

REVIEW

Preventing Geological Disasters in Loess Regions: Lessons Learned and Future Directions from Gansu and Similar Environments

Yucheng Wang

Gansu Zhiguang Geological Engineering Survey and Design Co., Ltd., Lanzhou City 730000, China

ABSTRACT

Loess areas represent the most susceptible geomorphological settings for geological disasters, thanks to distinctive soil properties, elevated porosity, and high water permeability. The study provides an updated overview of the mechanisms, features, and mitigation approaches for geological hazards in loess regions, using Gansu Province as a case study and comparing it with other loess regions worldwide. This research explores the geomorphological and environmental characteristics of loess, with an emphasis on the role of hydro-mechanical stress in landslides, debris flows, and collapses. This review, through the synthesis of case studies and literature, reveals the primary role of water in controlling various types of hazards, and also highlights the influence of human factors such as irrigation, urbanization, and slope alterations. Existing prevention and mitigation measures, such as monitoring, engineering, ecology, and policy-making, are assessed, showing gaps in their piecemeal implementation and long-term sustainability. This review is unique in its multi-scale and multi-disciplinary approach, which connects soil micromorphology, landscape dynamics, and socio-environmental interactions. It suggests future work in areas including the use of emerging technologies like artificial intelligence and multi-source observation, as well as the development of climate-resilient, adaptive management strategies. This research promotes an integrated strategy of technological, ecological, and social adaptation to improve resilience in loess regions.

Keywords: Loess Regions; Geological Hazards; Landslide Mechanisms; Disaster Prevention; Hydro-Mechanical Processes

*CORRESPONDING AUTHOR:

Yucheng Wang, Gansu Zhiguang Geological Engineering Survey and Design Co., Ltd., Lanzhou City 730000, China; Email: 18189670998@163.com

ARTICLE INFO

Received: 10 February 2026 | Revised: 26 April 2026 | Accepted: 11 May 2026 | Published Online: 18 June 2026

DOI: <https://doi.org/10.30564/jees.v8i6.13371>

CITATION

Wang, Y., 2026. Preventing Geological Disasters in Loess Regions: Lessons Learned and Future Directions from Gansu and Similar Environments. *Journal of Environmental & Earth Sciences*. 8(6): 142–162. DOI: <https://doi.org/10.30564/jees.v8i6.13371>

COPYRIGHT

Copyright © 2026 by the author(s). Published by Bilingual Publishing Group. This is an open access article under the Creative Commons Attribution-NonCommercial 4.0 International (CC BY-NC 4.0) License (<https://creativecommons.org/licenses/by-nc/4.0/>).

1. Introduction

Inhabiting around 10% of the world's continental area, loess deposits are formed mostly by aeolian processes during the Quaternary period and are found in many different places all over the world, such as the Loess Plateau of China, Central Asia, Eastern Europe, and North America^[1,2]. Such formations have a distinctive metastable structure, high porosity,

and low cementation, making them particularly vulnerable to collapse when exposed to moisture. The distribution of loess deposits and key study regions around the world is shown in **Figure 1**. Although many loess regions have been densely populated and heavily exploited for agricultural purposes due to their fertility and easy excavation, they are also among the most vulnerable geomorphological environments, associated with a broad range of geological hazards^[3-5].

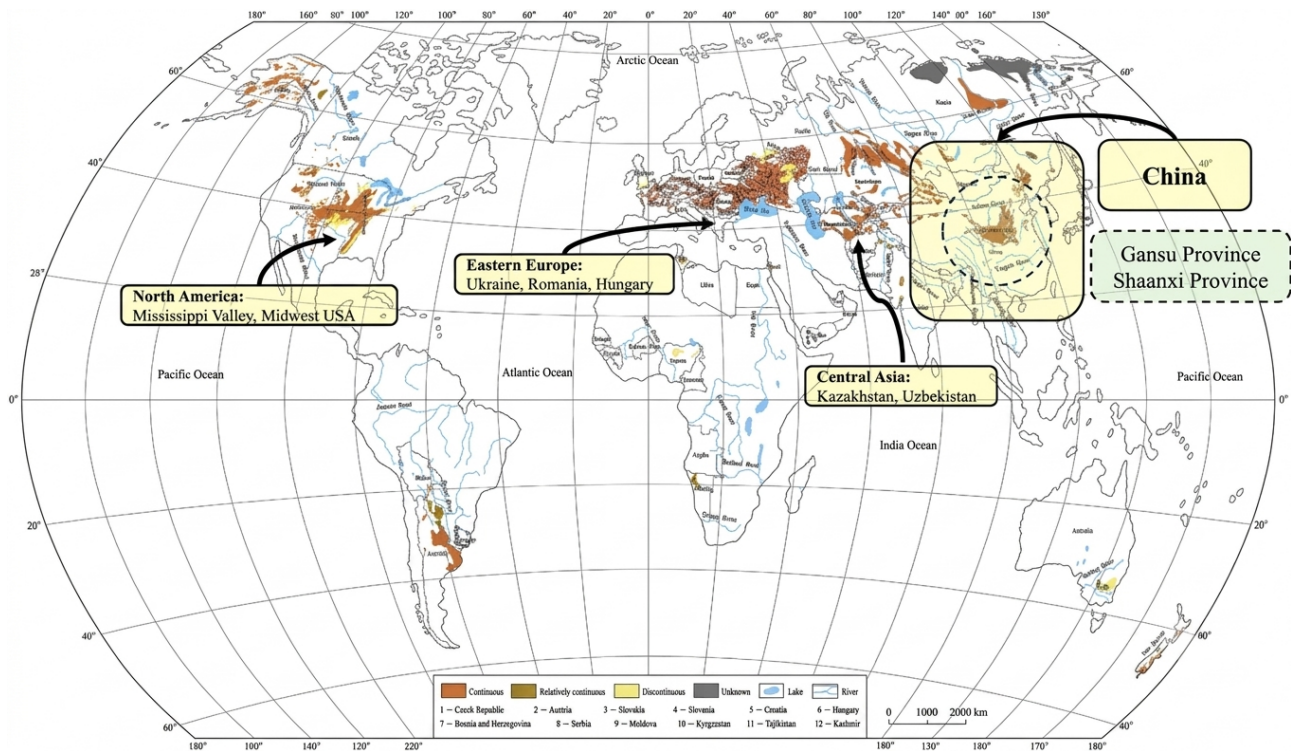


Figure 1. The global distribution of loess deposits and major regions is discussed in this study^[6].

Gansu Province is one of the more prone regions to suffer from disasters due to its unique topography, semi-arid to arid climate, and widespread loess deposits. This region experiences several geological disasters, such as loess landslides, debris flows, soil subsidence and gully erosion, which threaten infrastructure and human lives, and adversely affect agricultural yields. Over the past few decades, urban sprawl, the construction of large infrastructure projects, and intensified agriculture have contributed further to slope destabilization and hydrologic disturbances. These human activities, together with growing climate change and extreme rainfall, have resulted in an increased frequency and intensity of loess disasters^[7,8].

The processes underlying geological hazards in loess

areas are distinct from those in other soil and rock masses. Collapse, which is induced by moisture changes, is a key factor in loess slope failures. Infiltration of rainfall, leaking irrigation water, and groundwater level fluctuations all have the potential to trigger rapid loss of strength, resulting in catastrophic slope failures even on slopes that are not steep. Additionally, loess's vertical jointing and open structure promote deep-water infiltration, which increases the rate of failure and adds to forecasting challenges. These unique properties require tailored methods for hazard evaluation, monitoring, and mitigation beyond traditional geotechnical methods^[9].

Considerable advances have been made in recent decades regarding the understanding of loess and engineering

approaches to mitigate hazards. Research has focused on the hydro-mechanical behavior of loess, triggers for landslide events, and the performance of slope protection measures. Simultaneously, there have been significant improvements in remote sensing techniques, including Interferometric Synthetic Aperture Radar (InSAR) and unmanned aerial vehicles (UAVs), to monitor surface movements and issue early warnings for potential slope failures. Environmental restoration measures, including vegetation-involved slope stabilization and watershed management, have also shown potential to mitigate erosion and improve slope stability^[10–12].

However, there are several key gaps in the understanding of loess disasters. First, much of the current research examines only isolated components of loess dynamics or specific hazards, without providing an integrated, holistic view of disaster processes at multiple scales in time and space. Second, the adaptability of mitigation measures to other regions with different climatic, geological, and socioeconomic conditions is poorly understood. Third, the implementation of new technologies (e.g., artificial intelligence, big data, multi-source monitoring systems) in disaster prevention strategies is still in its infancy. Fourth, the rapidly changing climate, including the rising frequency of extreme rainfall, brings uncertainties that affect predictions and hazard mitigation^[13–16].

In this regard, we urgently need a comprehensive and integrated review of existing knowledge, experiences from high-risk areas, and future challenges for research and practice. This review seeks to provide such a synthesis, with Gansu Province as a typical case study of loess-dominated regions, while also including examples from other loess regions around the world. This review will explore the interactions between geological setting, climate change, and human factors to improve our understanding of geological hazards in loess regions and to inform mitigation and risk management strategies.

This review is novel in several respects. First, it takes a cross-scale approach, linking microstructural characteristics of loess with landscape-scale processes and regional hazards, thus bridging the gap between laboratory experiments and field practice. Second, it stresses the interactions between natural and human factors, including how changes in land-use patterns, water irrigation and urbanization affect soil properties and hazard development. Third, it ties the experience in Gansu Province to other loess regions, such as in Cen-

tral Asia and Eastern Europe, in order to draw lessons from experiences common to all regions and challenges unique to certain regions^[3,17,18].

Moreover, this paper builds on previous work by scrutinizing current prevention and mitigation measures from the perspectives of sustainability and resilience. It takes an integrated view of engineering, ecological, and policy-based measures, rather than considering them in isolation, and their integration into risk reduction strategies. This includes emerging methods, such as data-driven early warning systems, digital twin technologies and nature-based solutions, which have considerable potential for improving loess region resilience. In bringing together these threads of research, this review offers a vision for the future that resonates with international agendas for disaster risk reduction and sustainable development^[19–21].

Overall, this research adds to the existing literature on loess hazards by providing an overview, integration, and comparison of geological disaster prevention in loess regions. It not only synthesizes the current body of knowledge but also highlights key research gaps and offers practical insights for future work and practice. In highlighting both past experiences and future possibilities, the review seeks to contribute to the development of effective, resilient, and sustainable geological risk mitigation strategies in loess regions around the world.

2. Geological and Environmental Characteristics of Loess Regions

2.1. Formation and Distribution of Loess

Loess is a wind-blown (aeolian) sediment, mostly formed by silt-sized particles, which accumulated during glacial and interglacial periods. Its origin is closely associated with climatic change, glacial erosion, and deflation, which led to the large-scale generation of material that was subsequently blown across the continental interiors^[22]. The largest and best-studied loess accumulation is on the Loess Plateau, with thicknesses that reach several hundred meters. Similarly thick, albeit often thinner, loess sequences exist in Central Asia, Eastern Europe, and North America, reflecting generally similar formation processes but subsequent modification^[23,24]. **Table 1** provides a comparative overview of major loess regions, their features and major hazards.

Table 1. Global distribution and characteristics of major loess regions.

Region	Representative Areas	Thickness (m)	Climate Type	Characteristics	Dominant Hazards
East Asia	Loess Plateau, Gansu, Shaanxi	50–300+	Semi-arid to sub-humid	Thick deposits, strong vertical joints, high collapsibility	Landslides, debris flows, collapses
Central Asia	Kazakhstan, Uzbekistan	10–50	Arid to semi-arid	Discontinuous deposits, seismic influence	Landslides, seismic-triggered failures
Eastern Europe	Ukraine, Romania, Hungary	5–30	Temperate continental	Well-developed paleosols, moderate thickness	Slope instability, erosion
North America	Mississippi Valley, Midwest USA	5–20	Humid continental	Reworked loess, lower collapsibility	Erosion, shallow landslides

The distribution of loess is heavily influenced by paleowind directions, proximity to source and topographic obstacles. In areas like northwestern China, such as Gansu Province, loess thickness and stratigraphy are highly variable owing to the interactions between fluvial erosion, tectonic uplift and localised climate gradients. This variability affects slope stability and hazard assessment by impacting deformation and hydrologic properties, including layering, paleosol horizons, and calcite content.

In a critical sense, conventional theories that stress uniform aeolian deposition of loess are being tempered by the evidence for episodic deposition, soil development, and reworking. These contribute to high spatial variability that is frequently neglected in geohazard analyses. As such, the homogenization of loess profiles can result in simplistic engineering designs and mispredictions of failure mechanisms. As such, the research focus needs to shift towards detailed stratigraphy and sedimentological input into geotechnical models^[25–27].

2.2. Physical and Mechanical Properties of Loess

The complex engineering behavior of loess is controlled by its unique microstructure, which features a porous, metastable structure with loosely connected silt particles cemented together by weak bonding such as carbonates or clay minerals. The structure gives the material high porosity and low bulk density, but also makes it prone to collapse if the binding is destabilized by water. As shown in **Figure 2**, the 1 m sample has loose packing and weak cementation, leading to unstable overhead pores and higher collapsibility. These

metastable microstructures allow particles to slip and rearrange under external loads or moisture, reducing compressive strength. In contrast, the 25 m sample has a denser, more stable microstructure with stronger cementation and fewer overhead pores. This enhances structural stability, resulting in higher compressive strength and lower collapsibility^[28,29].

From a mechanical perspective, loess has low cohesion and average friction angles when it is dry, but its character deteriorates when it is moist. The loss of matric suction and dissolution of cementing agents cause a loss of structure, possibly accompanied by large volumetric strains and a substantial reduction in shear strength. This unsaturated soil behaviour sets loess apart from other, more stable soils and requires targeted constitutive models^[30]. The physical and mechanical characteristics of loess and their importance for engineering are listed in **Table 2**.

But one of the challenges is the variability of these properties in different loess deposits. These include variations in particle size, mineralogy, cementation, and prior stress history. For instance, in Gansu Province, loess deposits commonly show more cementation at greater depths (as a result of diagenesis) than on the surface (where collapsible properties may be present). This makes site characterization and stabilization design complex.

Crucially, the majority of geotechnical research on loess involves laboratory testing of remolded or small-size specimens, which may not adequately represent the in-situ characteristics of loess deposits. Sample disturbance during excavation and transportation may affect the fabric of loess, resulting in an underestimation or overestimation of the parameters. So, there is increasing recognition of the importance of more sophisticated testing methods, such

as in situ testing and microstructural investigations using scanning electron microscopy (SEM) and X-ray computed

tomography (CT), to understand the behavior of undisturbed loess^[31,32].

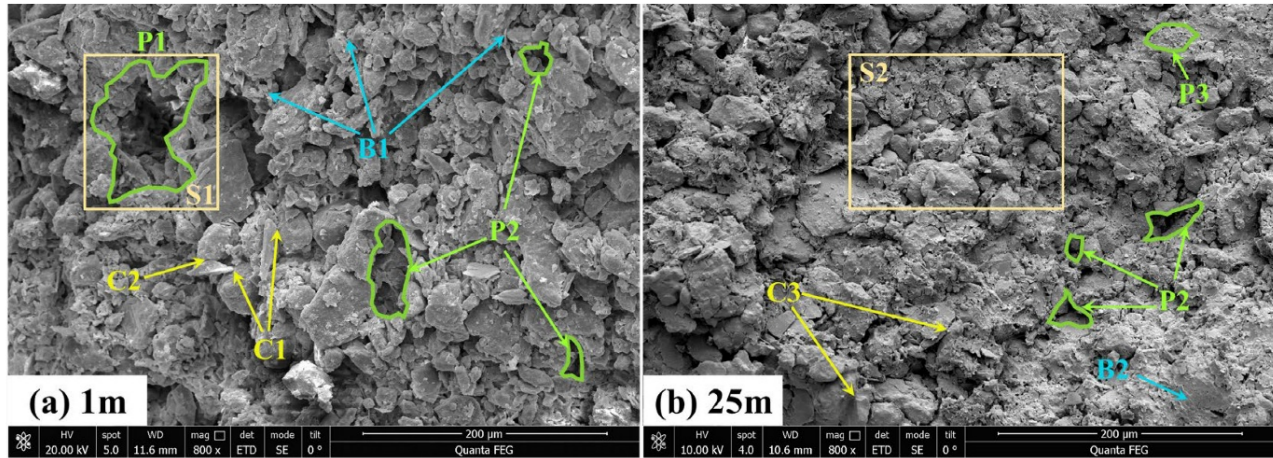


Figure 2. Microstructural characteristics of samples under SEM: (a) a 1 m sample showing loose particle packing and unstable overhead pores; (b) a 25 m sample with denser packing, stable cementation, and fewer overhead pores.

Note:

P1, overhead pores; P2, inter-aggregate pores; P3, intra-aggregate pores.

C1, point contact; C2, edge contact; C3, face bonding.

B1, weak cementation; B2, strong cementation.

S1, overhead structure; S2, interlocking structure.

Table 2. Physical and mechanical properties of loess and their engineering implications.

Property	Typical Range	Controlling Factors	Engineering Implications	Hazard Relevance
Porosity (%)	40–60	Deposition conditions, compaction	High compressibility	Collapse risk
Dry Density (g/cm ³)	1.2–1.6	Depth, cementation	Low bearing capacity	Subsidence
Cohesion (kPa)	10–40 (dry)	Moisture, structure	Rapid reduction when wetted	Landslides
Internal Friction Angle (°)	20–35	Grain size, structure	Moderate shear resistance	Slope stability
Permeability (m/s)	10 ⁻⁶ –10 ⁻⁴	Structure, cracks	Preferential flow paths	Deep failures
Collapsibility	High	Water content, structure	Sudden settlement	Ground collapse

2.3. Climatic and Hydrological Influences

The weather and water are the critical factors in the stability of loess slopes. Rainfall, in particular, is the main driver of many loess hazards. Rainwater infiltration decreases matric suction, increases the pore water pressure and reduces the interparticle cohesion, contributing to slope instability. In semi-arid climates such as Gansu Province, precipitation tends to be intense and short-lived, resulting in rapid infiltration and saturation.

Permeability and structure of loess play a crucial role in its response to rainfall. Although loess is generally moderately permeable, the occurrence of vertical joints and macro-

pores permits preferential flow and enhances the infiltration of water into the subsurface. This can lead to deep-seated slope failures that are hard to identify and anticipate. In addition, the formation of perched water tables and temporary saturation zones can lead to complex moisture distributions that are not well represented by simplified hydrologic models. Other seasonal processes, including freeze–thaw, also play a role in destabilising loess. Freeze–thaw cycles can cause microcracks, weaken particle cohesion and increase permeability, thus increasing the vulnerability of slopes to rainfall-induced landslides. In areas where temperature fluctuations are marked, this can build over time to decrease slope stability^[33,34].

More broadly, climate change is likely to amplify these issues through changes in precipitation and more extreme weather events. More intense rainfall events could surpass previously established criteria for slope failure, making early warning systems less efficient. This calls for flexible models that can account for changes in climate and better predict hazard events.

2.4. Anthropogenic Modifications and Their Impacts

Anthropogenic factors now play a major role in loess slope stability and can both directly trigger and indirectly contribute to geological hazards. In areas experiencing rapid urbanization, such as Gansu Province, major engineering works, such as road and city construction and irrigation, can lead to significant changes in slope geometry and water regimes. Cuts for construction often create overly steep slopes that exceed the angle of repose of loess. In the absence of proper reinforcement, this can increase the risk of slope instability, especially under conditions of intense rainfall. Likewise, digging cavities, such as traditional yaodong dwellings, can also create underground voids that reduce the stability of the overlying material and trigger collapses^[35].

Irrigation is another key anthropogenic influence. Irrigation is vital for crop production, but it can also add significant amounts of water into the subsurface, thus increasing moisture levels, which in turn increases collapsibility. Leakage from irrigation canals and reservoirs is a common cause of localized slope failures, particularly in areas where drainage systems are poorly designed or maintained. Urban development also contributes to an increase in runoff and a disruption of natural infiltration processes. Increased runoff can concentrate flow and cause erosion, while poor drainage can cause ponding and infiltration into unstable slopes. Additionally, the effects of multiple human activities can have complex and non-linear interactions that are challenging to quantify in traditional hazard assessment models.

Most importantly, many existing land-use practices take insufficient account of loess properties, resulting in a disconnect between planning and the environment. This highlights the need to embed geotechnical understanding into policy and land-use frameworks and encourage a multidisciplinary approach that takes into account both engineering

and socio-economic considerations^[36–38].

2.5. Integrated Perspective on Loess System Dynamics

The geomorphic features of loess regions are not independent but rather the result of the interaction of geological, climatic, and human factors across a range of scales. The metastable properties of loess suggest that small, natural or anthropogenic triggers can induce disproportionate effects, such as slope failure or collapses. This underscores the importance of a systems perspective in hazard and risk mitigation. A holistic view shows that many geological hazards in loess landscapes are not caused by a single trigger but rather a combination of processes. For instance, while a slope failure might be triggered by heavy rainfall, the probability and scale of the failure are affected by factors such as soil characteristics, human land use, and drainage networks. Likewise, the effects of climate change are not fully appreciable without understanding their interactions with human and geological processes^[17].

This requires, from a technical perspective, the integration of different data sources and methods such as field surveys, laboratory experiments, numerical simulations and remote sensing. The growing fields of data science and modeling provide opportunities to better represent these interactions and increase the level of confidence in predictions. But the adoption of such methods depends on both technological and institutional cooperation and data exchange. To summarise, the geological and environmental setting of loess areas poses a challenge as well as an opportunity for disaster management. Although the intrinsic characteristics of loess make it vulnerable to instability, a better understanding of loess behaviour—in addition to interdisciplinary and integrated approaches—can help to manage geological hazards sustainably^[39].

3. Types and Mechanisms of Geological Disasters in Loess Areas

3.1. Landslides in Loess Slopes

Landslides are the most prevalent and devastating geological hazards in loess areas, including the Loess Plateau and places like Gansu Province in China. Loess landslides

are distinguished from conventional landslides in hard rock or cohesive clays by the failure of a metastable soil structure and the rapid increase in moisture content from unsaturated to saturated. This leads to different modes of failure and temporal behaviour^[17].

Loess landslides can be broadly grouped into shallow and deep-seated landslides. Shallow landslides usually involve the uppermost meters of the slope and are often triggered by intense, short-duration rainfall. These landslides typically occur rapidly and on a small scale, but may still be destructive due to their sudden nature and potential to occur near human infrastructure. On the other hand, deep-seated landslides can involve larger masses and may initiate along planes of weakness such as paleosols or wetter areas. Such failures can develop gradually, but generally have more severe implications, such as large-scale slope deformation and long-runout movement. A characteristic of loess landslides is their response to water infiltration. Precipitation, irrigation leaks, and groundwater rises can all play a role in reducing matric suction and weakening particle bonds. But the role of rainfall in triggering landslides is complex. Although empirical rainfall thresholds exist, these may be constrained by local factors such as slope gradients, soil fabric and rainfall history. For instance, in Gansu Province, the same rainfall can trigger landslides under some hydrologic and geologic settings, but not under others^[40,41].

Another important mechanism is the progressive development of failure surfaces. In many instances, loess slopes experience a period of precursor deformation before failure, during which microfractures and shear surfaces develop. This indicates that landslides are not purely instantaneous failures but rather the end result of an extended degradation process. But it can be difficult to identify and track such early signals in remote or low-resource environments. Importantly, many models of loess landslides assume the soil is homogeneous and isotropic. This can result in inaccurate predictions of the failure mechanisms and extent, particularly in layered or jointed loess. As such, there is a clear need for more complex models considering structural variability, preferential flow, and time effects^[42].

3.2. Debris Flows and Gully Erosion

Gully erosion and debris flows are interconnected processes that are important for both shaping loess landscapes

and producing hazards. They are common in areas with extensive gully networks, where easily erodible material and occasional heavy rainfall provide suitable conditions for the rapid mobilization of debris.

Debris flows in loess landscapes are generally triggered by the wetting and activation of slope sediments, which are then transported down channel and across gullies. The silt-rich nature of loess means that debris flows can display both liquid and solid-like properties, depending on the amount of water and sediment present. This aspect makes debris flows difficult to predict and manage, as they can transition between fluid and granular behaviours^[43–45].

By contrast, gully erosion is a longer-term phenomenon involving the erosion and deepening of channels in the loess landscape. Although usually not classified as a hazard in and of itself, gully erosion can create conditions that increase the risk of slope instability by modifying drainage networks, steepening slopes, and removing protective layers. In many cases, gullies act as conduits for debris flows, amplifying their impact and extending their reach.

The relationship between debris flows and gullies is especially strong in Gansu Province. The semi-arid climate of the region results in infrequent but heavy rainfall events that can produce significant runoff. This water quickly erodes the loess surface, mobilising sediment and triggering debris flows that can travel long distances. The potential for debris flows to interact with human settlements or infrastructure is also increased by the presence of infrastructure within or adjacent to gully systems, which are often preferred for settlement, agriculture and transportation. Mechanistically, the triggering of debris flows in loess areas is closely related to pre-conditions, such as moisture, vegetation, and human activities. For instance, land clearing or overgrazing can destabilise the surface and lead to increased erosion, while inappropriate agricultural management can increase runoff and sediment supply^[8,46]. These considerations underline the need to account for both natural and human factors in debris flow processes.

Despite detailed studies, there is still much to be learned about the scaling of debris flows and estimating the magnitude and frequency of debris flow events. Models developed for specific locations may not apply to areas with different environmental settings. This suggests the need for more transferable models that consider variability across loess

landscapes^[47].

3.3. Ground Subsidence and Collapses

Subsidence and collapses are unique geohazards in the loess areas, mainly due to the compressibility of the soil and the presence of voids. These hazards are significant in areas with traditional underground dwellings (yaodong) or modern underground spaces and in regions impacted by irrigation or water leakage. Loess subsidence is usually linked to the progressive settlement of the land surface resulting from the collapse of the soil structure from wetting. This may occur naturally (e.g., due to rainfall) or as a result of human activities (e.g., irrigation, leakage from water pipes, groundwater level variations). The deformation can be quite uniform over large regions or very localised, depending on the moisture content and soil variability^[13,17].

Collapses, on the other hand, are more rapid and confined events that may involve the collapse of a cavity or weak zone. This can be particularly dangerous because of its unpredictability and lack of warning. Collapses linked to abandoned or poorly constructed Yaodong dwellings have been reported in Gansu Province, showcasing the role of cultural activities in geohazards.

Understanding the processes of subsidence and collapse also involves the role of water infiltration in weakening soils. Infiltration of water into the loess reduces suction and dissolves binding agents, causing a loss of stiffness and strength. When combined with existing voids, roof collapse and subsidence can occur. Therefore, the coupling of hydrologic and structural characteristics is a key factor in the occurrence and magnitude of hazards. From an engineering point of view, the prediction of subsidence and collapse is difficult because of subsurface uncertainties and the highly nonlinear behaviour of loess during wetting. Geophysical techniques, including ground-penetrating radar and electrical resistivity tomography, may provide valuable insights for identifying subsurface anomalies, although their use can be financially and technically challenging^[48,49].

Notably, subsidence and collapse hazards are often

overlooked in hazard assessments, as they may not cause immediate, large-scale effects like landslides or debris flows. But their impact on infrastructure sustainability and land degradation may be significant and should be better understood and addressed.

3.4. Case Studies from Gansu and Comparable Regions

Case studies from Gansu Province offer a wealth of information on the processes and effects of loess disasters. This area has seen a series of landslides, debris flows, and falls with potential loss of life and property damage. Such disasters reflect the interaction of geological, climatic and anthropogenic factors.

For example, some reported landslides in Gansu have been associated with irrigation-induced infiltration, where the continued input of water resulted in deep-seated saturation and slope failure. Alternatively, heavy rainfall has been responsible for triggering shallow landslides and debris flows, especially in regions with numerous gullies. Such findings reveal the roles of water as a natural and human-induced agent of instability. Comparing these findings across other loess deposits adds to the knowledge base. In Shaanxi Province, for example, similar rainfall-induced landslides and gully erosion patterns have been observed, but the differences in vegetation and land use affect the occurrence and magnitude of the events. In Central Asia, loess deposits are frequently exposed to earthquakes, which can provide an additional trigger for landslides. In Eastern Europe, loess hazards are often coupled with riverbank erosion and long-term erosion. These case studies highlight similarities and differences in hazard mechanisms. **Table 3** presents a comprehensive overview of major hazards, triggers and mechanisms in loess regions. Although the intrinsic characteristics of loess are fairly consistent, regional climate, topography and human factors are critical in influencing hazard development. This highlights the need for region-specific hazard evaluation and mitigation strategies and cross-regional lessons^[40,41,50,51].

Table 3. Summary of geological disaster types, triggers, and mechanisms in loess regions.

Hazard Type	Primary Triggers	Mechanisms	Spatial Scale	Typical Impacts
Landslides	Rainfall, irrigation, slope cutting	Loss of suction, structural collapse, shear failure	Local to regional	Infrastructure damage, casualties

Table 3. Cont.

Hazard Type	Primary Triggers	Mechanisms	Spatial Scale	Typical Impacts
Debris Flows	Intense rainfall, gully erosion	Sediment mobilization, channelized flow	Catchment scale	Burial, destruction of settlements
Ground Subsidence	Water infiltration, leakage	Collapse of soil structure	Local	Structural damage
Ground Collapse	Underground voids, wetting	failure of cavities	Highly localized	Sudden ground failure
Gully Erosion	Surface runoff, land degradation	Progressive incision	Landscape scale	Land loss, increased hazard susceptibility

3.5. Integrated Mechanisms and Interactions

Different forms of geological hazards in loess regions are not only linked but also share mechanisms and feedback loops. Debris flows, landslides, and subsidence events can act in concert or as a preconditioning phase to another event. For instance, gully erosion might weaken slopes and trigger landslides, and landslides might supply the material for debris flows.

Underlying these connections is loess' vulnerability to water and stress changes. Water provides a common thread among these different hazards, both in triggering and sustaining failure. But the mechanisms by which water influences stability vary greatly, depending on factors such as soil structure, permeability, and external forcing. In terms of systems thinking, the key to understanding these dynamics is to move away from single-hazard perspectives to more integrated models of loess systems. These models will need to consider spatial and temporal variation as well as interactions between natural and human influences. A comprehensive

conceptual model of the interplay between major hazard mechanisms in loess regions is presented here for landslides and debris flows. This model considers variables such as topography, soil characteristics and climate, which affect the outbreak and run-out of these hazards. Through the study of historical satellite data and DEM, a three-dimensional model of the topography was developed, showing the effects of slope thresholds and the slope of the arriving mass on the extent of landslides and the dissipation of their energy. This model, illustrated in **Figure 3**, offers a holistic view of hazard mechanisms and is a useful tool for risk assessment and mitigation of landslides and debris flows in loess areas [52,53].

To sum up, the processes of geological disasters in loess areas are complex and variable. Recognizing these mechanisms is crucial for effective disaster prevention and mitigation, especially in regions like Gansu Province. This section leverages information from various types of hazards and locations to lay the groundwork for integrated strategies described later.

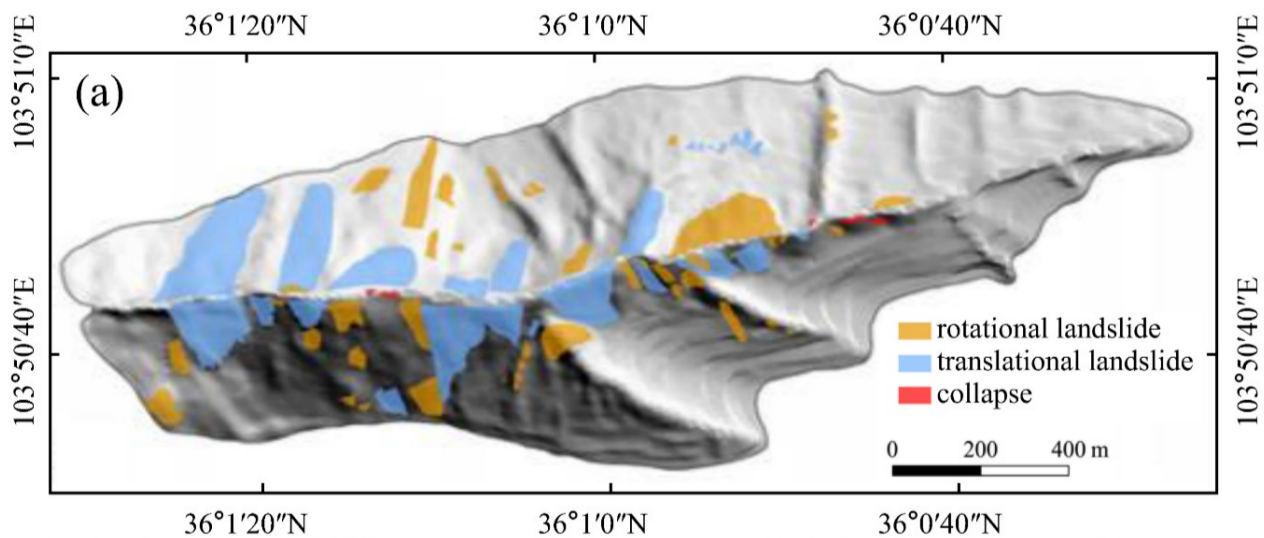


Figure 3. Cont.

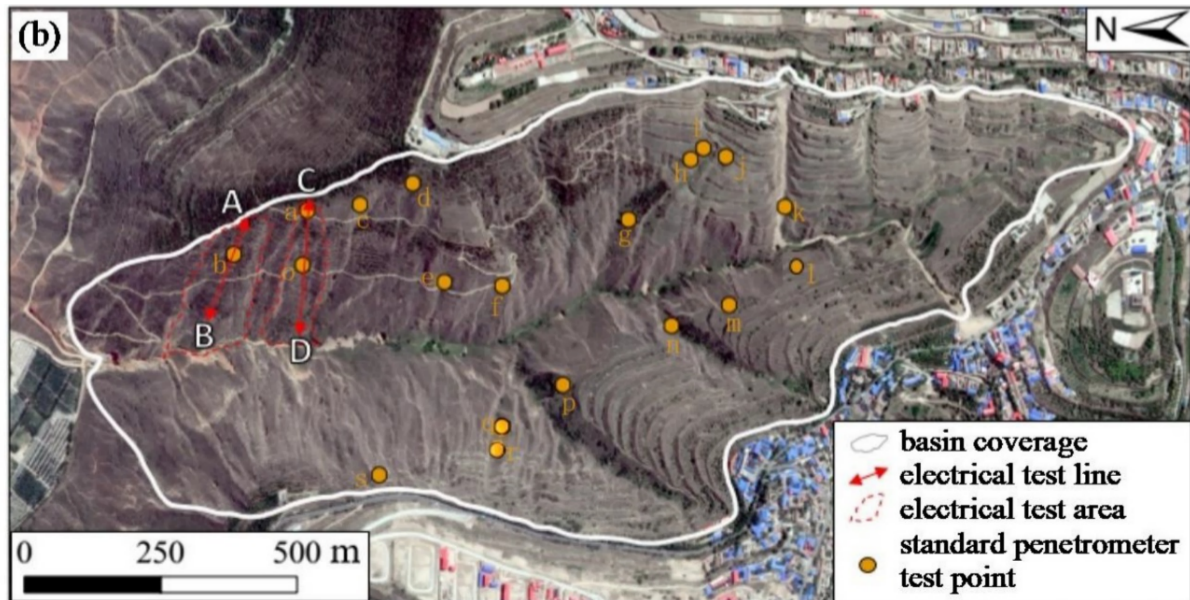


Figure 3. Distribution of landslides in the Laolang gully area, showing the spatial extent of rotational and translational landslides. Panel (a) illustrates the overall landslide distribution, while panel (b) highlights measurement points for landslide thickness using the standard penetrometer and the high-density electrical method^[54].

4. Current Prevention and Mitigation Strategies

4.1. Monitoring and Early Warning Systems

Early warning and monitoring systems represent the primary defense against geological hazards for loess areas, especially in high-risk areas like Gansu Province. Because of the sudden nature and potential for devastating impacts of loess-related hazards, early recognition of premonitory signs is essential to mitigate fatalities and property damage. In recent years, tremendous progress has been made in remote sensing and in-situ monitoring technologies to provide more systematic and continuous monitoring of slope movements^[4,55].

Space-based methods, such as Interferometric Synthetic Aperture Radar (InSAR), have provided a means to detect millimeter-scale deformation across wide areas. These methods are especially valuable in remote or inaccessible regions, where traditional monitoring approaches are difficult to implement. In loess areas, InSAR has been applied to detect creeping landslides and to capture pre-failure deformation patterns. However, they may suffer from issues related to vegetation cover, time resolution, and atmospheric noise, potentially masking subtle deformation or delaying detection. Unmanned aerial vehicles (UAVs)

have also been deployed to complement InSAR by providing high-resolution images and the ability to focus on specific areas of interest. Photogrammetry and LiDAR using UAVs can capture topographic variations, allowing for the detection of cracks, scarps, and other signs of deformation. These are valuable for post-failure assessment and model validation, but their use in real-time monitoring is limited by costs and logistics^[56–59].

In situ monitoring, using inclinometers, extensometers, piezometers, and rain gauges, offers essential data on slope displacement, pore water pressure, and rainfall. These systems enable the direct measurement of slope stability factors and can be used in early warning systems. In Gansu Province, for example, pilot studies have shown that integrating rainfall thresholds with real-time monitoring can be used to provide warnings and trigger evacuation procedures^[60].

However, there are still many challenges. Existing systems are often not integrated at different spatial and temporal scales. Real-time data processing and interoperability are also crucial issues, especially in rural areas. Additionally, the use of empirical rainfall thresholds may not fully account for the interactions between soil properties, antecedent conditions and triggering factors. The loss of life from these disasters is therefore driving a need for more information-rich, multi-parameter data-driven early warning systems.

4.2. Engineering Measures for Slope Stabilization

Engineering measures have traditionally been the mainstay of disaster prevention in loess areas, largely centred on slope stabilization and water infiltration. Such interventions include conventional structural methods, like retaining walls and grading, to more modern approaches such as soil reinforcement and drainage. Retaining walls, such as gravity walls, reinforced earth walls, and pile-supported structures, are commonly employed to provide lateral support and prevent slope failure. However, in loess areas, the design and construction of such structures must consider the specific characteristics of loess, such as its collapsibility and moisture sensitivity. Retaining walls that are not properly designed can worsen slope instability through changes in stress concentrations or by disrupting drainage. Slope stabilization measures, including soil nailing, anchors, and geosynthetics, have been successfully used to improve the shear resistance of loess slopes. These techniques increase the strength and cohesion of the soil mass and resist movement. But their effectiveness relies on proper installation and durability, especially in areas prone to wetting-drying cycles.

Water control is probably the most important engineering mitigation measure in loess areas. Ditches and diversion channels are used to minimize runoff and flow onto susceptible slopes. Subdrainage, including horizontal drains and gravel trenches, seeks to reduce pore water pressure and increase strength. In Gansu Province, many landslides have been attributed to the failure of drainage systems (often due to a lack of maintenance or incorrect design). Check dams and debris flow barriers are often used in gullies to catch sediment and slow debris flow. These barriers can substantially reduce the effects of debris flows, but require careful placement, design, and maintenance. They can lose effectiveness over time as they fill with sediment, requiring maintenance^[51,61,62].

Most importantly, engineering interventions are often applied in isolation without regard to landscape-scale processes. This may result in unintended impacts, including the reallocation of risk downslope or water flow blockages. We urgently need a more integrated approach, combining engineering, ecological, and land-use considerations, to sustainably reduce risk.

4.3. Ecological and Nature-Based Solutions

There has been a growing awareness of the importance of ecological and nature-based approaches to reducing geological hazards in loess areas in recent years. These solutions harness natural processes, such as plant growth and soil development, to improve slope stability and minimize erosion, and can be used as an addition to or in place of traditional engineering interventions. Plants are a key factor in slope stabilization of loess regions, acting both mechanically and hydrologically^[63]. The root systems of plants impart strength and cohesion to the soil, enhancing its shear resistance, and the foliage mitigates the effects of rainfall and surface erosion. Plants can also affect the moisture regime of the slope by increasing evapotranspiration and decreasing infiltration. Afforestation and grassland restoration initiatives on the Loess Plateau have had marked positive impacts on soil erosion control and landscape stability. These programs have converted vulnerable landscapes into more resilient ones, with benefits for hazard reduction and sustainability. But they require careful species selection, ongoing maintenance, and consideration of the local climate and soil^[64].

Nature-based solutions also include watershed management. These measures seek to improve water management at the watershed level by reducing surface runoff, increasing infiltration in safe areas, and reducing runoff concentration in hazardous areas. Contour planting, small retention ponds, and terracing are effective measures to control erosion and water runoff. While ecological solutions offer many benefits, they are not without their drawbacks. They may take many years to have an impact and may not be suitable in regions where immediate risk mitigation is needed. Also, the dynamics between plants, soil and water are complex and poorly understood, especially in a changing climate. So, there's a need for hybrid solutions that incorporate both ecological and engineering approaches to draw on the advantages of each^[65].

4.4. Policy, Planning, and Community-Based Approaches

Preventing disasters in loess regions also requires favorable legislative, planning, and community involvement in order to supplement technical solutions. Such socio-institutional factors are essential for ensuring that technical

mitigation measures are acceptable, effective, and sustainable. Land-use planning and hazard zoning are key strategies to mitigate geological hazards. Through mapping and zoning high-risk areas, they can avoid building infrastructure and habitation in risky areas. Hazard maps have been created in Gansu Province to inform planning, albeit with competing social and economic considerations that can limit their effective use.

Policies such as building regulations and environmental protection policies can also increase resilience by mandating that construction activities account for geological hazards. Slope designs, drainage systems and foundation construction, for instance, can enhance stability. But compliance with these measures can be difficult, especially in rural and rapidly urbanizing regions. Community-based strategies are also essential for disaster risk reduction, especially in areas where regulatory monitoring and enforcement are weak. Public education, training and co-planning can help communities understand and respond to early signs of imminent risk. Local indigenous knowledge and practices can also provide insights into the dynamics of the hazards and work alongside science-based methods^[66].

Early warning systems and evacuation plans are also important elements. These measures rely on both accurate warnings and rapid and effective action on the part of communities. This includes effective communication, trust in government and periodic training. Crucially, there is often a gap between research and policy, which leads to less-than-ideal outcomes. This includes working across disciplines, engaging stakeholders and translating scientific knowledge into guidelines. Additionally, incorporating disaster risk reduction into development strategies is paramount for future preparedness.

4.5. Integration and Emerging Trends in Mitigation Strategies

Geological hazards in loess areas are complex and require a holistic approach to prevention and mitigation, involving technological, engineering, ecological, and socio-institutional measures. There is a growing trend toward multifaceted approaches that address multiple risk factors. The use of integrated monitoring and decision support systems that draw on multiple data sources is an encouraging development. New sensor technologies, the Internet of Things

(IoT), and cloud computing technologies allow for real-time data collection and analysis from a range of sources, such as satellites, ground-based sensors, and weather stations. These approaches can help to better understand hazard processes and inform more rapid and precise decisions^[67]. A multi-tiered model of monitoring, engineering, ecological, and policy responses is shown in **Figure 4**.

Another emerging approach for hazard and risk assessment is the use of artificial intelligence and machine learning. These techniques can extract insights from big data to detect patterns and connections not obvious with conventional methods. For loess, AI-driven models have been applied to make landslide susceptibility maps more accurate and to tune rainfall thresholds for early warning systems. But the accuracy of these models relies on the data used and their “black box” approach may be difficult to interpret and accept. A related theory is that of digital twins—virtual models of a physical system that can be used to simulate and forecast system behavior. For loess hazards, digital twins can combine geological, hydrological, and engineering information to simulate slope stability processes in real time, allowing for proactive mitigation. This is an emerging concept with the potential to increase the accuracy and flexibility of hazard mitigation^[17].

Critically, the adoption of these cutting-edge technologies requires addressing various challenges related to data, technology, and institutional arrangements. These challenges are pronounced in many loess regions, especially in developing regions. So while there are many opportunities with new technology, it must be accompanied by capacity building and resource access.

4.6. Critical Evaluation of Current Practices

Although a broad set of prevention and mitigation measures has been created, their effectiveness is generally hampered by their fragmentation, inadequate integration, and poor recognition of local circumstances. Engineering solutions, though useful in the short term, might not be long-term sustainable without appropriate maintenance and might not involve dealing with the root causes of instability. The ecological methods are promising, but long-term commitment is required and might not offer immediate protection. Technological advances notwithstanding, monitoring systems are sometimes limited by gaps in data and poor coverage.

Among the most recent findings and observations is that there is no single methodology that can be used to manage the dynamics and complexity of the loess-related hazards. On the contrary, a set of measures specific to the environment and socio-economic factors is needed. A comparative analysis of key prevention and mitigation measures is outlined in **Table 4**. This requires a proactive rather than a reactive strategy with a heavy focus on prevention, adaptation, and

resilience^[69,70].

In conclusion, current prevention and mitigation strategies in loess regions have achieved notable successes but also face significant challenges. By critically evaluating existing practices and embracing integrated, adaptive approaches, it is possible to enhance the effectiveness and sustainability of disaster risk reduction efforts, particularly in high-risk areas such as Gansu Province.

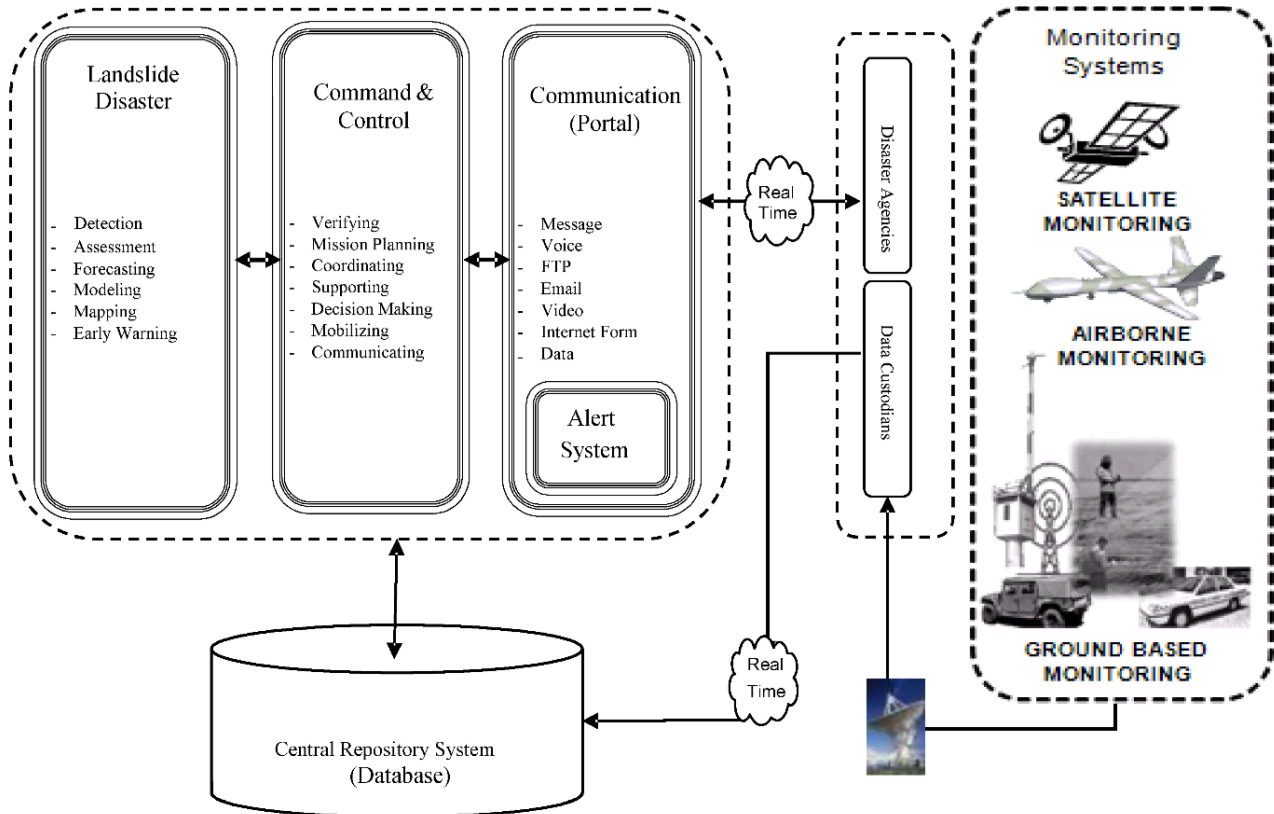


Figure 4. Integrated prevention and mitigation framework for geological hazards in loess regions^[68].

Table 4. Comparison of prevention and mitigation strategies in loess regions.

Strategy Type	Measures	Advantages	Limitations	Applicability
Monitoring & Early Warning	InSAR, UAV, sensors, rainfall thresholds	Real-time detection, early response	Data gaps, cost, integration challenges	Regional to local
Engineering Measures	Retaining walls, drainage, anchors	Immediate effectiveness, controllable	High cost, maintenance required	Site-specific
Ecological Solutions	Vegetation restoration, terracing	Sustainable, improves the environment	Slow effectiveness, climate dependent	Catchment scale
Policy & Planning	Hazard zoning, building codes	Reduces exposure, long-term impact	Enforcement challenges	Regional
Community-Based Approaches	Education, evacuation plans	Enhances resilience; low cost	Depends on awareness and participation	Local

5. Lessons Learned and Future Directions

5.1. Lessons from Gansu

The long history of disasters and disaster mitigation practice in Gansu Province can serve as a strong source of empirical evidence on the strengths and weaknesses of prevailing strategies in loess land. Among the most important lessons, the key role that water plays in regulating the stability of loess slopes warrants mention. In many documented events, be it during landslides or collapses or both, or during the movement of debris, water infiltration, either due to rainfall or irrigation or due to infiltration of irrigation or infrastructure, has always been found to be the first trigger. This highlights the fact that disaster prevention in loess lands is essentially a water management issue^[41].

Nevertheless, the ability to control water in loess soils is intrinsically complicated because of the dual nature of the soil: both absorbent and able to quickly send water through the macropores and through vertical joints. Gansu has recorded numerous failures, not out of excessive rainfall, but as a result of continuous infiltration over time in conjunction with a lack of proper drainage systems. This demonstrates a fatal flaw with the conventional methods that focus so much on short-term precipitation thresholds without taking into consideration antecedent water conditions and the flow processes in the underlying soils.

The second important lesson is that one-measure solutions are insufficient. Drainage control has always been applied along with engineering interventions, without considering ecological restoration or retaining walls. These measures have brought short-term stability in many situations but have collapsed under different environmental conditions or due to inadequate maintenance. On the contrary, in regions with a high intensity of hazards or steep slopes, ecological methods, including the restoration of vegetation, might not be adequate protection. The Gansu experience shows clearly that mitigation must be effective, and a combination of structural, hydrological and ecological measures is needed^[51,71].

The third key lesson relates to the nature of human activities as sources of, as well as magnifiers of, geological risk. The fast growth of infrastructure, the rise of agriculture, and urbanization have dramatically changed the natural balance of loess scenery. Irrigation and slope reworking in Gansu

have often been identified as causes of disasters, indicating that there is a way to better balance development planning and geotechnical constraints. This implies that the issue of disaster prevention cannot be viewed as a strictly technical problem but rather within the context of much broader socio-economic and land-use questions^[72].

Last but not least, the role of local knowledge and community involvement has become more and more apparent. In much of Gansu, rural life, the denizens have a comprehensive hands-on knowledge of slope behavior, seasonal cycles, and pre-disaster indications. This knowledge could supplement the efficacy of early warning and response techniques when utilized in conjunction with scientific surveillance. Nonetheless, this integration is still limited, and the prospects of more participatory and inclusive risk management practices were noted.

5.2. Challenges and Knowledge Gaps

Despite significant advances, several critical knowledge gaps hinder effective disaster prevention in loess regions. First, predictive models remain poorly constrained by the inherent heterogeneity of loess deposits; variations in particle size, cementation, paleosol layers, and joint networks create site-specific behaviors that limit the transferability of findings across regions. Second, monitoring infrastructure is sparse and fragmented, particularly in rural Gansu, resulting in insufficient long-term records of rainfall, soil moisture, pore pressure, and slope deformation needed to validate early warning thresholds. Third, the impacts of climate change, especially intensifying extreme rainfall events, on loess slope stability are poorly quantified, as most existing models rely on historical data that may no longer represent future conditions. Fourth, a persistent disconnect exists between scientific research and practical implementation; engineering and ecological interventions are often evaluated only for short-term performance, with little documentation of long-term sustainability under variable environmental conditions^[38].

The second big obstacle is the scarcity and quality of data, especially in remote or less developed regions. The networks are relatively few, and long-term records of rainfall, soil moisture, and slope deformation are unavailable. This lack of data makes it difficult to detect trends, validate models, and create trusted early warning methods. Data integration and interoperability problems can hinder effective

tive analysis and decision-making even where the data are available. Another source of uncertainty is climate change. There is growing evidence to indicate that instances of extreme rainfall are on the increase, and the severity of extreme rainfall is increasing in frequency and severity, especially in semi-arid areas like Gansu Province. Such modifications can cause shifts in landslide initiation thresholds and increase pre-existing vulnerabilities. But the exact effects of climate change on the stability of loess have not been effectively studied, which is partly because of the somewhat complicated interactions between climatic, hydrological, and geological processes^[73].

Future research must prioritize multi-scale, process-based investigations that link microstructural mechanics (e.g., collapse mechanisms under wetting) to landscape-scale hazard dynamics. Priority should be given to expanding and integrating monitoring networks—combining in-situ sensors, satellite InSAR, and UAV-based surveys—into unified, real-time early warning systems enhanced by artificial intelligence and machine learning. Development of climate-resilient, adaptive management frameworks is essential, including scenario-based modeling that accounts for non-stationary rainfall regimes. Equally important is the need for standardized, transferable mitigation protocols that combine engineering, ecological, and community-based measures, alongside rigorous long-term performance evaluations. Finally, strengthening international collaboration among loess regions (East Asia, Central Asia, Eastern Europe, North America) will facilitate data sharing, model validation, and cross-regional learning, accelerating progress toward sustainable geological disaster risk reduction.

5.3. Emerging Technologies and Innovative Approaches

The latest technical progress presents new possibilities to overcome certain of those difficulties and to improve disaster prevention in loess territories. Among them, artificial intelligence (AI) and machine learning have proven to be rather promising in terms of enhanced hazard forecasting and risk evaluation. Through the analysis of big data across a variety of sources, these methods can determine intricate patterns and relationships that conventional models might not be able to detect. Here are some examples of machine learning applications to refine landslide susceptibility maps

and to create more precise rainfall thresholds^[74].

But AI use in the area of losses is not a developed concept and is limited in multiple ways. Availability of good quality data is a major factor in the success of these models, and in many areas, this is not available. As well, it may be challenging to gain the trust of practitioners and decision-makers and to interpret the results due to the black box nature of certain algorithms. There is therefore a need for more transparent and explainable AI approaches, as well as for efforts to improve data collection and standardization.

Another significant change is the integration of multi-source monitoring systems. The introduction of sensor technology and the Internet of Things (IoT) has made it possible to roll out a network of sensors that are dense enough to offer real-time information about soil moisture, pore water pressure, and slope movement. These systems can help provide a complete picture of hazard conditions and enable more timely and accurate early warning in combination with satellite observations and meteorological data.

Digital twin is a relatively new technology with massive potential in loess hazard management. Digital twins provide the ability to simulate the behavior of a physical system by building a virtual representation of the physical system in a variety of situations, enabling proactive risk assessment and decision-making. In loess areas, digital twins have the potential to combine geological, hydrological, and engineering information to simulate the impacts of rain, land use alterations, and mitigation interventions on-the-fly. Being still rather experimental, this track shows a direction of future studies and applications^[75,76].

Even nature-based solutions are developing, placing a greater focus on streamlining their design and blending with engineering solutions. To provide an example, vegetation used in conjunction with artificial drainage systems may improve both the mechanical stability and hydrological control. New opportunities to increase the resilience of loess slopes are provided by improvements in ecological engineering, including the application of bioengineering methods and soil amendments.

5.4. Toward Climate-Resilient and Adaptive Management

The increasing role of climate change requires a transition to more adaptive and resilient disaster prevention in

loess areas. Historical-based and design parameters, or other traditional approaches, might not be adequate in a dynamic environment. Rather, we need flexible structures that can adapt to changing risks and uncertainties.

Climate projections are one of the important features of adaptive management because they are included in hazard assessment and planning. This goes beyond revising rainfall thresholds and design standards, but also takes into account the potential effects of extreme events that are outside the control of history. Here, scenario-based modeling may be of significance, enabling the investigation of various future states and the analysis of mitigation responses in a varied set of possible future outcomes^[34]. The strength and flexibility of infrastructure systems also contribute to resilience. In loess areas, this can entail developing slopes and drainage systems capable of handling the variability in water input and capable of tolerating extreme events without catastrophic collapse. System reliability can be supported by providing redundancy and fail-safe systems, and long-term reliability can be ensured by usual system maintenance and monitoring.

It is also vital to community resilience. Disaster preparedness and response should be collaboratively empowered at the local level to enhance the capacity to manage the vulnerable, especially in rural settings where formal relief networks might be weak. Communities can be empowered to take proactive actions and respond to warnings through education and training and participatory planning. Notably, adaptive management involves ongoing learning and feedback. The collection of data and post-event analysis and performance evaluations need to be incorporated systematically into the decision-making process, whereby models and strategies can be improved over time^[77]. This process is iterative, and loess systems are complex and dynamic, with uncertainty and variability built in.

5.5. Future Research Priorities and Strategic Directions

For the future, there are a number of key directions that can be taken to improve geological disaster prevention in loess areas. First, there must be increased multi-scale studies that address microstructural processes and macro-scale observations. Multiscale interactions are crucial for improving models. Second, improving data availability and quality

should be a priority. This includes increasing monitoring sites, developing consistent data collection protocols, and improving data sharing between institutions and regions. Websites and open databases can help with knowledge sharing and create opportunities for more universal models. Third, collaboration should be encouraged. Understanding loess-related hazards requires inputs from geologists, engineers, hydrologists, ecologists, and social scientists. This can result in more integrated approaches that consider both technical and socio-economic aspects of risk. The fourth point is to focus more on knowledge transfer. This includes the creation of guidelines, tools, and decision-making frameworks for practitioners and decision-makers. Demonstration projects can be valuable in this regard.

Finally, global partnerships should be strengthened to share knowledge and lessons among different loess areas. Although this review has focused on Gansu Province, the lessons derived from this experience apply to many other regions around the world. Through international collaboration, progress can be accelerated, and more sustainable ways to manage geological hazards in loess regions can be found. The experience in Gansu and other such environments demonstrates advances and remaining challenges in the prevention of geological disasters in loess regions. Recent progress has been made in identifying the mechanisms of hazards and potential mitigation measures, but the diversity of loess environments remains a major challenge.

The key lesson from this assessment is that integration across disciplines, scales, and sectors is critical. Preventing geological disasters demands both technological advances and institutional and societal coordination, participation, and sustainability. Through adaptive, big data, and crowdsourced approaches, we can strive for a more resilient future in loess regions.

Here, Gansu Province is an illustrative case study. It serves as a reminder that we need to learn from the past, yet also look ahead to new challenges. The key to preventing disasters in loess regions will be to combine knowledge, innovation, and adaptation^[20,78–81].

6. Conclusion

The loess areas are considered to be one of the most vulnerable geomorphological environments on our planet,

where interactions between particular loess soil characteristics, climate and human activities create a dynamic risk environment. This study has brought together existing understanding of the geological and environmental setting of loess and the mechanisms of major hazards, as well as prevention and mitigation measures currently adopted in high-risk regions, such as Gansu Province, China, and other parts of the world.

One key outcome of this research is that the metastability and collapsibility of loess material are unique among geological formations and demand dedicated approaches to hazard analysis and mitigation. Water, whether in the form of rainfall, irrigation, or groundwater, plays a key role as a major control factor for almost all types of loess-related disasters. As a result, mitigation efforts in these settings are inexorably tied to hydrological knowledge and management, especially in a changing climatic environment.

The review has identified that, despite significant advances in monitoring systems, engineering measures, and ecological treatments, existing approaches to hazard reduction are scattered and insufficient if used independently. Engineering solutions offer immediate stability but can be ineffective without coordinated drainage and maintenance. Ecological measures provide long-term solutions, but take time and need to be carefully tailored. Likewise, monitoring and early warning systems have become more effective in detecting incidents but still need to overcome issues of data integration, model development, and implementation. Insight from Gansu Province highlights the importance of integrated and multi-sectoral measures that incorporate structural, ecological, technological and policy-based measures. The success of these strategies relies on technical considerations, socio-economic adaptation, land-use integration and social engagement. In this context, improving the link between science and policy has a vital role.

Looking ahead, the growing impacts of climate change, as these affect extreme rainfall events, present a challenge for future disaster prevention in loess regions. Existing models and design criteria based on historical data may need to be replaced by adaptive and resilient approaches. New technologies such as artificial intelligence, multi-source monitoring technologies, and digital twins hold the potential to improve forecasting and decision-making. But their effectiveness will depend on better data, collaboration, and

capacity building. This review highlights a number of priorities for future research and practice. These include a greater understanding of loess behavior at multiple scales and based on processes, expanding and linking monitoring networks, robust and transferable mitigation measures, and international cooperation between loess regions. Additionally, it is critical to include community engagement and local expertise in disaster risk reduction strategies to ensure that scientific and social considerations are integrated and sustainable.

In summary, avoiding geological disasters in loess regions requires a shift from reactive “single-measure” responses to proactive, integrated, and adaptive strategies. By building on lessons from places like Gansu Province and in concert with new technologies and ideas, we can achieve better risk reduction. Finally, to be resilient in loess regions, we need to cross-fertilize knowledge across disciplines, scales, and regions, and ensure that this knowledge translates into action that protects human communities and their environment.

Funding

This work was funded by the 2023 Guangxi Young and Middle aged Teachers’ Research Basic Ability Enhancement Project (2023KY1258) and Guangxi Department of Education 2023 Guangxi Vocational Education Teaching Reform Research Project (GXGZJG2023B103).

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

All the data is presented in the article.

Conflicts of Interest

The author declares no conflict of interest.

AI Use Statement

The author declares that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

References

- [1] Li, Y., Zhao, J., Li, B., 2017. Loess and Loess Geohazards in China. CRC Press: London, UK.
- [2] Crouvi, O., Sun, J., Rousseau, D.-D., et al., 2025. Loess records. In Reference Module in Earth Systems and Environmental Sciences. Elsevier: Amsterdam, The Netherlands. pp. 505–528.
- [3] Juang, C.H., Dijkstra, T., Wasowski, J., et al., 2019. Loess geohazards research in China: Advances and challenges for mega engineering projects. *Engineering geology*. 251, 1–10.
- [4] He, P., Guo, Z., Chen, H., et al., 2023. Research and Application of Early Identification of Geological Hazards Technology in Railway Disaster Prevention and Control: A Case Study of Southeastern Gansu, China. *Sustainability*. 15(24), 16705.
- [5] Du, Y., Lyu, M., Xie, M., et al., 2025. Recent Progress in and Future Perspectives on the Monitoring, Assessment, and Mitigation of Geological Disasters. *ISPRS International Journal of Geo-Information*. 14(8), 310.
- [6] Li, Y., Shi, W., Aydin, A., et al., 2020. Loess genesis and worldwide distribution. *Earth-Science Reviews*. 201, 102947.
- [7] Haase, D., Fink, J., Haase, G., et al., 2007. Loess in Europe—Its spatial distribution based on a European Loess Map, scale 1 : 2,500,000. *Quaternary Science Reviews*. 26(9–10), 1301–1312.
- [8] Hu, G., Zhao, C., Chen, N., et al., 2019. Characteristics, mechanisms and prevention modes of debris flows in an arid seismically active region along the Sichuan–Tibet railway route, China: A case study of the Basu–Ranwu section, southeastern Tibet. *Environmental Earth Sciences*. 78(18), 564.
- [9] Wang, J., Fang, F., Wang, J., et al., 2024. Evolutionary characteristics and influencing factors of wheat production risk in Gansu Province of China under the background of climate change. *Theoretical and Applied Climatology*. 155(6), 5389–5415.
- [10] Wang, Y., Zhang, Q., Wang, S.-P., et al., 2017. Characteristics of agro-meteorological disasters and their risk in Gansu Province against the background of climate change. *Natural Hazards*. 89(2), 899–921.
- [11] Wu, W.J., Su, X., Meng, X.M., 2014. Characteristics and origin of loess landslides on loess terraces at Heifangtai, Gansu Province, China. *Applied Mechanics and Materials*. 694, 455–461.
- [12] Liu, Y., Zhou, J., Li, Z., et al., 2026. Emergency investigation and failure mechanism analysis of the 2025 Junlian landslide based on interferometric synthetic aperture radar and terrestrial laser scanning. *Journal of Rock Mechanics and Geotechnical Engineering*. In Press. DOI: <https://doi.org/10.1016/j.jrmge.2026.02.009>
- [13] Wei, L., Zeng, Z., Yan, J., 2024. Factors affecting the stability of loess landslides: A review. *Applied Sciences*. 14(7), 2735.
- [14] Xu, Q., Zhao, B., Dai, K., et al., 2023. Remote sensing for landslide investigations: A progress report from China. *Engineering Geology*. 321, 107156.
- [15] Shafapourtehrany, M., Batur, M., Özener, H., et al., 2026. Conventional and advanced geospatial techniques for landslide detection and modeling: A comprehensive overview. *Geoenvironmental Disasters*. 13(1), 3.
- [16] Zhu, Y., Qiu, H., Liu, Z., et al., 2021. Detecting Long-Term Deformation of a Loess Landslide from the Phase and Amplitude of Satellite SAR Images: A Retrospective Analysis for the Closure of a Tunnel Event. *Remote Sensing*. 13(23), 4841.
- [17] Derbyshire, E., 2001. Geological hazards in loess terrain, with particular reference to the loess regions of China. *Earth-Science Reviews*. 54(1–3), 231–260.
- [18] Wang, X., Zhang, C., Wang, C., et al., 2021. GIS-based for prediction and prevention of environmental geological disaster susceptibility: From a perspective of sustainable development. *Ecotoxicology and Environmental Safety*. 226, 112881.
- [19] Peng, J., Sun, P., Igwe, O., et al., 2018. Loess caves, a special kind of geo-hazard on loess plateau, northwestern China. *Engineering Geology*. 236, 79–88.
- [20] Chen, Y., Li, P., Wang, Y., et al., 2024. Unraveling the Mystery of Water-Induced Loess Disintegration: A Comprehensive Review of Experimental Research. *Sustainability*. 16(6), 2463.
- [21] Liu, X., Shao, S., Shao, S., et al., 2025. Prioritizing landslide risk areas in the Loess Plateau of China: A multi-level hazard intensity classification framework. *Advances in Space Research*. 76(8), 4076–4091.
- [22] Wright, J., Smith, B., Whalley, B., 1998. Mechanisms of loess-sized quartz silt production and their relative effectiveness: Laboratory simulations. *Geomorphology*. 23(1), 15–34.
- [23] Dave, A.K., 2022. Understanding Quaternary Aeolian Landscape-Climate Interaction in the Piedmonts of Central Asia Using Luminescence and Electron Spin Resonance Techniques. *Universitätsbibliothek der Johannes Gutenberg-Universität Mainz: Mainz, Germany*.
- [24] Bengloan, L., 2025. Detailed Luminescence Dating of Late Quaternary Loess at Belcoute, Jersey, Channel Islands [Master's Thesis]. Uppsala University: Uppsala, Sweden.
- [25] Gao, X., Hao, Q., Ge, J., et al., 2021. Paleowind directions from the magnetic fabric of loess deposits in

- the western Chinese Loess Plateau and implications for dust provenance. *Quaternary Research*. 103, 74–87.
- [26] Wang, X., Vandenberghe, J., Lu, H., et al., 2017. Climatic and tectonic controls on the fluvial morphology of the Northeastern Tibetan Plateau (China). *Journal of Geographical Sciences*. 27(11), 1325–1340.
- [27] Liang, M., Wang, Z., Zhou, S., et al., 2014. The provenance of Gansu Group in Longxi region and implications for tectonics and paleoclimate. *Science China Earth Sciences*. 57(6), 1221–1228.
- [28] Sadeghi, H., Kiani, M., Sadeghi, M., et al., 2019. Geotechnical characterization and collapsibility of a natural dispersive loess. *Engineering geology*. 250, 89–100.
- [29] Lv, Y., Zhang, C., Zhao, J., 2023. Collapsibility mechanisms and water diffusion morphologies of loess in Weibei area. *Sustainability*. 15(11), 8573.
- [30] Wang, L., Qin, B., Li, X., et al., 2025. Transient hydromechanical response of loess during wetting process: Numerical simulation and field test verification. *Engineering Geology*. 359, 108439.
- [31] Xue, Y., Zhang, X., Li, S., et al., 2019. Sensitivity analysis of loess stability to physical and mechanical properties: Assessment model. *International Journal of Geomechanics*. 19(7), 06019012.
- [32] Ali, A., Zhang, N., Santos, R.M., 2023. Mineral characterization using scanning electron microscopy (SEM): A review of the fundamentals, advancements, and research directions. *Applied Sciences*. 13(23), 12600.
- [33] Pham, T.A., Vanapalli, S.K., Unified Thermal-Hydro-Mechanical Framework for Stability Analyses of Climate-Resilient Slopes. Preprint. DOI: <https://dx.doi.org/10.2139/ssrn.5650379>
- [34] Bračko, T., Žlender, B., 2026. A Climate–Geomechanics Interface for Adaptive and Resilient Geostructures. *Climate*. 14(1), 23.
- [35] Gu, T., Zhang, M., Wang, J., et al., 2019. The effect of irrigation on slope stability in the Heifangtai Platform, Gansu Province, China. *Engineering geology*. 248, 346–356.
- [36] Gao, X., 2017. Urban development with the constraint of water resources: A case study of Gansu section of western longhai-lanxin economic zone. In: Glavan, M. (Ed.). *Water Challenges of an Urbanizing World*. IntechOpen: London, UK.
- [37] Wang, Q., Shi, J., Chen, G., et al., 2002. Environmental effects induced by human activities in arid Shiyang River basin, Gansu province, northwest China. *Environmental Geology*. 43(1), 219–227.
- [38] Song, S., Wang, S., Li, X., et al., 2025. An investigation into the spatial distribution patterns and influencing factors of fortresses in Tianshui, Gansu Province, China. *Humanities and Social Sciences Communications*. 12(1), 1337.
- [39] Wei, H., Xiong, L., Zhao, F., et al., 2022. Large-scale spatial variability in loess landforms and their evolution, Luohe River Basin, Chinese Loess Plateau. *Geomorphology*. 415, 108407.
- [40] Wang, H., Sun, P., Zhang, S., et al., 2020. Rainfall-induced landslide in loess area, Northwest China: A case study of the Changhe landslide on September 14, 2019, in Gansu Province. *Landslides*. 17(9), 2145–2160.
- [41] Guo, C., Cao, J., Liu, J., et al., 2025. Deformation mechanism of large deep loess-mudstone landslide under the coupling effect of loess collapsibility and earthquakes: A case study of the Yangpo landslide in Min County, Gansu province, China. *Natural Hazards*. 121(15), 18227–18248.
- [42] Xu, X.-Z., Guo, W.-Z., Liu, Y.-K., et al., 2017. Landslides on the Loess Plateau of China: A latest statistics together with a close look. *Natural Hazards*. 86(3), 1393–1403.
- [43] Qu, L., Li, Y., Chen, Z., et al., 2022. Exploring the spatiotemporal variation characteristics and influencing factors of gully agricultural production transformation in the Chinese Loess Plateau: A case study of loess hilly and gully region in Yan'an City. *Land Use Policy*. 123, 106369.
- [44] Zhu, B., Zhou, Z., Li, Z., 2021. Soil erosion and controls in the slope-gully system of the Loess Plateau of China: A review. *Frontiers in Environmental Science*. 9, 657030.
- [45] Belayneh, L., Dewitte, O., Gulie, G., et al., 2022. Landslides and gullies interact as sources of lake sediments in a rifted context: Insights from a highly degraded mountain environment. *Geosciences*. 12(7), 274.
- [46] Yan, Y., Hu, S., Zhou, K., et al., 2023. Hazard characteristics and causes of the “7.22” 2021 debris flow in Shenshuicao gully, Qilian Mountains, NW China. *Landslides*. 20(1), 111–125.
- [47] Gao, Y.C., Chen, N.S., Hu, G.S., et al., 2019. Magnitude-frequency relationship of debris flows in the Jiangjia Gully, China. *Journal of Mountain Science*. 16(6), 1289–1299.
- [48] Gong, W., Juang, C.H., Wasowski, J., 2021. Geohazards and human settlements: Lessons learned from multiple relocation events in Badong, China—Engineering geologist’s perspective. *Engineering Geology*. 285, 106051.
- [49] Zhang, S., Sun, P., Li, R., et al., 2022. Distribution feature and development characteristics of geohazards in Wudu district, Gansu province, Northwest China. *Geoenvironmental Disasters*. 9(1), 23.
- [50] Zhang, S., Sun, P., Ren, J., et al., 2022. Successful emergency evacuation from a catastrophic loess landslide reactivated by the torrential rain in October 2021 in Tianshui, Gansu, NW China. *Geoenvironmental Disasters*. 9(1), 19.
- [51] Bilal, M., Xing, A., Hazarika, H., 2025. The Chinese

- loess plateau, earthquakes, and flowslides: the need to enhance geotechnical disaster resilience. *Landslides*. 22, 591–596.
- [52] Li, P., Wu, J., Zhou, W., et al., 2023. *Hazard Hydrogeology*. Springer: Cham, Switzerland.
- [53] Alcántara-Ayala, I., 2025. Landslides in a changing world. *Landslides*. 22, 2851–2865.
- [54] Wan, B., An, N., Bai, G., 2024. Monitoring and Evaluation of Debris Flow Disaster in the Loess Plateau Area of China: A Case Study. *Water*. 16(17), 2539.
- [55] Ding, W., Wang, G., Yang, Q., et al., 2023. Risk assessment and control of geological hazards in towns of complex mountainous areas based on remote sensing and geological survey. *Water*. 15(18), 3170.
- [56] Chen, Y., Dai, K., Chang, L., et al., 2025. The pre-processing InSAR feasibility assessment method for wide-area slope displacement monitoring. *International Journal of Applied Earth Observation and Geoinformation*. 136, 104336.
- [57] Cheng, Y., Pang, H., Li, Y., et al., 2025. Applications and Advancements of Spaceborne InSAR in Landslide Monitoring and Susceptibility Mapping: A Systematic Review. *Remote Sensing*. 17(6), 999.
- [58] Kara, B.C., Hastaoglu, K.Ö., 2026. AI-Augmented Synthetic Aperture Radar (SAR) for ground deformation: Introducing the Adaptive Regional AI System (ARAIIS). *Environmental Earth Sciences*. 85(3), 77.
- [59] Cui, J., Ran, Y., Hu, X., et al., 2025. Investigating subsidence characteristics of Kyoto imperial garden cultural heritage shaped by historical landscape construction, through remote sensing. *npj Heritage Science*. 13(1), 630.
- [60] Shi, X., Zhao, Z., Dai, Y., et al., 2025. Post-Disaster High-Frequency Ground-Based InSAR Monitoring and 3D Deformation Reconstruction of Large Landslides Using MIMO Radar. *Remote Sensing*. 17(18), 3183.
- [61] Lin, Z., Xu, Z., Zhang, M., 2008. Loess in China and landslides in loess slopes. In: Chen, Z., Zhang, J.-M., Ho, K., et al. (Eds.). *Landslides and Engineered Slopes: From the Past to the Future*, Two Volumes + CD-ROM: Proceedings of the 10th International Symposium on Landslides and Engineered Slopes, 30 June–4 July 2008, Xi'an, China. CRC Press: London, UK. pp. 129–144.
- [62] Fan, J., Zhang, Y., Peng, Y., et al., 2025. Study on the disaster mechanism and prevention technology of embankment slip-collapse after extreme rainfall in the loess area. *Scientific Reports*. 15(1), 20613.
- [63] Capobianco, V., Palau, R.M., Solheim, A., et al., 2024. The potential use of nature-based solutions as natural hazard mitigation measure for linear infrastructure in the Nordic Countries. *Geoenvironmental disasters*. 11(1), 27.
- [64] Poratelli, F., Cocuccioni, S., Accastello, C., et al., 2020. State-of-the-art on ecosystem-based solutions for disaster risk reduction: The case of gravity-driven natural hazards in the Alpine region. *International Journal of Disaster Risk Reduction*. 51, 101929.
- [65] Capobianco, V., Fraccica, A., Anselmucci, F., et al., 2025. Nature-and bio-based solutions for ecosystem restoration, landslide hazard mitigation, and ground improvement: Research and application novelties. *Ecological Engineering*. 219, 107710.
- [66] Leknoi, U., Duangden, B., Tanapalungkorn, W., et al., 2025. A multi-level perspective on implementing vetiver grass as a nature-based and social innovation for landslide risk reduction. *Environmental Development*. 57, 101371.
- [67] Ferdowsi, S., Németh, K., 2025. Geoparks Management in Tourism Destinations: Integrating Development and Conservation. *Sustainable Development*. 34(S2), 1034–1056.
- [68] Assilzadeh, H., Levy, J.K., Wang, X., 2010. Landslide Catastrophes and Disaster Risk Reduction: A GIS Framework for Landslide Prevention and Management. *Remote Sensing*. 2(9), 2259–2273.
- [69] Zhang, L., Liu, Y., Dong, Y., et al., 2024. Regional difference and prevention strategy of farmland erosion induced by extreme rainstorms in the Loess area and Rocky mountain area of Northern China. *Earth Surface Processes and Landforms*. 49(9), 2704–2722.
- [70] Zhang, J., Ge, Y., Yuan, G., et al., 2022. Consideration of high-quality development strategies for soil and water conservation on the loess plateau. *Scientific Reports*. 12(1), 8336.
- [71] Wang, J., Fang, F., Wang, J., et al., 2023. Grain risk analysis of meteorological disasters in Gansu province using probability statistics and index approaches. *Sustainability*. 15(6), 5266.
- [72] Jiang, C., Zhang, H., Wang, X., et al., 2019. Challenging the land degradation in China's Loess Plateau: Benefits, limitations, sustainability, and adaptive strategies of soil and water conservation. *Ecological Engineering*. 127, 135–150.
- [73] Huang, J., Xue, D., Huang, M., 2025. Rural Resilience Evaluation and Risk Governance in the Middle Reaches of the Heihe River, Northwest China: An Empirical Analysis from Ganzhou District, a Typical Irrigated Agricultural Area. *Land*. 14(5), 926.
- [74] Kordi, M., Ertz, M., 2026. Deciphering technological advancements for efficient disaster management and community resilience. *Technology in Society*. 84, 103057.
- [75] Ghaffarian, S., Taghikhah, F.R., Maier, H.R., 2023. Explainable artificial intelligence in disaster risk management: Achievements and prospective futures. *International Journal of Disaster Risk Reduction*. 98, 104123.
- [76] Linardos, V., Drakaki, M., Tzionas, P., et al., 2022. Machine Learning in Disaster Management: Recent

- Developments in Methods and Applications. Machine Learning and Knowledge Extraction. 4(2), 446–473.
- [77] Amorim-Maia, A.T., Olazabal, M., 2025. Beyond adjustment: A new paradigm for climate change adaptation in a complex world. *Global Environmental Change*. 93, 103027.
- [78] Ji, C., Xie, W., Yang, Q., et al., 2025. Microstructural Mechanisms Influencing Soil-Interface Shear Strength: A Case Study on Loess and Concrete Plate Contact. *Buildings*. 15(19), 3512.
- [79] Liu, X., Dong, J., Tang, C., et al., 2025. Instability mechanism of loess-mudstone landslides under rainfall infiltration conditions. *Scientific Reports*. 15(1), 17591.
- [80] Qin, Y., Pan, Z., Liu, Z., et al., 2021. Influence of the Particle Size of Porous Media on the Formation of Natural Gas Hydrate: A Review. *Energy & Fuels*. 35(15), 11640–11664.
- [81] Esmacili, M., Beni, T., Gigli, G., et al., 2025. Rock mass exposure fracture detection through 2D close-range images using image processing techniques: A review. *Earth Science Informatics*. 18(3), 494.