-state creep rate slope method (SCRSM)	survey and monitor (loess)	[28–30,70,80]
	shear strength parameters	back analysis	survey (non-loess)	[91]
collapsibility, granular frame structure	microstructure of loess, slide width, slide thickness, slide volume, vertical drop, slide length, dip direction angle, slope angle, coefficient of collapsibility	electron microscope observation, predictive modeling, distribution fitting, field investigation and monitoring, geotechnical test	survey (loess)	[27,43,98]
shear strength	engineering properties, fissure angle, degree of saturation, moisture content, residual strength, macropores, deep joints, angle between slope and bedrock, deepness, volume, run-out distance, apparent friction angle, cohesion, angle of internal friction, deformation modulus	soil mechanics, wet–dry cycles compression tests, chemical analyses, oedometer, undrained triaxial shear tests, ring shear tests, microstructure observation, aerial images and Digital Elevation Model analysis, geotechnical tests, numerical method	survey (loess)	[1,15,17–19,22,23,38,42,92,95]
	pore water pressure, residual shear strength, interparticle force, shear strength parameters, residual friction angle	shear test, weathered red mudstone test, back analysis, upper bound theory of limit analysis	survey (non-loess)	[13,16,91,94]

Table 1. *Cont.*

Analytical Factors	Measured Parameters	Methods	Application	References
pore water pressure	tensile cracks, volumetric moisture content, matric suction	model test, early warning threshold model, field experiments, numerical simulation, soil moisture sensors, tensiometers, earth pressure cells	survey and monitor (loess)	[29,30]
	shear strength	shear tests	survey (non-loess)	[13]
creep	long term strength, peak strength, moisture content, stratum lithology, rainfall	creep model tests, triaxial creep tests, steady-state creep rate slope method (SCRSM)	survey (loess)	[14,91,97]
	line-of-sight deformation velocity	hot spot analysis, optical satellite image analysis	survey and monitor (non-loess)	[26]

3. Comprehensive Analysis of Loess Landslides

Stability refers to the interrelationship between undamaged, potentially damaged, and destroyed states. Therefore, after obtaining the measured parameters we have discussed above, a comprehensive analysis of loess landslides must be considered. It should include an understanding of the causes, a determination of the impact of these factors on stability, and an exploration of strategies to improve stability. Due to its direct impact on the construction of engineering works and structures, as well as on the preliminary design of transport and water conservancy facilities, the investigation of loess slopes or loess foundations is of greater importance in the field of engineering. In the case of slope instability, variations in individual parameters play a decisive role, from stabilization through the critical state to the damage stage. Therefore, a comprehensive analysis of damage to loess slopes, taking into account these influencing factors, together with interdisciplinary responses, is essential. This is a research challenge. Only through such a comprehensive analysis can we fully understand the condition of loess slopes, reduce constraints and multiple solutions, and improve the accuracy of hazard prediction. It will provide a reliable basis for landslide hazard prevention and early warning. Previous studies on landslide stability, with particular emphasis on factors of influence, with the tests carried out and the methods of analysis, are presented below.

3.1. Analytical Factors

Collapsibility is an important characteristic that distinguishes loesses from other soil types, and it is this characteristic that distinguishes loess landslides from rock landslides and normal soil landslides. Under a certain pressure, the soil structure is quickly damaged and characterized by subsidence because it is wetted by water. The stability of various parameters is therefore significantly affected by this property. Not all types of loess are collapsible. The thickness of collapsible loesses is not great. It is usually about 10–15 m in the upper part. Its specific granular framework structure determines the collapsibility of loesses [27]. At the peak of the collapsibility coefficient, the structural weakening induced by water saturation reaches its maximum [98]. The collapsibility of loess samples can be visualized under a scanning electron microscope. It is a macroscopic manifestation resulting from changes in intergranular cementation. In addition, continued wetting also causes the fracture to widen further [96]. In the humidification test, the softening effect of water exceeds its fracturing effect on the soil, especially when the water content is high [97]. The inherent structural strength of loesses and the external pressure applied strongly influence the deformation damage characteristics of loesses caused by the humidification process [89]. The main blocky nature of sand particles and the flaky nature of silt particles are shown in Figure 7. Flaky particles have flat surfaces with clean edges and irregular fractures. Bulk particles have rough surfaces, uneven edges, and jagged fractures. Lamellar particles are mainly horizontally stacked. Only a few are found in the spacing or intergranular pores formed by both particle types. Furthermore, silt particles are observed enveloped in clay sheets. The clay particles fill the interstitial and intergranular pores and bind the sand and silt together to strengthen the particle bonds and form the overall structure [96]. It is therefore clear that both internal and external factors are involved in causing loesses to collapse. The interaction between loess collapsibility and water is vividly illustrated under microscopic conditions. Experimental data suggest that loess collapsibility correlates with water content.

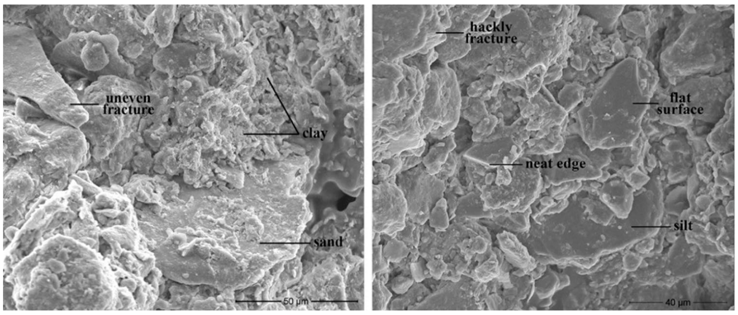

Figure 7. The types of particles and fracture of Malan loess in South Jingyang Plateau, China. Reprinted/adapted with permission from Ref. [96]. 2019, Springer Nature.

Loess landslide parameters (e.g., fractures, volume, resistivity, shear, water content, etc.) that can be measured directly (it is possible to instrument the parameters) or indirectly (requiring further derivation, conversion, modelling, and inversion) and factors (collapsibility) have been discussed previously. For the stability of loess landslides, these parameters and factors are crucial. A single factor may dominate the stability of a landslide, but it is usually determined by a combination of factors. Therefore, since the influencing factors cannot be isolated, it is essential to analyze and evaluate them comprehensively. For example, loess slopes will creep due to vibration, creep will produce cracks, cracks will lead to the generation of water infiltration, water infiltration due to the collapsibility of loesses will increase the deformation of loess slopes, and deformation in turn will increase the creep and cracks; such a cycle will lead to the destabilization of landslides and damage. The deformation and collapse of the slope shoulder play a critical role in slope instability and damage, as it experiences the highest amplification factor for seismic acceleration [30,99]. Loess stability and susceptibility to collapse under water infiltration are significantly influenced by physical migration of fine particles and chemical dissolution during internal erosion [37]. Figure 8 shows how the hydrological response of the slope to heavy rainfall varies at different times.

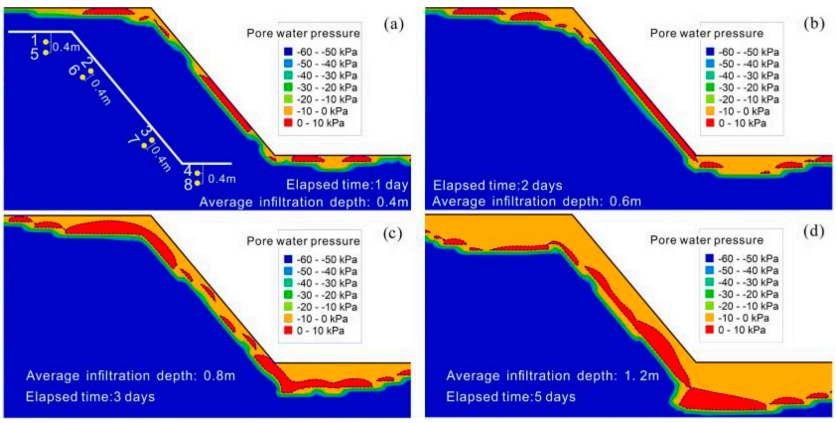

Figure 8. (**a**–**d**) The numerical results showing hydrological response of slope under heavy rain at different times in Jingyang County, Shaanxi, China. Reprinted/adapted with permission from Ref. [30]. 2021, Elsevier.

3.2. Stability Tests

Landslide stability requires the performance of tests. These include both indoor and field tests. However, field tests provide more reliable results for modeling slope stability than values obtained from indoor tests [100]. By studying the dynamic properties under artificial rainfall conditions, the relationship between rainfall infiltration and the stability of loess slopes can be quantified [79]. In the Loess Plateau region, irrigation-induced water infiltration can be shown to lead to failure of loess slope stability by combining water column tests with permeability characterization simulations [74].

3.3. Analytical Method

There are a number of different methods in use for the stability of landslides. The emphasis is on how the results can be analyzed more closely to the actual situation. For example, the stability of landslides can be calculated and evaluated using techniques such as limit equilibrium analysis and the finite element method [20,101]. By incorporating uncertainty in the physical mechanics of geotechnical bodies, methods for assessing landslide stability include calculating the probability of instability for grid cells. In addition, assessment methods that take into account the spatial and temporal scales as well as the physical processes specific to landslides can be applied [99,102]. A contribution to the understanding of the dynamic response characteristics and destabilization mechanisms of loess slopes is made by the study of the combined effects of earthquakes and rainfall, particularly under moderate and low rainfall conditions [90]. It is undoubtedly more productive to analyze loess slopes according to their typical characteristics, although there are different methods of analysis, for example, from the point of view of irrigation. Irrigation leads to an increase in the water content of loess, according to the relationship between initial water content and loess collapsibility, which is inversely proportional [61]. We know that in the arid loess area, loess collapsibility is very high when the initial water content is low. Therefore, the loess is more susceptible to deformation and damage when it is just exposed to water. The interpretation of geophysical methods requires geological data for correction. Otherwise, it is prone to inaccurate interpretation or the problem of multi-interpretations. For example, considering the medium–high resistivity ore body to the high resistivity surrounding rock and determining the seismic reflection interface of lithological layers are prone to multi-interpretation.

4. Discussion

Loess landslides cause significant losses to the national economy, human life, and property every year. Loess landslides are not widespread; they are confined to specific geographical areas, but there are significant number of people living in the Loess Plateau region in China. Emergency rescue during landslide hazards is a major challenge due to the unique geographical location, large area, and high population density. Therefore, it is crucial to conduct a thorough study to understand the causes and mechanisms of loess landslides. The improvement of monitoring, simulation, early warning systems, prevention measures, and control strategies for loess landslides is also necessary.

Analyzing landslides requires multidisciplinary integration; it cannot be achieved by a single method or a few underlying principles. There are still many problems to be addressed. Firstly, correlating geophysical interpretation with hydrological or geotechnical parameters (e.g., water content, pore water pressure, and shear strength) is still challenging. Secondly, it is difficult to integrate remote sensing parameters with subsurface measurements. Thirdly, correlating geophysical measured parameters (e.g., resistivity) with geochemical measured ions is an obstacle. Additionally, the accuracy of geophysical methods (e.g., SRT and ERT) in measuring trace elements needs improving. Moreover, using electrical methods to reduce the multivalence of stratigraphic layering is still in development. Multi-disciplinary cooperation and the integration of multiple parameters are significant for these challenges. These parameters can be obtained from several places, such as the surface and subsurface and at high altitudes. Mechanical, electrical, seismic, and infrared methods are used to obtain these parameters. This emphasizes the importance of integrated approaches for the study of landslides in the Loess Plateau region. Conducting independent studies with limitations for specific targets may result in multivalence. For example, the increase in resistivity observed in cracked soils cannot be only attributed to the decrease in soil water content [33].

When collecting and analyzing parameters, accuracy, practicality, and non-destructiveness are essential considerations. The most important requirement is that the data collected for scientific purposes must be reliable and accurate. Additionally, data must be easily collected by different methods. Moreover, damage or disturbance are inevitable when collecting data for landslides. To assess the structural integrity of the landslide, techniques such as trenching and drilling are not suitable. A major challenge of new techniques and improvements in equipment is to determine the optimum approach obtaining slope parameters whilst minimizing disturbance.

The universality and practicality of the methodology needs to be improved. The data processing and inversion methods are the main focus of the methodology. As mentioned earlier, there are several data processing methods, e.g., correlation analysis, multi-parameter coupling, two-dimensional finite unit, smoothing constrained least squares, numerical simulation, and inverse analysis. However, there is currently no standardized specification for these methods, and there is no method that fully adapts to the realistic situation in data processing and inverting. Further studies are significant in the challengeable multi-parameter joint inversion, in which the interaction of several factors has to be considered. The main challenge is the joint inversion of field resistivity and other electromagnetic/hydrogeological parameters and the methodology of integration with other geophysical methods [36]. Field experiments are often more convincing than lab experiments; thus, valid methods in lab experiments need to be verified in realistic field conditions.

To provide a more intuitive understanding of the morphological characteristics of loess landslides, many research studies have developed 3D and 4D models. The spatial distribution of water content, as indicated by resistivity, is used to construct these models. In addition to the 2D and 3D resistivity models, the 4D models incorporate time series analysis and other relevant factors. This is a step forward in capturing the complexity of the geological patterns of landslides. It is essential to improve our understanding of how other parameters in the models respond, in order to accurately represent the multi-dimensional situation in the realistic scenario. Thus, the models need to be built through in-depth analysis of large datasets using advanced data analysis platforms, including state-of-the-art artificial intelligence algorithms. We can improve the accuracy of landslide prediction by improving the capabilities of machine learning, i.e., understanding the mechanisms of landslide evolution in complex geological conditions simulated by machine learning.

5. Conclusions

This paper systematically summarized recent research on the causes and stability of landslides, especially loess landslides. As shown in Table 1, these studies mainly cover the properties of landslides' structure, resistivity, rainfall, spatial and temporal relationships, matrix suction, shear strength, pore water pressure, and creep. Irrigation and collapsibility are also considered for loess landslides. We found that a comprehensive understanding of the factors that influence the stability of loess landslides cannot be achieved by a single method; it must be considered within specific constraints. The internal structure, moisture content, water saturation, and shear strength of loess landslides have been investigated in previous studies. A few approaches have been used to analyze these factors, from both internal and external perspectives, including indoor and field experiments, calculations, and inversions. We found that further integration between disciplines can diminish multivalence of single method. In addition, subjectivity in data interpretation should be minimized by continuous improvement of innovative methods and the scale and accuracy of monitoring tools in studies of loess landslides. Furthermore, preventing reactivation of old landslides and monitoring new landslides are crucial. In the era of big data analysis, we should make efforts to integrate enormous amounts of information to support landslide stability analysis. Results that closely reflect realistic geological conditions are accessible through intelligent technologies, e.g., deep learning. The ultimate goal is to provide robust support for monitoring, simulating, analyzing, early warning, and preventing landslide hazards.

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References

1. Xu, Z.J.; Lin, Z.G.; Zhang, M.S. Loess in China and Loess landslides. *CJRME* **2007**, *26*, 1297–1312. (In Chinese with English Abstract)
2. Zhang, K.; Wang, S.; Bao, H.J.; Zhao, X.M. Characteristics and influencing factors of rainfall-induced landslide and debris flow hazards in Shaanxi Province, China. *Nat. Hazards Earth Syst.* **2019**, *19*, 93–105. [CrossRef]
3. Bruno, F.; Martillier, F. Test of high-resolution seismic reflection and other geophysical techniques on the Boup landslide in the Swiss Alps. *Surv. Geophys.* **2000**, *21*, 333–348. [CrossRef]
4. Derbyshire, E. Geological hazards in loess terrain, with particular reference to the loess regions of China. *Earth-Sci. Rev.* **2001**, *54*, 231–260. [CrossRef]
5. Koestel, J.; Kemna, A.; Javaux, M.; Binley, A.; Vereecken, H. Quantitative imaging of solute transport in an unsaturated and undisturbed soil monolith with 3-D ERT and TDR. *Water Resour. Res.* **2008**, *44*, 12. [CrossRef]
6. Samyn, K.; Travelletti, J.; Bitri, A.; Grandjean, G.; Malet, J.P. Characterization of a landslide geometry using 3D seismic refraction traveltime tomography: The La Valette landslide case history. *J. Appl. Geophys.* **2012**, *86*, 120–132. [CrossRef]
7. Szalai, S.; Szokoli, K.; Novák, A.; Tóth, Á.; Metwaly, M.; Prácser, E. Fracture network characterisation of a landslide by electrical resistivity tomography. *Nat. Hazards Earth Syst. Sci. Discuss.* **2014**, *2014*, 3965–4010. [CrossRef]
8. Szalai, S.; Szokoli, K.; Metwaly, M.; Gribovszki, Z.; Prácser, E. Prediction of the location of future rupture surfaces of a slowly moving loess landslide by electrical resistivity tomography. *Geophys. Prospect.* **2017**, *65*, 596–616. [CrossRef]
9. Gelisli, K.; Ersoy, H. Landslide investigation with the use of geophysical methods: A case study in Eastern Turkey. *Adv. Biol. Earth Sci.* **2017**, *2*, 52–64.
10. Holmes, J.; Chambers, J.; Meldrum, P.; Wilkinson, P.; Boyd, J.; Williamson, P.; Huntley, D.; Sattler, K.; Elwood, D.; Sivakumar, V.; et al. Four-dimensional electrical resistivity tomography for continuous, near-real-time monitoring of a landslide affecting transport infrastructure in British Columbia, Canada. *Near Surf. Geophys.* **2020**, *18*, 337–351. [CrossRef]
11. Mreyen, A.S.; Cauchie, L.; Micu, M.; Onaca, A.; Havenith, H.B. Multiple geophysical investigations to characterize massive slope failure deposits: Application to the Balta rockslide, Carpathians. *Geophys. J. Int.* **2021**, *225*, 1032–1047. [CrossRef]
12. Lapenna, V.; Perrone, A. Time-Lapse Electrical Resistivity Tomography (TL-ERT) for Landslide Monitoring: Recent Advances and Future Directions. *Appl. Sci.* **2022**, *12*, 1425. [CrossRef]
13. Wang, G.H.; Sassa, K.; Fukuoka, H.; Tada, T. Experimental study on the shearing behavior of saturated silty soils based on ring-shear tests. *J. Geotech. Geoenviron.* **2007**, *133*, 319–333. [CrossRef]
14. Wang, B.; Zhu, J.B.; Tang, H.M.; Xiang, W. Study on Creep Behavior of Slip Band Soil of Huangtupo Landslide. *J. Yangtze River Sci. Res. Inst.* **2008**, *25*, 49–52. (In Chinese with English Abstract)
15. Xu, J.; Zhou, L.Y.; Hu, K.; Li, Y.F.; Zhou, X.G.; Wang, S.H. Influence of Wet-Dry Cycles on Uniaxial Compression Behavior of Fissured Loess Disturbed by Vibratory Loads. *KSCE J. Civ. Eng.* **2022**, *26*, 2139–2152. [CrossRef]

16. Wen, B.P.; He, L. Influence of lixiviation by irrigation water on residual shear strength of weathered red mudstone in Northwest China: Implication for its role in landslides' reactivation. *Eng. Geol.* **2012**, *151*, 56–63. [CrossRef]
17. Fan, X.M.; Xu, Q.; Scaringi, G.; Li, S.; Peng, D.L. A chemo-mechanical insight into the failure mechanism of frequently occurred landslides in the Loess Plateau, Gansu Province, China. *Eng. Geol.* **2017**, *228*, 337–345. [CrossRef]
18. Lian, B.Q.; Peng, J.B.; Zhan, H.B.; Huang, Q.B.; Wang, X.G.; Hu, S. Formation mechanism analysis of irrigation-induced retrogressive loess landslides. *Catena* **2020**, *195*, 104441. [CrossRef]
19. Zhu, Z.B.; Wang, X.G.; Zhu, R.S.; Xue, C.; Liu, K. Ring shear test on the shear characteristics of sliding zone soil of loess in Heifangtai, Gansu. *J. Arid Land Resour. Environ.* **2021**, *35*, 144–150. (In Chinese with English Abstract)
20. Chen, D.W.; Wu, Z.J.; Liang, C.; Zhou, H.X. Deformation Characteristics and Disaster-causing Mechanism Analysis of Tongwei Loess Landslide. *J. Disaster Prev. Mitig. Eng.* **2022**, *42*, 24–33. (In Chinese with English Abstract)
21. Budhu, M.; Gobin, R. Slope instability from ground-water seepage. *J. Hydraul. Eng.* **1996**, *122*, 415–417. [CrossRef]
22. Leng, Y.Q.; Peng, J.B.; Wang, Q.Y.; Meng, Z.J.; Huang, W.L. A fluidized landslide occurred in the Loess Plateau: A study on loess landslide in South Jingyang tableland. *Eng. Geol.* **2018**, *236*, 129–136. [CrossRef]
23. Peng, D.L.; Xu, Q.; Liu, F.Z.; He, Y.S.; Zhang, S.; Qi, X.; Zhao, K.Y.; Zhang, X.L. Distribution and failure modes of the landslides in Heitai terrace, China. *Eng. Geol.* **2018**, *236*, 97–110. [CrossRef]
24. Zaalishvili, V.; Chotchaev, K.; Melkov, D.; Burdzieva, O.; Dzeranov, B.; Kanukov, A.; Archireeva, I.; Gabaraev, A.; Dzobelova, L. Geodetic, geophysical and geographical methods in landslide investigation: Luar case study. *E3S Web Conf.* **2020**, *164*, 01014. [CrossRef]
25. Huang, G.W.; Du, Y.; Meng, L.M.; Huang, G.W.; Wang, J.; Han, J.Q. Application Performance Analysis of Three GNSS Precise Positioning Technology in Landslide Monitoring. *Lect. Notes Electr. Eng.* **2017**, *437*, 137–148. [CrossRef]
26. Zhu, Y.R.; Qiu, H.J.; Cui, P.; Liu, Z.J.; Ye, B.F.; Yang, D.D.; Kamp, U. Early detection of potential landslides along high-speed railway lines: A pressing issue. *Earth Surf. Proc. Land.* **2023**, *48*, 3302–3314. [CrossRef]
27. Gao, G.R. Microstructure of Loess Soil in China Relative to Geographic and Geologic Environment. *Acta Geol. Sin.* **1984**, *3*, 265–272. (In Chinese with English Abstract)
28. Jiang, Y.; Chen, W.W.; Wang, G.H.; Sun, G.P.; Zhang, F.Y. Influence of initial dry density and water content on the soil-water characteristic curve and suction stress of a reconstituted loess soil. *Bull. Eng. Geol. Environ.* **2017**, *76*, 1085–1095. [CrossRef]
29. Zhang, S.; Zhang, X.C.; Pei, X.J.; Wang, S.Y.; Huang, R.Q.; Xu, Q.; Wang, Z.L. Model test study on the hydrological mechanisms and early warning thresholds for loess fill slope failure induced by rainfall. *Eng. Geol.* **2019**, *258*, 105135. [CrossRef]
30. Sun, P.; Wang, H.J.; Wang, G.; Li, R.J.; Zhang, Z.; Huo, X.T. Field model experiments and numerical analysis of rainfall-induced shallow loess landslides. *Eng. Geol.* **2021**, *295*, 106411. [CrossRef]
31. Schrott, L.; Sass, O. Application of field geophysics in geomorphology: Advances and limitations exemplified by case studies. *Geomorphology* **2008**, *93*, 55–73. [CrossRef]
32. Li, F.; Zhou, H.F.; Ge, H. Electrical characteristics of different types of landslide bodies investigated by high-density electrical method. *Geophys. Geochem. Explor.* **2019**, *43*, 215–221. (In Chinese with English Abstract)
33. Ackerson, J.P.; Morgan, C.L.S.; Everett, M.E.; McInnes, K.J. The Role of Water Content in Electrical Resistivity Tomography of a Vertisol. *Soil Sci. Soc. Am. J.* **2014**, *78*, 1552–1562. [CrossRef]
34. Dietrich, S.; Weinzettel, P.; Varni, M. Infiltration and Drainage Analysis in a Heterogeneous Soil by Electrical Resistivity Tomography. *Soil Sci. Soc. Am. J.* **2014**, *78*, 1153–1167. [CrossRef]
35. Uhlemann, S.; Hagedorn, S.; Dashwood, B.; Maurer, H.; Gunn, D.; Dijkstra, T.; Chambers, J. Landslide characterization using P- and S-wave seismic refraction tomography—The importance of elastic moduli. *J. Appl. Geophys.* **2016**, *134*, 64–76. [CrossRef]
36. Perrone, A.; Lapenna, V.; Piscitelli, S. Electrical resistivity tomography technique for landslide investigation: A review. *Earth-Sci. Rev.* **2014**, *135*, 65–82. [CrossRef]
37. Zhuang, J.Q.; Peng, J.B.; Zhu, Y.; Leng, Y.Q.; Zhu, X.H.; Huang, W.L. The internal erosion process and effects of undisturbed loess due to water infiltration. *Landslides* **2021**, *18*, 629–638. [CrossRef]
38. Sun, P.; Peng, J.B.; Chen, L.W.; Lu, Q.Z.; Igwe, O. An experimental study of the mechanical characteristics of fractured loess in western China. *Bull. Eng. Geol. Environ.* **2016**, *75*, 1639–1647. [CrossRef]
39. Li, Y.; Mao, J.; Xiang, X.; Mo, P. Factors influencing development of cracking–sliding failures of loess across the eastern Huangtu Plateau of China. *Nat. Hazards Earth Syst. Sci.* **2018**, *18*, 1223–1231. [CrossRef]
40. Xie, W.L.; Guo, Q.Y.; Wu, J.Y.; Li, P.; Yang, H.; Zhang, M.S. Analysis of loess landslide mechanism and numerical simulation stabilization on the Loess Plateau in Central China. *Nat. Hazards* **2021**, *106*, 805–827. [CrossRef]
41. Göktürkler, G.; Balkaya, C.; Erhan, Z. Geophysical investigation of a landslide: The Altindag landslide site, Izmir (western Turkey). *J. Appl. Geophys.* **2008**, *65*, 84–96. [CrossRef]
42. Gance, J.; Grandjean, G.; Samyn, K.; Malet, J.P. Quasi-Newton inversion of seismic first arrivals using source finite bandwidth assumption: Application to subsurface characterization of landslides. *J. Appl. Geophys.* **2012**, *87*, 94–106. [CrossRef]
43. Capizzi, P.; Martorana, R. Integration of constrained electrical and seismic tomographies to study the landslide affecting the cathedral of Agrigento. *J. Geophys. Eng.* **2014**, *11*, 045009. [CrossRef]
44. Sauvin, G.; Lecomte, I.; Bazin, S.; Hansen, L.; Vanneste, M.; L'Heureux, J.S. On the integrated use of geophysics for quick-clay mapping: The Hvittingfoss case study, Norway. *J. Appl. Geophys.* **2014**, *106*, 1–13. [CrossRef]

45. Bottari, C.; Albano, M.; Capizzi, P.; D'Alessandro, A.; Doumaz, F.; Martorana, R.; Moro, M.; Saroli, M. Recognition of Earthquake-Induced Damage in the Abakainon Necropolis (NE Sicily): Results from Geomorphological, Geophysical and Numerical Analyses. *Pure Appl. Geophys.* **2018**, *175*, 133–148. [CrossRef]
46. Mezerreg, N.E.; Kessasra, F.; Bouftouha, Y.; Bouabdallah, H.; Bollot, N.; Baghdad, A.; Bougdal, R. Integrated geotechnical and geophysical investigations in a landslide site at Jijel, Algeria. *J. Afr. Earth Sci.* **2019**, *160*, 103633. [CrossRef]
47. Akingboye, A.S.; Ogunyele, A.C. Insight into seismic refraction and electrical resistivity tomography techniques in subsurface investigations. *Rud-Geol-Naft. Zb.* **2019**, *34*, 93–111. [CrossRef]
48. Imani, P.; Tian, G.; Hadiloo, S.; Abd El-Raouf, A. Application of combined electrical resistivity tomography (ERT) and seismic refraction tomography (SRT) methods to investigate Xiaoshan District landslide site: Hangzhou, China. *J. Appl. Geophys.* **2021**, *184*, 104236. [CrossRef]
49. Marciniak, A.; Kowalczyk, S.; Gontar, T.; Owoc, B.; Nawrot, A.; Luks, B.; Cader, J.; Majdanski, M. Integrated geophysical imaging of a mountain landslide—A case study from the Outer Carpathians, Poland. *J. Appl. Geophys.* **2021**, *191*, 104364. [CrossRef]
50. Wrobel, M.; Stan-Kleczek, I.; Marciniak, A.; Majdanski, M.; Kowalczyk, S.; Nawrot, A.; Cader, J. Integrated Geophysical Imaging and Remote Sensing for Enhancing Geological Interpretation of Landslides with Uncertainty Estimation-A Case Study from Cisiec, Poland. *Remote Sens.* **2023**, *15*, 238. [CrossRef]
51. Aguzzoli, A.; Arosio, D.; Mulas, M.; Ciccarese, G.; Bayer, B.; Winkler, G.; Ronchetti, F. Multidisciplinary non-invasive investigations to develop a hydrogeological conceptual model supporting slope kinematics at Fontana Cornia landslide, Northern Apennines, Italy. *Environ. Earth Sci.* **2022**, *81*, 471. [CrossRef]
52. Himi, M.; Anton, M.; Sendrós, A.; Abancó, C.; Ercoli, M.; Lovera, R.; Deidda, G.P.; Urruela, A.; Rivero, L.; Casas, A. Application of Resistivity and Seismic Refraction Tomography for Landslide Stability Assessment in Vallcebre, Spanish Pyrenees. *Remote Sens.* **2022**, *14*, 6333. [CrossRef]
53. Zhang, Z.; Wang, T.; Wu, S.; Tang, H.; Liang, C. The role of seismic triggering in a deep-seated mudstone landslide, China: Historical reconstruction and mechanism analysis. *Eng. Geol.* **2017**, *226*, 122–135. [CrossRef]
54. Wang, L.-M.; Wu, Z.-J.; Xia, K. Effects of site conditions on earthquake ground motion and their applications in seismic design in loess region. *J. Mt. Sci.* **2017**, *14*, 1185–1193. [CrossRef]
55. Xu, Q.; Li, H.J.; He, Y.S.; Liu, F.Z.; Peng, D.L. Comparison of data-driven models of loess landslide runout distance estimation. *Bull. Eng. Geol. Environ.* **2019**, *78*, 1281–1294. [CrossRef]
56. Zhou, Y.F.; Tham, L.G.; Yan, W.M.; Dai, F.C.; Xu, L. Laboratory study on soil behavior in loess slope subjected to infiltration. *Eng. Geol.* **2014**, *183*, 31–38. [CrossRef]
57. Zhuang, J.Q.; Peng, J.B.; Wang, G.H.; Javed, I.; Wang, Y.; Li, W. Distribution and characteristics of landslide in Loess Plateau: A case study in Shaanxi province. *Eng. Geol.* **2018**, *236*, 89–96. [CrossRef]
58. Chen, Q.; Zhang, S.; Chang, S.L.; Liu, B.; Liu, J.; Long, J.H. Geophysical Interpretation of a Subsurface Landslide in the Southern Qinshui Basin. *J. Environ. Eng. Geoph.* **2019**, *24*, 433–449. [CrossRef]
59. Liu, G.H.; Wang, Z.Y.; Huang, J.P. Research on electrical resistivity feature of soil and it's application. *Acta Geotech.* **2004**, *26*, 83–87. (In Chinese with English Abstract)
60. Zhang, G.Y.; Liu, S.M.; Sun, H.Z. A Study of Factors Influencing Soil Resistivity in Tarim Region. *Acta Pedol. Sin.* **2006**, *43*, 160–163. (In Chinese with English Abstract)
61. Long, J.H.; Li, T.L.; Zhang, Z. Experimental Study on Identification of Sliding Zone in Loess Slopes with Electrical Resistivity Method. *Chin. J. Eng. Geol.* **2007**, *15*, 268–272. (In Chinese with English Abstract)
62. Zha, F.S.; Liu, S.Y.; Du, Y.J.; Cui, K.R. Characteristics of electrical resistivity of compacted loess. *Rock. Soil. Mech.* **2011**, *32*, 155–158. (In Chinese with English Abstract)
63. Song, J.; Li, S.C.; Liu, B.; Xu, X.J.; Wang, C.W.; Nie, L.C. Quantitative assessment method of unsaturated soil compaction degree based on resistivity property. *J. Chang. Univ.* **2015**, *35*, 33–41. (In Chinese with English Abstract)
64. Liu, H.; Hu, W.L.; Wang, T.X.; Niu, Z.L.; Gu, H.Q.; Hu, P.F. Experimental research on the resistivity characteristics of contaminated remolded Q3 loess by water content and com-paction degree. *J. Xi'an Univ. Arch. Tech.* **2021**, *53*, 337–343. (In Chinese with English Abstract)
65. Garré, S.; Günther, T.; Diels, J.; Vanderborght, J. Evaluating Experimental Design of ERT for Soil Moisture Monitoring in Contour Hedgerow Intercropping Systems. *Vadose Zone J.* **2012**, *11*, vzj2011.0186. [CrossRef]
66. Zhang, S.B.; Zhu, C.H.; Yuan, J.G. Laboratory model tests on moisture migration in remolded loess under rainfall conditions. *J. Hydraul. Eng.* **2019**, *50*, 621–630. (In Chinese with English Abstract)
67. Sun, B.; Gu, T.F.; Kong, J.X.; Zhang, F.C.; Sun, J.X. Experimental Research on Relationship between Resistivity and Moisture Content of Unsaturated Loess. *Northwest Geol.* **2020**, *53*, 216–222. (In Chinese with English Abstract)
68. Duan, Z.; Cheng, W.C.; Peng, J.B.; Wang, Q.Y.; Chen, W. Investigation into the triggering mechanism of loess landslides in the south Jingyang platform, Shaanxi province. *Bull. Eng. Geol. Environ.* **2019**, *78*, 4919–4930. [CrossRef]
69. Yan, R.X.; Peng, J.B.; Huang, Q.B.; Chen, L.J.; Kang, C.Y.; Shen, Y.J. Triggering Influence of Seasonal Agricultural Irrigation on Shallow Loess Landslides on the South Jingyang Plateau, China. *Water* **2019**, *11*, 1474. [CrossRef]
70. Gu, T.F.; Zhang, M.S.; Wang, J.D.; Wang, C.X.; Xu, Y.J.; Wang, X. The effect of irrigation on slope stability in the Heifangtai Platform, Gansu Province, China. *Eng. Geol.* **2019**, *248*, 346–356. [CrossRef]

71. Gu, T.F.; Sun, P.P.; Wang, J.D.; Lin, H.; Xu, Y.J.; Kong, J.X.; Sun, B. An Experimental and Numerical Study of Landslides Triggered by Agricultural Irrigation in Northwestern China. *Adv. Civ. Eng.* **2020**, *2020*, 8850381. [CrossRef]
72. Guo, F.Y.; Zhang, L.S.; Wang, X.; Song, X.L. Analysis on evolution process and movement mechanism of the Luojiapo landslide in Heifangtai, Gansu Province. *Chin. J. Geol. Hazards Control* **2023**, *34*, 11–20. (In Chinese with English Abstract)
73. Chen, G.; Meng, X.M.; Qiao, L.; Zhang, Y.; Wang, S.Y. Response of a loess landslide to rainfall: Observations from a field artificial rainfall experiment in Bailong River Basin, China. *Landslides* **2018**, *15*, 895–911. [CrossRef]
74. Hou, X.K.; Vanapalli, S.K.; Li, T.L. Water infiltration characteristics in loess associated with irrigation activities and its influence on the slope stability in loess highland, China. *Eng. Geol.* **2018**, *234*, 27–37. [CrossRef]
75. Zeng, R.Q.; Meng, X.M.; Zhang, F.Y.; Wang, S.Y.; Cui, Z.J.; Zhang, M.S.; Zhang, Y.; Chen, G. Characterizing hydrological processes on loess slopes using electrical resistivity tomography—A case study of the Heifangtai Terrace, Northwest China. *J. Hydrol.* **2016**, *541*, 742–753. [CrossRef]
76. Bai, Y.; Feng, B.; Zhang, J.F. Application of Multi-electrode Resistivity Method in Groundwater Level Detection in Loess Tableland of Jingyang Area, Shaanxi, China. *JESE* **2020**, *42*, 791–800. (In Chinese with English Abstract)
77. Duan, G.X.; Jia, X.X.; Bai, X.; Liu, C.G.; Wei, X.R. Variation of Soil Water over Slopes and Retained Lands in Loess Region: Investigated Using Electrical Resistivity Tomography. *J. Irrig. Drain.* **2023**, *42*, 104–111. (In Chinese with English Abstract)
78. Bian, S.Q.; Yang, Y.P.; Ma, J.H.; Chen, G.; Zeng, R.Q.; Zhang, Y.; Meng, X.M. Two-Dimensional Imaging Study of Internal Moisture in Loess Slope: A Case Study of the Luojiapo Landslide in Hei-fangtai Terrace. *J. Eng. Geol.* **2020**, *28*, 840–851. (In Chinese with English Abstract)
79. Wu, L.Z.; Zhou, Y.; Sun, P.; Shi, J.S.; Liu, G.G.; Bai, L.Y. Laboratory characterization of rainfall-induced loess slope failure. *Catena* **2017**, *150*, 1–8. [CrossRef]
80. Wang, X.G.; Wang, J.D.; Zhan, H.B.; Li, P.; Qiu, H.J.; Hu, S. Moisture content effect on the creep behavior of loess for the catastrophic Baqiao landslide. *Catena* **2020**, *187*, 104371. [CrossRef]
81. Robinson, D.A.; Lebron, I.; Kocar, B.; Phan, K.; Sampson, M.; Crook, N.; Fendorf, S. Time-lapse geophysical imaging of soil moisture dynamics in tropical deltaic soils: An aid to interpreting hydrological and geochemical processes. *Water Resour. Res.* **2009**, *45*, 4. [CrossRef]
82. Wehrer, M.; Slater, L.D. Characterization of water content dynamics and tracer breakthrough by 3-D electrical resistivity tomography (ERT) under transient unsaturated conditions. *Water Resour. Res.* **2015**, *51*, 97–124. [CrossRef]
83. Senkaya, M.; Babacan, A.E.; Karsli, H.; San, B.T. Origins of diverse present displacements in a paleo-landslide area (Isiklar, Trabzon, northeast Turkey). *Environ. Earth Sci.* **2022**, *81*, 245. [CrossRef]
84. Kang, C.; Zhang, F.Y.; Pan, F.Z.; Peng, J.B.; Wu, W.J. Characteristics and dynamic runout analyses of 1983 Saleshan landslide. *Eng. Geol.* **2018**, *243*, 181–195. [CrossRef]
85. Li, S.H.; Li, C.; Yao, D.; Liu, C.C. Interdisciplinary asperity theory to analyze nonlinear motion of loess landslides with weak sliding interface. *Landslides* **2020**, *17*, 2957–2965. [CrossRef]
86. Zhang, J.Q.; Gurung, D.R.; Liu, R.K.; Murthy, M.S.R.; Su, F.H. Abe Barek landslide and landslide susceptibility assessment in Badakhshan Province, Afghanistan. *Landslides* **2015**, *12*, 597–609. [CrossRef]
87. Putro, S.T.J.; Arif, N.; Sarastika, T. Land surface temperature (LST) and soil moisture index (SMI) to identify slope stability. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *986*, 012022. [CrossRef]
88. Zhou, X.; Zhang, S.C.; Zhang, Q.; Liu, Q.; Ma, Z.M.; Wang, T.; Tian, J.; Li, X.R. Research of Deformation and Soil Moisture in Loess Landslide Simultaneous Retrieved with Ground-Based GNSS. *Remote Sens.* **2022**, *14*, 5687. [CrossRef]
89. Li, J.; Cao, F. Characteristics Analysis of Collapsible Loess Structure in Sanmenxia Area. *Henan Sci. Technol.* **2022**, *15*, 107–110. (In Chinese with English Abstract)
90. Pu, X.W.; Wang, L.M.; Wang, P.; Chai, S.F. Study of shaking table test of seismic subsidence loess landslides induced by the coupling effect of earthquakes and rainfall. *Nat. Hazards* **2020**, *103*, 923–945. [CrossRef]
91. Zhao, L.H.; Zuo, S.; Lin, Y.L.; Li, L.; Zhang, Y.B. Reliability back analysis of shear strength parameters of landslide with three-dimensional upper bound limit analysis theory. *Landslides* **2016**, *13*, 711–724. [CrossRef]
92. Pei, X.J.; Zhang, X.C.; Guo, B.; Wang, G.H.; Zhang, F.Y. Experimental case study of seismically induced loess liquefaction and landslide. *Eng. Geol.* **2017**, *223*, 23–30. [CrossRef]
93. Whiteley, J.S.; Chambers, J.E.; Uhlemann, S.; Wilkinson, P.B.; Kendall, J.M. Geophysical Monitoring of Moisture-Induced Landslides: A Review. *Rev. Geophys.* **2019**, *57*, 106–145. [CrossRef]
94. Chen, W.W.; Song, B.H.; Wu, W.J.; Sun, Y.F.; Song, Y.P. Direct and reversal shear behaviors of three kinds of slip zone soil in the Northwest of China. *Bull. Eng. Geol. Environ.* **2021**, *80*, 3939–3952. [CrossRef]
95. Leng, X.L.; Wang, C.; Zhang, J.; Sheng, Q.; Cao, S.L.; Chen, J. Deformation Development Mechanism in a Loess Slope with Seepage Fissures Subjected to Rainfall and Traffic Load. *Front. Earth Sci.* **2021**, *9*, 769257. [CrossRef]
96. Zhang, X.Z.; Lu, Y.D.; Li, X.; Lu, Y.C.; Pan, W.S. Microscopic structure changes of Malan loess after humidification in South Jingyang Plateau, China. *Environ. Earth Sci.* **2019**, *78*, 287. [CrossRef]
97. Wang, X.G.; Liu, K.; Wang, Y.L.; Zhang, P.D.; Shi, W.; Luo, L. An experimental study of the creep characteristics of loess landslide sliding zone soil with different water content. *Hydrogeol. Eng. Geol.* **2022**, *49*, 137–143. (In Chinese with English Abstract)
98. Pan, L.; Zhang, Y.F.; Chen, J.Z.; Zhang, Y.H. Research on the relationship between loess macro-structure and collapsibility coefficient. *J. Water Resour. Water Eng.* **2018**, *29*, 220–224. (In Chinese with English Abstract)

99. Liu, L.; Yin, K.L.; Wang, J.J.; Zhang, J.; Huang, F.M. Dynamic evaluation of regional landslide hazard due to rainfall: A case study in Wanzhou central district, Three Gorges Reservoir. *Chin. J. Rock Mech. Eng.* **2016**, *35*, 558–569. (In Chinese with English Abstract)
100. Dijkstra, T.A. Geotechnical thresholds in the Lanzhou loess of China. *Quatern Int.* **2001**, *76–77*, 21–28. [CrossRef]
101. Gu, T.F.; Wang, J.D.; Wang, N.Q. Geological features of loess landslide at Lüliang airport and its 3D stability analysis. *Rock Soil Mech.* **2013**, *34*, 2009–2016. (In Chinese with English Abstract)
102. Zhou, Y. Rainfall-Induced Landslide Susceptibility and Dynamic Hazard Evaluation Study in Loess Hilly Region—A Case Study of Qin'an County, Gansu Province. Master's Thesis, Chengdu University of Technology, Chengdu, China, 2018. (In Chinese with English Abstract)