

Article

Toward Sustainable Infrastructure: Advanced Hazard Prediction and Geotechnical Risk Management in the Jiroft Dam Project, Iran

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Abstract: The Jiroft Dam, situated in Kerman province, Iran, serves as a crucial infrastructure for water management, flood control, and agricultural development in the region. However, the surrounding mountainous terrain presents considerable geotechnical challenges that threaten the stability of access roads and other essential infrastructure. This study is based on comprehensive field surveys and mapping, which have revealed significant ground displacements and evidence of slope instabilities in the area. The investigation identifies key factors, including soil composition, rock formations, groundwater flow, and seismic activity, that contribute to these shifts in the terrain. To ensure the accuracy of the elevation data, the study employed Monte Carlo simulation techniques to analyze the statistical distribution of the collected survey data. By simulating various possible outcomes, this study enhanced the precision of the elevation models, allowing for better identification of critical instability zones. Additionally, the Overall Equipment Effectiveness (OEE) was utilized to evaluate the effectiveness of the current monitoring equipment and infrastructure, providing a clearer understanding of operational efficiency and areas for improvement. The findings of this study highlight the immediate need for effective risk management strategies to mitigate the potential hazards of landslides and infrastructure failure. Addressing these challenges is essential to ensure the long-term sustainability of the region's infrastructure. In response to these observations, this research proposes practical engineering solutions such as slope stabilization techniques and improved drainage systems to address the identified instabilities. Furthermore, this study underscores the necessity of the continuous monitoring and the implementation of early warning systems to detect further ground movements and mitigate associated risks. In addition to technical interventions, this research emphasizes the importance of integrating local knowledge and expertise into the risk management process.



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1. Introduction

Mountain slopes are prone to instability due to natural processes like weathering, erosion, and hydrological forces, which are intensified by environmental changes and extreme weather events driven by climate change. Seasonal stream channels, often overlooked, play a key role in slope instability by increasing erosion and altering soil moisture during wet periods, and causing soil desiccation in dry periods, further weakening slopes [1].

Seasonal streams and their role in slope instability, especially in mountainous regions, remain poorly understood. This study aims to address this by exploring how seasonal stream channels influence slope stability through interactions like erosion, water infiltration, and sediment transport. It highlights critical thresholds where stream activity leads to slope failure, emphasizing the importance of these findings in light of climate change and extreme weather events. The results contribute to risk assessment tools, early warning systems, and strategies for protecting communities, with broader implications for sustainable land use and disaster resilience in mountain regions [2].

Understanding the interaction between seasonal streams and weathered slopes is crucial for land use planning in unstable areas [3]. Previous studies have highlighted the role of groundwater accumulation in landslide reactivation [4] and demonstrated that short-period rainfall intensities exceeding specific thresholds are the primary triggers for landslides in steep, weathered terrains [5].

Heavy rainfall and pre-existing geological conditions are significant factors in triggering catastrophic landslides and debris flows. Research has highlighted the dynamics of rockslide-debris flows triggered by rainfall, emphasizing the importance of geological hazard identification for disaster prevention in urban planning [6]. Additionally, the role of landslides in providing material for debris flows has been analyzed, with a focus on the influence of pyroclastic substrates and bedrock discontinuities on their triggering mechanisms [7].

Heavy rainfall, seismic activity, and geological conditions significantly influence landslide and debris flow occurrences. Research has shown that antecedent and high-intensity rainfall are critical triggers for landslides, with thresholds identified for rainfall intensity and cumulative rainfall that guide risk prediction and emergency preparedness [8–10]. Additionally, seismic activity, such as the Wenchuan earthquake, amplifies landslide frequency and scale, as observed in post-seismic rainfall-triggered events [11]. Other works have highlighted the role of topography, lithology, and tectonics in predisposing areas to landslides, emphasizing the need for comprehensive hazard assessment [12]. Weathering stages of granitic batholiths further influence landslide types and frequencies, with progressively lower critical slope angles in humid regions [13]. Advanced modeling techniques, such as the quasi-three-dimensional LFEM, provide valuable tools for simulating landslide dynamics and informing hazard zoning and land use management [14].

Combined rainfall and seismic events can significantly impact landslide occurrence, with certain earthquakes, such as the 2004 Mid-Niigata Prefecture earthquake, triggering large landslides due to preceding rainfall, while other events in dry regions do not. Additionally, landslides can be triggered by small earthquakes in some cases. The relationship between climate change and landslides is still uncertain, though warming clearly affects slope stability. Various methods for assessing these impacts, including modeling approaches, highlight the importance of considering uncertainties in projections. Using ensembles of climate scenarios can improve future risk assessments, emphasizing the need for better adaptation and risk reduction strategies in response to climate-driven landslide threats [15,16].

This study aimed to conduct a precise survey of the displacements occurring along the spillway path of the Jiroft Dam and to propose initial stabilization measures based on field

observations. Additionally, this research contributes to environmental science by enhancing our understanding of the complex relationships between hydrology, geology, and slope mechanics in mountainous terrains. Beyond the immediate risks posed by slope instability, this study also provides valuable data to inform landscape restoration efforts in regions affected by erosion or landslides. Understanding the hydrological processes involved can help design restoration strategies that stabilize slopes and reduce the frequency of future landslides. In areas where land degradation is an ongoing issue, particularly in developing countries, this research offers critical insights for disaster risk reduction programs and climate adaptation initiatives aimed at strengthening the resilience of mountain communities. To ensure the accuracy of the elevation data, we conducted a total of approximately 100 survey measurements using both total stations and GPS equipment. By employing Monte Carlo simulation, we analyzed the statistical distribution of the elevation data obtained from these surveys. This allowed us to identify the optimal elevation points, which were then computed and optimized using MATLAB software. The findings of this study have the potential to advance scientific knowledge in geotechnical engineering, hydrology, and environmental science by improving our understanding of the processes contributing to slope instability.

2. Landslide Mechanics and Stabilization Strategies

Landslides are a significant geotechnical hazard, affecting both natural landscapes and engineered structures. They result from the interaction of various factors, including slope stability mechanics, soil properties, hydrological dynamics, and external forces such as rainfall, seismic activity, or human-induced environmental changes. Understanding these factors is crucial for predicting landslides, evaluating material displacement potential, and developing effective mitigation strategies [16]. The occurrence of landslides is fundamentally governed by the balance between driving and resisting forces on a slope. Driving forces are primarily caused by the weight of the material on the slope, influenced by factors such as slope angle and additional loads from rainfall or man-made structures. Resisting forces arise from material cohesion, friction between particles, and the strength of the underlying rock or soil [15]. When the driving forces exceed the resisting forces, failure occurs, resulting in the downslope movement of materials. This can result in a landslide, ranging from a slow, creeping movement to a sudden and catastrophic failure, depending on the material type (e.g., clay, sand, rock) and environmental conditions.

In areas like the Jiroft Dam region, landslides pose significant challenges to the stability and safety of infrastructure projects. The region's geology, marked by fractured and weathered rock formations, is particularly vulnerable to slope failure. The Jiroft Dam is located in a zone susceptible to geotechnical risks. Therefore, a thorough assessment of the surrounding terrain is essential to ensure the stability of both the dam's foundation and the adjacent slopes.

Hydrological factors, such as seasonal rainfall, can significantly affect the stability of the slopes surrounding the dam. Rainfall infiltrates the soil and rock, increasing the weight of the materials and reducing their cohesion, especially in weathered zones. Seasonal streams in the area exacerbate these effects by carrying water through the slopes, leading to erosion, undermining rock masses, and triggering landslides. The flow of water can also saturate the soil, reducing the internal friction of materials and making them more susceptible to sliding. The seismic activity in the region is another contributing factor to landslide risk. Earthquakes or even minor tremors can trigger landslides by disturbing the fragile balance between driving and resisting forces on a slope. Given the geological instability in the area surrounding the Jiroft Dam, seismic activity must be considered

in any slope stability evaluation, as even small seismic events can trigger significant landslides [17].

To mitigate the risk of landslides around the Jiroft Dam, a comprehensive approach is required. Detailed geotechnical surveys should be conducted to assess the soil properties, fault zones, and slope angles. Advanced slope stability models, incorporating factors such as soil strength, hydrological effects, and seismic activity, can be used to predict potential failure scenarios and design effective reinforcement measures. Techniques such as rock bolting, soil nailing, and reinforced embankments should be employed to increase the resisting forces and stabilize the slopes. Moreover, hydrological management is crucial for controlling the movement of water, especially around seasonal streams [17]. Proper drainage systems that divert excess water, combined with the regular monitoring of groundwater levels, can prevent soil saturation and reduce the risk of landslides. The use of retaining walls and drainage galleries around the dam is also crucial in controlling the movement of water and maintaining slope integrity.

2.1. Key Factors in Landslide Initiation

The stability of slopes is influenced by several key factors, each playing a critical role in determining the likelihood of landslides. One of the most important factors is the shear strength of the slope material, which represents its internal resistance to failure. Shear strength is primarily governed by soil cohesion and the internal friction angle, but it is also affected by other variables such as moisture content and the presence of clay minerals. The geometry of the slope, particularly its steepness, is another crucial factor. As the angle of the slope increases, so does the driving force acting on the material [18]. Steeper slopes are more susceptible to failure due to the greater gravitational forces, which tend to overcome the internal resistance of the soil or rock. Water saturation is also a significant contributor to slope instability. When water infiltrates the soil, whether through rainfall, snowmelt, or surface runoff, it can reduce the cohesion between soil particles and increase pore water pressure. This process effectively weakens the slope material and, in many cases, leads to destabilization and failure, especially when the material becomes saturated.

External forces, such as earthquakes, heavy rainfall, or human activities like construction or deforestation, can further exacerbate the risk of landslides. These forces can trigger the rapid movement of materials, sometimes pushing slopes beyond their natural threshold of stability [18]. Finally, the material properties of the slope, including the type of material (whether rock, soil, or a combination), its density, friction, and porosity, all contribute to how the material responds to stress. These properties determine the material's strength and its ability to withstand external forces, making them essential in assessing slope stability. Landslide displacement and slope stability are typically analyzed using limit equilibrium models (LEMs) and finite element models (FEMs). Both methods are useful in assessing the potential for slope failure, but they approach the problem from different angles. The Limit Equilibrium Method is one of the most common approaches used for landslide evaluation. It calculates the factor of safety (FoS) of a slope to determine its stability. The Factor of Safety is the ratio of the resisting forces to the driving forces. If the FoS is greater than 1, the slope is stable, while an FoS less than 1 indicates a potential for failure [19].

The most commonly used LEM methods include the following: Coulomb's failure criterion, a linear relationship between shear stress and normal stress, is used to define the strength of the material. Simplified Bishop's Method is an analytical solution for circular slip surfaces commonly used in slope stability analysis. The finite element method offers a more detailed approach by dividing the slope into smaller elements and solving for the displacement, stress, and strain within each element. FEMs can be used to simulate

complex geometries, heterogeneous materials, and varying boundary conditions, providing a more comprehensive and accurate representation of slope behavior [19].

2.2. Displacement Evaluation in Landslides

Landslide displacement plays a critical role in assessing the potential risk to infrastructure and understanding the extent of damage caused during a landslide event. There are various approaches used to evaluate and predict the amount of displacement that might occur during such events, with each approach offering unique insights based on different principles and data sources. One of the most commonly used methods is empirical modeling, which relies on historical data and observations of previous landslides [20]. By analyzing past events, empirical models apply statistical techniques to predict displacement based on factors such as slope steepness, material properties, and the moisture content of the soil. These models are particularly useful in regions where historical data are abundant, allowing for relatively straightforward assessments based on past trends.

Another key approach is analytical modeling, which involves calculating displacement based on the forces acting on the slope. This includes gravitational forces, internal cohesion, and frictional forces. Analytical models provide a more detailed understanding of how the materials on the slope behave under stress. A widely used analytical technique is the Newmark method, which applies either pseudo-static or dynamic equations to evaluate displacement, particularly in the context of seismic activity or other dynamic events. This method helps to assess how the slope might behave during an earthquake or similar disturbance, providing important data for both risk assessment and mitigation planning. Together, empirical and analytical models offer a comprehensive toolkit for evaluating landslide displacement and understanding the potential consequences of slope failure. These methods, when used in combination, can provide more accurate predictions and help guide preventive measures to protect infrastructure and mitigate damage [20].

The Newmark Sliding Block Analysis model calculates the displacement of a block sliding along a slope:

$$D = \frac{a}{g} \times (\text{Slope} - \text{angle}) \cdot t \quad (1)$$

D = Displacement;

a = Acceleration;

g = Gravitational acceleration;

t = Time.

Numerical Models: Finite Difference and finite element models are increasingly being used for displacement evaluation. These models solve for the deformation of materials based on their physical properties and external loading conditions. Displacement can be assessed at multiple points within the slope, helping to identify the zones most likely to experience significant movement.

2.3. Fundamental Solutions for Landslides

To prevent or mitigate landslides, it is essential not only to understand their theoretical causes but also to apply practical solutions that address various contributing factors such as slope stability, water drainage, and soil cohesion. Several techniques and strategies can be employed to reduce the risk of landslides in vulnerable areas. One of the primary approaches for landslide mitigation is slope stabilization. Techniques such as soil nailing involve inserting steel bars into the slope and grouting them to provide structural support, thereby helping to prevent soil movement. Another common method is the construction of retaining walls, typically made from concrete or masonry, which act as barriers to prevent materials from sliding downhill. Rock bolting also plays a vital role, particularly in areas with loose or fractured rock. Steel rods are anchored into the bedrock to stabilize the upper

layers of soil or rock. Geogrid reinforcement, in which synthetic grids are inserted into the soil, helps distribute stresses more evenly and increases the soil's shear strength, making it less prone to sliding under pressure [21].

In addition to stabilizing the slope, effective drainage control is crucial for reducing the risk of landslides. Surface drainage systems, such as ditches and channels, help divert water away from slopes, preventing water from accumulating in critical areas where it could trigger a landslide. Meanwhile, subsurface drainage techniques, such as perforated pipes, are installed beneath the slope to remove excess water within the soil. By reducing pore water pressure, these systems help stabilize the soil, making it less prone to losing its strength and triggering a landslide. Vegetative measures also provide a natural yet effective solution to prevent landslides. Reforestation and grass cover not only reduce erosion by anchoring the soil with roots, but they also absorb water, reducing the impact of rainfall on the slope. Plant roots help improve soil cohesion, increasing its resistance to sliding. In more advanced applications, bioengineering techniques combine vegetation with engineered structures, such as geotextiles or mesh, to further reinforce the soil.

These methods are particularly effective in areas prone to erosion, providing a sustainable and environmentally friendly solution for slope stability. Another critical approach involves reducing the steepness of the slopes, which is achieved through excavation or reinforcement. By cutting back the hillside or reinforcing the lower part of the slope, gravitational forces acting on the soil are diminished, thereby significantly enhancing slope stability. Moreover, monitoring systems and early warning technologies are essential for detecting potential landslides. Instruments such as tiltmeters and inclinometers provide real-time data on slope movements and displacement changes. These tools enable the early detection of unusual shifts in the slope, which could indicate the onset of a landslide. Rainfall monitoring is also crucial in early warning systems, as heavy or prolonged rainfall often triggers landslides, especially in saturated soils. By tracking rainfall and comparing it to established thresholds, these systems can predict landslide risks, enabling timely evacuations or mitigation measures [18].

Finally, the integration of mathematical models and functions into landslide analysis enhances the prediction and understanding of slope behavior. Functions simulating forces acting on slopes, such as gravitational forces, shear stresses, and frictional coefficients, are used to model slope stability over time. Through combining these functions with real-time data from monitoring systems, more accurate predictions regarding the timing and location of landslides can be made, thereby improving risk management strategies [19].

According to Equation (2), the Safety Factor (FOS) is calculated using the Mohr-Coulomb failure criterion by comparing the resisting forces against the driving forces at each point of the slope. These calculations are performed under Limit Equilibrium conditions, where the resisting forces are exactly equal to the driving forces, and the Safety Factor is equal to 1,

$$Fos = \frac{c \times L + (\sigma \cdot \tan(\phi)) \times L}{W \times \sin(\theta)} \quad (2)$$

C = Soil cohesion;

L = Length of the failure surface;

σ = Normal stress;

Φ = Internal friction angle;

W = Weight of the sliding mass;

θ = Slope angle.

The displacement function could be written as follows:

$$D(t) = \frac{1}{2} \times (a - g) \times t^2 \quad (3)$$

In finite element models, dynamic equations are solved for displacement and stress over time as follows:

$$[M] \times \frac{d^2u}{dt^2} + [C] \times \frac{dU}{dt} + [K] \times U = F(t) \quad (4)$$

M = Mass matrix;

C = Damping matrix;

K = Stiffness matrix;

U = Displacement vector;

$F(t)$ = External force vector.

Effective landslide risk management also depends on community involvement and public awareness. Educational campaigns that inform residents about recognizing early warning signs and emergency responses are vital for reducing casualties. Engaging local communities in monitoring efforts can supplement high-tech systems, providing real-time observations that enhance early warning systems. Additionally, autonomous systems such as drones and robots revolutionize landslide monitoring and cleanup. Drones equipped with LiDAR and high-resolution cameras can map slopes in hazardous areas, while autonomous sensors can detect early signs of instability and alert authorities for timely action. As technologies continue to evolve, an integrated approach combining advanced engineering, real-time data, and community involvement is expected to be essential in mitigating landslide risks and adapting to the challenges posed by climate change [22].

3. Case Study

The construction of the Jiroft Dam in southeastern Iran posed significant challenges due to the mountainous and seismically active terrain in which it is located. The dam itself is a concrete gravity dam, standing approximately 50 m high and 180 m long at the top. It creates a reservoir with a storage capacity of 320 million cubic meters, serving a crucial role in water supply for both irrigation and drinking purposes. The region, known for its complex geology and high seismicity, presents concerns related to mountain instability, which could jeopardize both the construction process and the long-term stability of the dam. The Halil River Valley in Kerman Province is characterized by steep slopes composed of a mix of sedimentary and metamorphic rocks, which are often weakened by weathering and fracturing. These conditions make the area prone to rockfalls and slippage. Due to the resulting instability and complex structural features, the region requires special attention and thorough field surveys for ongoing monitoring (Figure 1). Additionally, the area's vulnerability to seismic activity further exacerbates the situation, as earthquakes can destabilize the slopes, leading to landslides or rockfalls, particularly during construction or after seismic events. To assess displacement and monitor changes in the region, field surveys were employed to track soil movement and structural shifts over time. These surveys provided critical data for evaluating the extent of the instability and informed the design of mitigation measures tailored to the specific needs of the region.

To mitigate the risks posed by mountain instability, an extensive geotechnical study was conducted to assess the rock mass properties, including its strength, fracture patterns, and susceptibility to erosion. The dam's foundation needed to be designed to withstand both the weight of the structure and the seismic forces from potential earthquakes. Engineers also had to ensure that slopes surrounding the dam site were stable enough to support the large-scale construction without the risk of landslides, which could damage the infrastructure or delay the project. In addition, the steep inclines of the surrounding mountains necessitated careful attention to slope stability and the prevention of rockfalls. The region's significant weathering processes, due to extreme temperature fluctuations

and seasonal rainfall, also posed risks to the long-term durability of the dam. Freeze–thaw cycles, in particular, were a concern, as they could accelerate the deterioration of rock and soil, increasing the likelihood of instability.



Figure 1. Jiroft Dam and Halil River valley.

Figure 2 illustrates the critical fracture and weathering zones encountered along the construction path of the Jiroft Dam. These zones are characterized by extensive rock fractures and weathered rock, which pose significant challenges to the stability of the dam's structure. From another perspective, the river must always flow with a steep gradient, and under no circumstances should stagnant water be allowed to flow toward and fill the spillway channel. Additionally, the landslide of the rock mass surrounding the river must not block its course or divert stagnant water toward the spillway channel.

In addition to natural weathering caused by factors such as rainfall, temperature fluctuations, and freeze–thaw cycles, which further deteriorate the rock and increase its susceptibility to erosion, rockfalls, and landslides, the region is also seismically active. This adds another layer of complexity to the construction. The fractures, some of which are deep and wide, further exacerbate the instability of the terrain, particularly in the event of an earthquake. To address these concerns, the project incorporated monitoring systems to track movements in the rock mass and detect any early signs of instability. The seismic risks of the region required the dam to be designed with specialized features to withstand not only the direct impact of an earthquake but also its secondary effects, such as foundation settlement or slope failure. These features included reinforced foundation designs, flexible connections between structural components, and the use of energy-dissipating materials that can absorb seismic forces. Additionally, the seasonal stream and water flow during certain periods contribute to further erosion and weathering of the rock, gradually altering its structure and composition.

The road, built on an embankment near the dam, has been gradually losing stability due to prolonged exposure to seasonal rainfall and the intermittent flow of water channels. These natural processes have caused significant erosion along the embankment's edges, leading to progressive landslides and structural damage to the road. Heavy rainfall has exacerbated the situation by saturating the soil, further weakening its integrity and increasing the risk of slope failure. Over time, these factors resulted in partial or complete blockages, severely affecting the road's accessibility and safety. This scenario underscores the vulnerability of infrastructure in such environments, where hydrological and geological forces can lead to severe instability. It highlights the urgent need for effective engineering solutions

to mitigate these risks and ensure the long-term stability and functionality of the road. This situation, as illustrated in Figure 3, vividly demonstrates the impact of landslides and erosion on the embankment, emphasizing the critical importance of engineering measures to address these ongoing challenges. Ultimately, the success of the Jiroft Dam project hinged on effectively addressing these mountain instability patterns. Through careful geotechnical analysis, seismic-resistant design, and slope stabilization techniques, the risks associated with the mountainous terrain were managed. These strategies ensured the safe construction of the dam and provided valuable insights into how large-scale infrastructure can be developed in geologically complex and seismically active regions. The project demonstrated the importance of integrating both engineering expertise and environmental considerations in overcoming the challenges posed by mountain instability in dam construction.



Figure 2. (A,B) The fracture and weathering zones along the Jiroft Dam path. (C,D) The position of the dam spillway channel among unstable areas. (E) The dam spillway channel runs parallel to the river and is connected to it through a curved path.



Figure 3. Impact of seasonal rainfall on road stability, shown from the left and right perspectives of the same section of the road.

Field Measurement and Equipment Efficiency

The integration of precise field measurements and advanced data analysis techniques plays a crucial role in assessing soil displacement and deformation during the project. A total of 200 data points were measured—100 points using a total station device (Topcon GT-503, Topcon Corporation, Tokyo, Japan) and an additional 100 points obtained through GPS (Leica GS18 T, Leica Geosystems, Heerbrugg, Switzerland). The total station device provided highly accurate distance and angle measurements, enabling precise 3D coordinates for the surveyed points, while the GPS data helped cover a broader spatial area, ensuring consistency in the elevation measurements across the entire study region. To ensure maximum accuracy, all measuring equipment, including total stations, GPS receivers, and leveling instruments, underwent regular certification by the National Calibration Center and were calibrated according to international standards. Prior to each measurement, the equipment was meticulously adjusted and verified for accuracy. To minimize potential inconsistencies, multiple measurements—specifically, 10 repeated readings—were taken at each monitoring point. These repeated measurements allowed for the identification of any deviations and helped to reduce errors. The standard deviations for each measurement are documented in the tables, ensuring transparency and precision in the results. In addition to these field measurements, environmental factors such as temperature, humidity, and atmospheric pressure were continuously monitored, as they can influence the precision of the readings. The calibration process, measurement protocols, and error reduction strategies were strictly followed to maintain the highest level of reliability in the data.

For more comprehensive analysis, the field data were enhanced using Monte Carlo simulations. This technique allowed us to generate a larger set of simulated data points, expanding the sample size and capturing a wide range of potential variations in elevation values. The Monte Carlo simulations modeled inherent uncertainties in the measurements, providing a statistical representation of the potential distribution of elevation values. Random sampling of the simulated data was performed, and the optimal elevation values were identified by evaluating the best estimates derived from these simulations. The optimal points were then computed and refined using MATLAB, chosen for its powerful

computational capabilities, which facilitated the efficient processing and visualization of the simulated data. This methodology, referred to as Overall Equipment Efficiency (OEE), ensured a statistically sound analysis and the reliable identification of the optimal elevation points for further use in geospatial applications and decision-making processes. The repeated field measurements, coupled with the Monte Carlo simulations and MATLAB-based optimization, allowed for the precise evaluation of soil movement and provided valuable insights into the project's progress.

Field teams were expected to conduct repeated measurements at the designated points, capturing both horizontal and vertical displacements [23]. The repeated measurements over time allowed for the identification of any significant shifts or trends in the movement of the soil mass. This analysis may help identify potential risks or areas of concern, and the findings are anticipated to inform decision-making for future engineering interventions or mitigation strategies. By integrating accurate field measurements with sophisticated data analysis, the project aims to contribute valuable insights into soil behavior, ensuring the continued safety and stability of the site near the Jiroft Dam power plant.

The study area encompassed a soil mass located near the Jiroft Dam power plant, which served as the central focus of this monitoring project. Throughout the duration of the contract, the displacement of selected survey points was expected to be assessed in six distinct stages, spanning a period of nine months. These stages were planned to be conducted during the months of summer to the end of winter, specifically from June to February. The timing of the stages was strategically chosen to capture seasonal variations and environmental factors that may influence soil behavior, such as temperature fluctuations, precipitation patterns, and seismic activity. The points chosen for monitoring include s1, s3, s5, BM4, BM6, and BM2, each strategically positioned to capture different aspects of soil movement across the area. These points were carefully selected based on their proximity to critical structures and areas of potential concern. To ensure comprehensive monitoring, a total of six points have been surveyed, and their geographic coordinates have been precisely recorded. These locations, along with the topography, are shown in Figure 4.

The displacement patterns observed in our study are strongly correlated with the seasonal variations in rainfall, particularly during the rainy seasons in the region. The influence of pore water pressure, which fluctuates with these seasonal changes, plays a significant role in the observed displacements. Given the increasing concern over climate change, projected shifts in precipitation patterns could have profound effects on the behavior of seasonal streams and the pore water pressure dynamics, further exacerbating displacement in the future. It is anticipated that these changes may influence both the magnitude and timing of the displacements, and this relationship warrants further investigation in subsequent studies. The specific dates of these six surveying stages are outlined in the project schedule. The field comparisons of the measurements from the six stages were reviewed against each other on different dates, and the results are presented in Figure 5. In the course of the project, the survey data collected from the six stages were compared to evaluate the consistency and accuracy of the measurements over time. These comparisons were conducted at regular intervals to monitor any potential variations or discrepancies between the data from each stage (Each month). The results of these analyses provide valuable insights into the stability and reliability of the survey process. The detailed findings of these comparisons and Mont Carlo analyses are summarized in Table 1, where the results from each of the six stages are presented side by side. This allows for the easy identification of any significant changes or trends that may have emerged throughout the course of the surveying operations. The table serves as an important reference for assessing the overall progress and accuracy of the surveying work during the contract period.

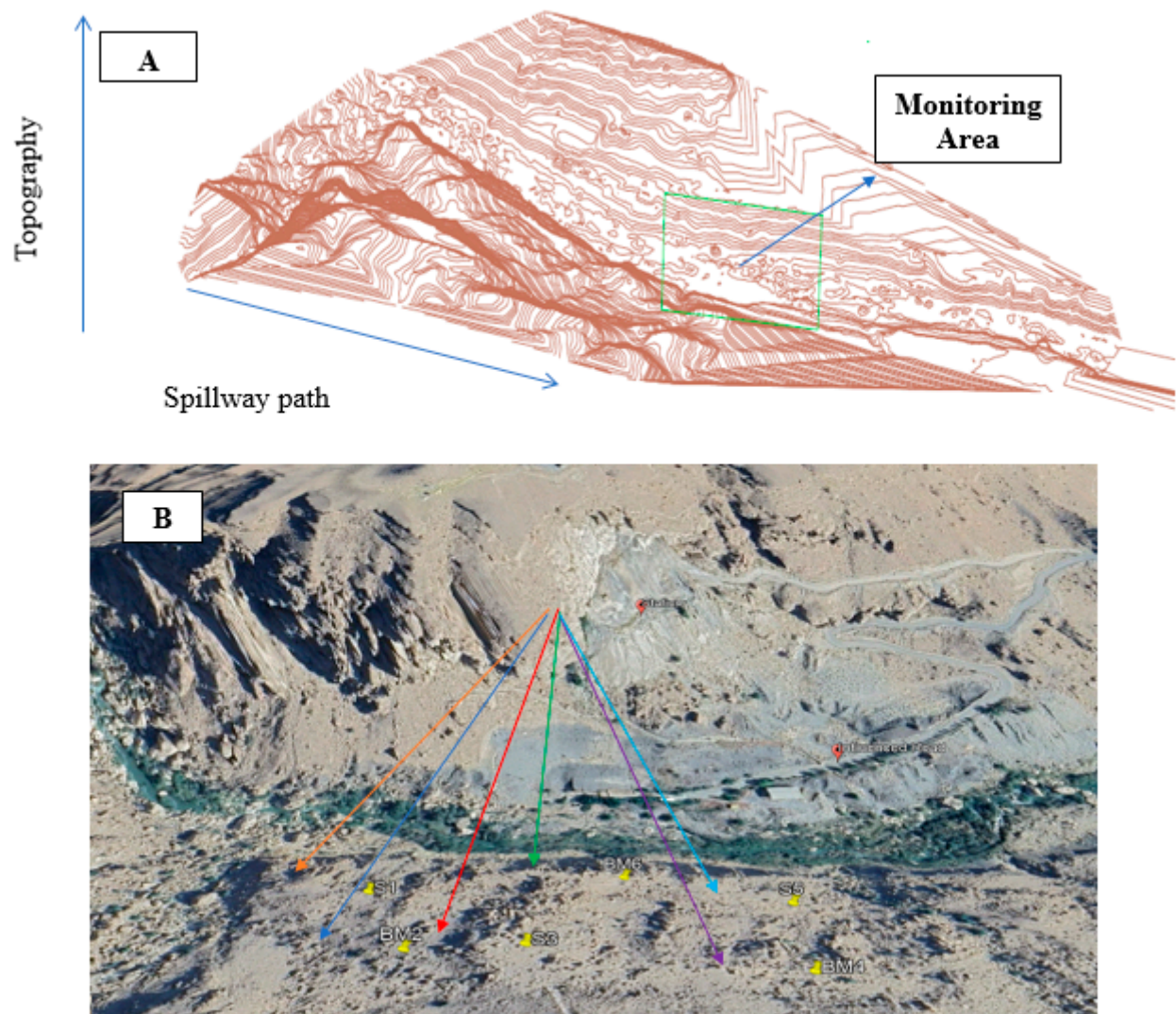


Figure 4. (A) Survey location and topography and (B) survey pattern.

Table 1. Comparison of the elevation codes of the points during the six surveying stages (9 months).

ID	Stage 0 Elevation	Stage 1 Elevation	Stage 2 Elevation	Stage 3 Elevation	Stage 4 Elevation	Stage 5 Elevation	Stage 6 Elevation	Difference Elevation Codes (cm)	Standard Deviation (cm)	Accuracy (cm)
BM2	1099.0614	1099.0614	1099.111	1098.85	1098.953	1099.068	1098.766	29.58	0.12	0.12
BM4	1121.8484	1121.8484	1121.912	1121.75	1121.7422	1122.0195	1121.3937	45.47	0.1	0.05
BM6	1074.9424	1074.9424	1074.949	1074.898	1074.8777	1074.9074	1075.113	−17.06	0.05	0.13
S1	1084.3152	1084.3152	1084.315	1084.315	1084.315	1084.315	1084.315	0.02	0.09	0.11
S3	1116.5554	1116.5554	1116.789	1116.57	1116.5666	1116.577	1116.5645	−0.91	0.11	0.06
S5	1090.478	1070.4785	1070.673	1070.552	1070.5372	1070.5574	1070.533	−5.45	0.05	0.08

Based on the data presented in the table above, field surveys conducted over the past 9 months reveal noteworthy elevation variations and displacements across various points in the study area. The results show both horizontal and vertical shifts, with some locations experiencing significant changes, such as a 45 cm difference in elevation at BM4. The data show a wide range of elevation variations across the different stages for each monitoring point, highlighting the dynamic nature of the area. For example, BM2 shows an elevation difference of 29.58 cm, while BM6 exhibits a downward shift of −17.06 cm.

These variations are indicative of both local and larger-scale geological or environmental factors that could be influencing the region's stability. The consistency in elevation changes across multiple stages at some points, such as at S1, where the elevation remains constant at 1084.315 cm, suggests relative stability in certain areas. However, other points, like S3 and S5, display minor but notable shifts (e.g., -0.91 cm at S3 and -5.45 cm at S5), which may reflect localized instability.

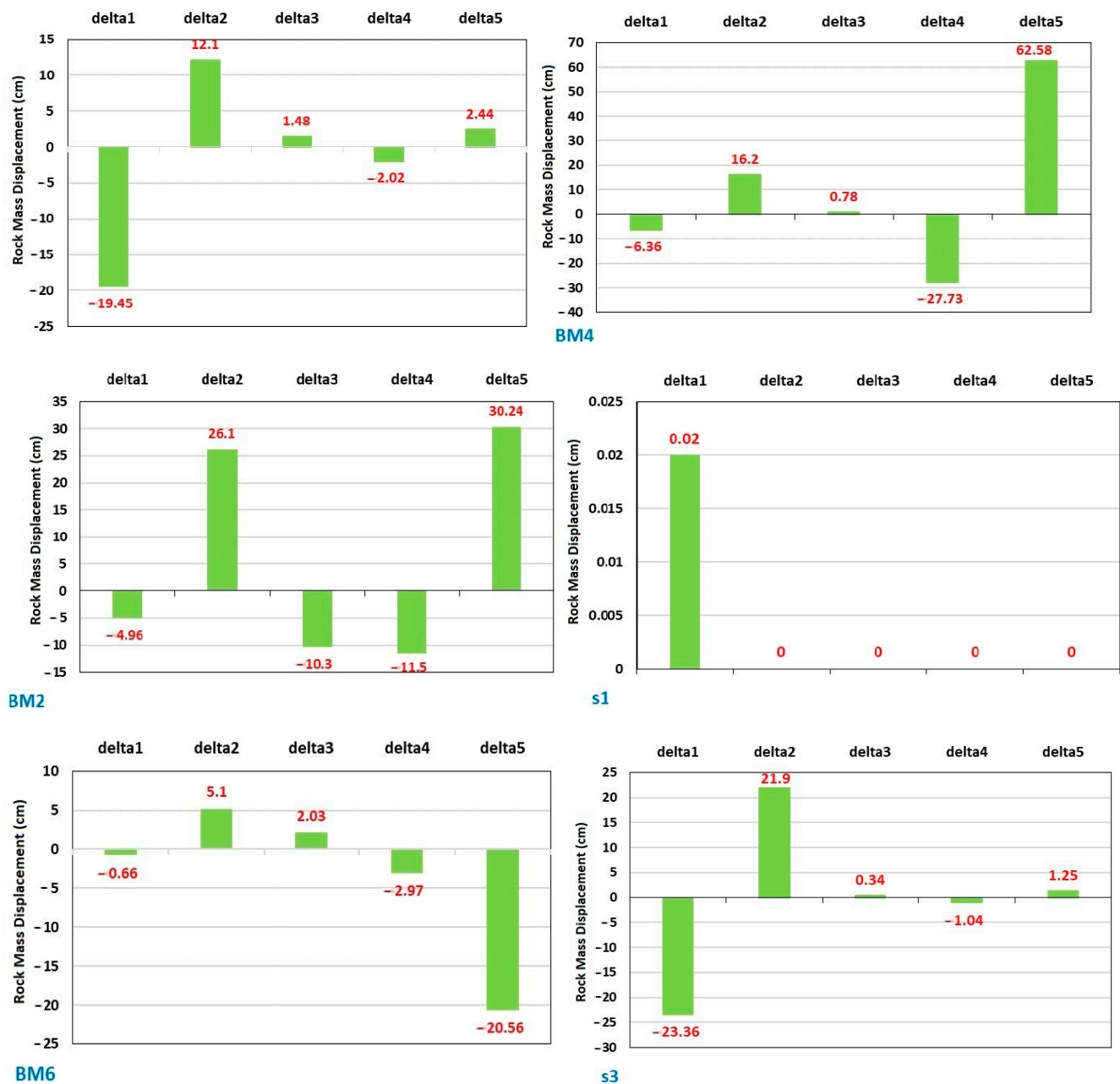


Figure 5. Vertical displacement of various points.

These findings underline the importance of continuous monitoring in the region to assess potential risks and identify underlying causes of displacement. The combination of both horizontal and vertical shifts suggests complex interactions between environmental and geological factors, emphasizing the need for further investigation to ensure the long-term stability of the area.

In Table 1, all cumulative data are presented, reflecting the final displacements observed over the nine-month data collection period. This table offers an overall summary

of the displacement trends. On the other hand, Figure 5 provides a more detailed view of the collected data, presenting a finer level of granularity. It illustrates the individual measurements taken at each survey point, offering a clearer and more nuanced understanding of the variations in displacement throughout the monitoring process. Together, these two representations provide a comprehensive perspective on the soil mass's behavior, combining both an overview and detailed insights for a thorough analysis. In Figure 6, the flowchart represents the process outlined in this paper for review.

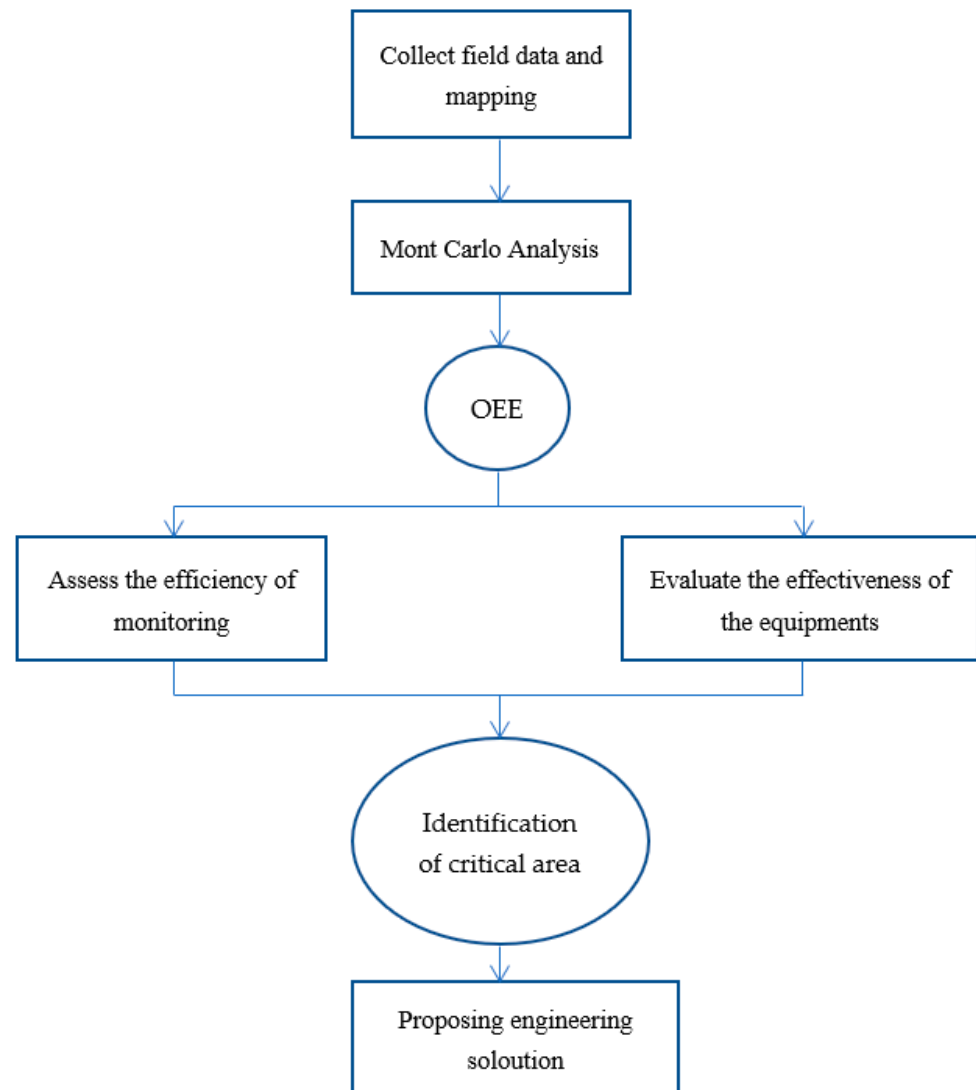


Figure 6. Operational flowchart for Jiroft Dam.

4. Discussion

It is essential to investigate whether these movements are linked to natural processes such as erosion, tectonic activity, or other environmental factors. Such knowledge is crucial for determining the necessary steps to address the situation and prevent further destabilization. In light of these findings, urgent action is required to ensure the long-term stability of the mountainous areas in the region. Given the severe fragmentation and significant displacement observed, stabilization efforts should focus on more cohesive engineering solutions. Approaches such as dry-stone walls, precast concrete walls, and combined mesh systems with shotcrete are recommended, as they are better suited to handle the extensive ground movement and shifting soil and rock formations in the region. Additionally, continuous monitoring should be prioritized to assess the effectiveness of

these interventions and reduce the risks associated with further displacements. The use of rock bolts and anchoring systems is not advisable in this region due to the lack of a proper locking mechanism, which is essential for their stability.

The results of the surveys emphasize the importance of taking proactive measures to protect both the natural environment and human infrastructure. Ensuring the safety of the region requires a comprehensive strategy that integrates both immediate actions and long-term planning to mitigate further shifts and preserve the integrity of the area. The control of these displacements is critically important, particularly in preventing the blockage of the spillway of the Jiroft Dam. Any significant shifts in the area could potentially obstruct the spillway, disrupting its ability to safely manage water flow during heavy rainfall or high reservoir levels. Such an obstruction could lead to dangerous flooding, posing risks to both the surrounding environment and local communities.

Therefore, immediate and ongoing actions to address the instability, including engineering solutions and regular surveillance, are necessary to prevent any catastrophic scenarios that could arise from blocked water channels. By taking proactive measures, we can safeguard the functionality of the dam and mitigate the risk of severe environmental and infrastructural damage.

Global Landslide Events and Stabilization Techniques

Looking globally, numerous large-scale landslides have occurred in areas with similar geological characteristics to the Jiroft region. For instance, the La Conchita landslide (California, 2005), which involved a displacement of over 300 m, resulted in significant damage to infrastructure and homes. Following the event, engineers implemented soil nailing, retaining walls, and geo-grids to stabilize the slope and prevent further movement. Monitoring systems were also set up to detect early signs of instability. These approaches have been extensively studied and show great potential for application in other seismically active areas [24–26]. Similarly, the Gansu Province landslide (China, 2010), which displaced soil and rock over 500 m, led to the implementation of flexible rock bolts and geo-grids to manage the seismic forces, with a focus on preventing further displacement and ensuring slope stability under seismic loading conditions [27,28]. The Vajont Dam disaster (Italy, 1963), where earth shifted 800 m into the reservoir, resulted in a catastrophic wave that overtopped the dam, causing widespread destruction. Post-disaster stabilization efforts have focused on rock bolting, retaining walls, and advanced monitoring systems to detect soil movements and prevent similar events in the future [29,30].

The global case studies outlined above highlight the importance of a multi-faceted approach to landslide stabilization. For the Jiroft region, incorporating slope stabilization and monitoring techniques used successfully in these regions could be a prudent strategy. However, it is also important to consider economic solutions that are both effective and cost-efficient, especially in regions with limited resources. Precast concrete walls and dry-stone walls are two such methods that could provide a balance between durability and affordability. Precast concrete walls, which are manufactured off-site and assembled on-site, offer several advantages in terms of quick installation, cost efficiency, and structural integrity. These walls are particularly beneficial in areas where speed is essential to mitigate immediate threats posed by landslides or erosion. Their pre-fabricated nature reduces labor costs and minimizes the disruption of local infrastructure.

5. Conclusions

The observed land displacement and the growing instability around the Jiroft Dam pose a serious and imminent threat to the integrity of this crucial infrastructure. The vertical displacements, some exceeding 45 cm, indicate not only minor disruptions but also the

potential for significant structural failure if not addressed. Such a disaster could result in irreparable damage to the dam, catastrophic flooding, and the loss of invaluable water resources—consequences that would be felt far beyond the immediate area. The need for action is not only urgent but critical; failure to act now could lead to an irreversible disaster that would forever alter the landscape and the lives of those who depend on the dam’s stability. To prevent such a bleak future, it is essential that a combination of advanced technological solutions, innovative engineering, and proactive vigilance be employed. The power of numerical modeling, utilizing sophisticated simulations, can offer us foresight into the future, enabling us to predict how the ground and structures may react under various stresses, such as erosion or tectonic shifts. These models are not just theoretical tools but critical lifelines that can guide the development of stronger, more resilient infrastructure. Additionally, the use of Monte Carlo simulations to determine the OEE (Overall Equipment Efficiency) in MATLAB has shown promising results in the field, demonstrating effective outcomes in the accuracy of field surveys and providing valuable insights into performance efficiency. Equally important is the establishment of a continuous, real-time monitoring system that integrates cutting-edge Remote Sensing, GPS, and geophysical sensors. These technologies are expected to act as an early warning system, remaining vigilant and alerting us to shifts in the earth’s behavior, thus giving us precious time to intervene before disaster strikes. Along with this, ongoing geotechnical investigations may deepen our understanding of the underlying causes of the instability, allowing for precise, targeted interventions in the most vulnerable areas of displacement. In terms of stabilization methods, considering the severe fragmentation and significant displacement observed, efforts should focus on more cohesive and robust engineering solutions. Approaches such as dry-stone walls, precast concrete walls, and combined mesh systems with shotcrete are recommended, as they are better suited to address the extensive ground movement and shifting soil and rock formations in the region. These methods provide a stable and adaptive foundation, reducing the risk of further degradation and displacement.

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References

1. Krøgli, I.K.; Devoli, G.; Colleuille, H.; Boje, S.; Sund, M.; Engen, I.K. The Norwegian forecasting and warning service for rainfall-and snowmelt-induced landslides. *Nat. Hazards Earth Syst. Sci.* **2018**, *18*, 1427–1450. [[CrossRef](#)]
2. Akpan, A.E.; Ekwok, S.E.; Ebong, E.D. Seasonal reversals in groundwater flow direction and its role in the recurrent Agwagune landslide problem: A geophysical and geological appraisal. *Environ. Earth Sci.* **2016**, *75*, 429. [[CrossRef](#)]
3. Guthrie, R.H.; Mitchell, S.J.; Lanquaye-Opoku, N.; Evans, S.G. Extreme weather and landslide initiation in coastal British Columbia. *Q. J. Eng. Geol. Hydrogeol.* **2010**, *43*, 417–428. [[CrossRef](#)]

4. Borgatti, L.; Corsini, A.; Barbieri, M.; Sartini, G.; Truffelli, G.; Caputo, G.; Puglisi, C. Large reactivated landslides in weak rock masses: A case study from the Northern Apennines (Italy). *Landslides* **2006**, *3*, 115–124. [\[CrossRef\]](#)
5. Brand, E.W.; Premchitt, J.E.R.A.S.A.K.; Phillipson, H.B. Relationship between rainfall and landslides in Hong Kong. In Proceedings of the 4th International Symposium on Landslides, Toronto, OT, Canada, 16–21 September 1984; Canadian Geotechnical Society: Toronto, OT, Canada, 1984; Volume 1, pp. 276–284.
6. Yin, Y.; Cheng, Y.; Liang, J.; Wang, W. Heavy-rainfall-induced catastrophic rockslide-debris flow at Sanxicun, Dujiangyan, after the Wenchuan Ms 8.0 earthquake. *Landslides* **2016**, *13*, 9–23. [\[CrossRef\]](#)
7. Chen, H.; Dadson, S.; Chi, Y.G. Recent rainfall-induced landslides and debris flow in northern Taiwan. *Geomorphology* **2006**, *77*, 112–125. [\[CrossRef\]](#)
8. Peng, J.; Fan, Z.; Wu, D.; Zhuang, J.; Dai, F.; Chen, W.; Zhao, C. Heavy rainfall triggered loess–mudstone landslide and subsequent debris flow in Tianshui, China. *Eng. Geol.* **2015**, *186*, 79–90. [\[CrossRef\]](#)
9. Li, C.; Ma, T.; Zhu, X.; Li, W. The power–law relationship between landslide occurrence and rainfall level. *Geomorphology* **2011**, *130*, 221–229. [\[CrossRef\]](#)
10. Hong, Y.; Hiura, H.; Shino, K.; Sassa, K.; Suemine, A.; Fukuoka, H.; Wang, G. The influence of intense rainfall on the activity of large-scale crystalline schist landslides in Shikoku Island, Japan. *Landslides* **2005**, *2*, 97–105. [\[CrossRef\]](#)
11. Tang, C.; Zhu, J.; Qi, X.; Ding, J. Landslides induced by the Wenchuan earthquake and the subsequent strong rainfall event: A case study in the Beichuan area of China. *Eng. Geol.* **2011**, *122*, 22–33. [\[CrossRef\]](#)
12. Wen, B.; Wang, S.; Wang, E.; Zhang, J. Characteristics of rapid giant landslides in China. *Landslides* **2004**, *1*, 247–261. [\[CrossRef\]](#)
13. Durgin, P.B. Landslides and the Weathering of Granitic Rocks. In *Reviews in Engineering Geology*; Geological Society of America: Boulder, CO, USA, 1977; Volume III.
14. Chen, H.; Lee, C.F. A dynamic model for rainfall-induced landslides on natural slopes. *Geomorphology* **2003**, *51*, 269–288. [\[CrossRef\]](#)
15. Sassa, K.; Fukuoka, H.; Wang, F.; Wang, G. Landslides induced by a combined effect of earthquake and rainfall. *Prog. Landslide Sci* **2007**, *1*, 193–207.
16. Gariano, S.L.; Guzzetti, F. Landslides in a changing climate. *Earth-Sci. Rev.* **2016**, *162*, 227–252. [\[CrossRef\]](#)
17. Sujatha, E.R.; Sudarsan, J.S.; Nithiyanantham, S. A review on sustainable reinforcing techniques to stabilize slopes against landslides. *Int. J. Environ. Sci. Technol.* **2023**, *20*, 13873–13882. [\[CrossRef\]](#)
18. Guzzetti, F.; Gariano, S.L.; Peruccacci, S.; Brunetti, M.T.; Melillo, M. Rainfall and landslide initiation. In *Rainfall*; Elsevier: Amsterdam, The Netherlands, 2022; pp. 427–450.
19. Amarasinghe, U.B. Mechanism of slow-moving slope failure in Kahagolla, Sri Lanka. *J. Geol. Soc. Sri Lanka* **2022**, *23*, 55–67. [\[CrossRef\]](#)
20. Ishii, Y.; Ota, K.; Kuraoka, S.; Tsunaki, R. Evaluation of slope stability by finite element method using observed displacement of landslide. *Landslides* **2012**, *9*, 335–348. [\[CrossRef\]](#)
21. Murgia, I.; Giadrossich, F.; Mao, Z.; Cohen, D.; Capra, G.F.; Schwarz, M. Modeling shallow landslides and root reinforcement: A review. *Ecol. Eng.* **2022**, *181*, 106671. [\[CrossRef\]](#)
22. Kim, S.S.; Kim, D.Y.; Nho, H. Risk Assessment of Steep Slope Using Drone Mapping and Terrestrial LIDAR in Korea. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2020**, *44*, 81–86. [\[CrossRef\]](#)
23. Savvaidis, P.D. Existing landslide monitoring systems and techniques. In Proceedings of the Conference from Stars to Earth and Culture, Thessaloniki, Greece; 2003; Volume 1, pp. 242–258.
24. Sitar, N.; Dooley, J. Landslide stabilization techniques for the La Conchita landslide, California. *J. Geotech. Geoenviron. Eng.* **2007**, *133*, 1715–1725.
25. Crozier, M.J. Landslide risk assessment and management in the La Conchita area: A case study. *Landslides* **2010**, *7*, 247–256.
26. He, Y.; Liu, S. Application of geo-grids in slope stabilization after the La Conchita landslide. *Soil Dyn. Earthq. Eng.* **2015**, *75*, 34–42.
27. Zhao, L.; Zhang, Y. Stabilization measures for landslides in Gansu Province, China: A case study. *Eng. Geol.* **2013**, *163*, 1–12. [\[CrossRef\]](#)
28. Liu, J.; Wang, L. Seismic stability analysis of slopes in Gansu Province, China, and mitigation strategies. *Landslides* **2014**, *11*, 723–732.
29. Coccia, S.; Vannucci, P. The Vajont disaster: Geotechnical analysis and lessons learned. *Landslides* **2010**, *7*, 475–485.
30. Todorov, M.; Stoyanov, S. Landslide mitigation and monitoring systems at dams: Lessons from the Vajont disaster. *Geotech. Test. J.* **2012**, *35*, 198–210.

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