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A Systematic Review on Slope Stability and Deformation Analysis Subjected to Rainfall and Earthquake

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ABSTRACT: The most common type of natural disaster is a landslide which impact millions of people and costing tens of thousands of lives and billions of dollars in damage every year. Earthquakes have the potential to trigger landslides of varying sizes in mountainous regions, endangering the residential communities situated at the base of the mountains. The earthquake impact on the slope stability during the subsequent rains is not considerable in certain regions where the earthquake impact is not high enough to produce major soil movement. However, in some Landslide prone regions, the stability of slopes that are impacted by subsequent rains is significantly influenced by massive fissures on the surface of the slopes that are generated by earthquake shaking. The coupling effect of these two factors can significantly reduce the stability and safety of slopes, leading to catastrophic consequences. This paper reviewed the response of slopes under the combined influence of rain and seismic loading. This critical review highlights the importance of integrating rainfall and earthquake parameters simultaneously in slope deformation studies. In addition to slope stability analysis, slope deformation analysis should also receive equal attention. Future directions of this research should be focused on developing robust models and algorithms to simulate and assess slope failures caused by earthquakes and heavy rainfall in light of technological advancements, improvement of computational efficiency.

KEYWORDS: Slope Deformation, Seismic slope stability, Deterministic Approach, and Probabilistic Approach.

1. INTRODUCTION

Landslides induced by rainfall are among the most widespread types of catastrophes that occur across the globe (Froude & Petley, 2018; Petley, 2012), and they have been the focus of a significant amount of study over the course of the last several decades. Analysis of the mechanisms that cause slope failure under a variety of situations (Moriwaki et al., 2004a; Take et al., 2004; G. Wang & Sassa, 2001; S. Wang et al., 2021), such as predicting slope stability during rainfall based on vegetation modelling (Ng et al., 2016; Ni et al., 2018; Switała & Wu, 2018), using reinforced slopes to assess their performance that have been subjected to rainfall (Bhattacherjee & Viswanadham, 2019; K.-H. Yang et al., 2018), and computational models of the landslides that are caused by rainfall in the field are all examples of typical studies (Liu et al., 2020; Y. Tang et al., 2019; H. Xu et al., 2022). The accompanying results have substantially enhanced comprehension of how slopes behave during rainfall and have made significant contributions to the prediction and prevention of landslides. On the other hand, experts in geological disaster prevention and mitigation are increasingly worried about a different kind of rainfall-induced landslip that starts on slopes with fractures caused by earthquakes. When an earthquake creates tensile fissures on the surface of a slope, the next downpour sometimes causes the slope to completely collapse, leading to a landslide (J. Xu et al., 2022a). Traditional subjects within geotechnical engineering encompass the analysis of slope failure mechanisms and stability. Recently, there has been an increase in the number of geotechnical disasters, which include landslides, collapses, rock explosions, and water inrushes (G. Feng et al., 2021; G.-L. Feng et al., 2015). Researchers previously used Limit Equilibrium Methods (LEM) to calculate slopes stability ,including the Fellenius Method (FM) (Fellenius, 1936), the Simplified Bishop Method (SBM) (Bishop, 1955), the Spencer Method (SM) (Spencer, 1967), the Janbu Method (N Janbu, 1975), the Sarma Method (S. K. Sarma & Tan, 2006), the Wedge Method (WM) and the Strength Reduction Method based on FEM (Kelesoglu, 2016; Nian et al., 2012; Tiwari et al., 2015). The most common approach in conventional slope stability assessments is the limit equilibrium slice technique (Faramarzi et al., 2017; Matthews et al., 2014; Moriwaki et al., 2004b; G. Sun et al., 2017; X. P. Zhou & Cheng, 2014). In order to do a static slope stability analysis with a certain slip surface, a number of various limit equilibrium slice approaches make a number of assumptions regarding the direction and the action line of thrust between slices, as well as the action point of the force. For example, extreme solutions to the LEM that are physically admissible, and slope stability evaluation based on charts that uses the generalized Hoek-Brown criterion (Su et al., 2018; Zheng et al., 2018). Additionally, researchers have proposed four criteria for the selection of potential sliding surfaces. These criteria include a -dimensional equilibrium equation that is based on some specific assumptions, a minimum parameter value criterion, an upper limit criterion for slope active reinforcement forces, a lower limit criterion for surfaces which are sliding, and a sliding and upper bound criterion (C. Tang et al., 2015; Zheng et al., 2018). Slope stability has been the subject of much research because to the high number of tragedies it causes. Numerous natural slopes may be found in the mountainous southwest area of China. Most of the communities in this area are situated on the mountain top, while most of the roads and bridges are constructed on the flatter plain underneath the mountain. If the mountainside is levelled, the repercussions will be catastrophic. Landslides, caused by natural slope instability, are common in areas prone to earthquakes and heavy rainfall, among other high external loadings. Hence, to avoid catastrophes, it is crucial to make slopes more stable.

Landslides may happen for many different causes, although earthquakes and rainfall are a common cause (Jagodnik & Arbanas, 2022). As an example, 73,671 homes were destroyed in the 2017 Jiuzhaigou earthquake due to the many landslides that were produced by the earthquake (Fan et al., 2018). A massive landslip was set in motion in Hokkaido, Japan, on September 6, 2018, because of an earthquake (Cui et al., 2021). More than 10,000 people were put in danger when a seismic event struck in Yunnan Province, in 2014. The earthquake set off the landslide in Hongshiyan and a landslide dam in the Niulan River is created (Luo et al., 2019; Shi et al., 2017). A landslip in Wangjiayan, Beichuan County, after the 2008 Wenchuan earthquake engulfed losts of the countries and killed over 1700 people (Dai et al., 2011; Z. Ren et al., 2018; Song et al., 2016; G. Wang et al., 2014; Yuan et al., 2014). A several landslides were caused by the 2013 Lushan earthquake (S. Zhou et al., 2015). Therefore, there is a need of constructing physical modelling in laboratory which simulate the seismic effects also. Researcher (Cheng et al., 2021) used a centrifuge model test to investigate how various parameters of earthquake which affect the rock as well as the soil mass moves. They looked at how various seismic accelerations affected the dynamic performance of slopes. According to a uniaxial compression test performed on hard rock (R. Xu et al., 2023), the deformation and strength properties of the rock mass are significantly affected by the loading rate. To sum up, the earthquake itself isn't nearly as bad as the landslip calamity that follows it. Because of this, making slopes in stable conditions during earthquakes is of the utmost importance (L. Zhou et al., 2023). It is also possible to fail slope as a result of the foot being undercut or excavated, or as a result of the progressive breakdown of the soil structure. The occurrence of slides may take place in almost every imaginable way, gradually or abruptly, and with or without any apparent provocation (Digvijay P. et al., 2017). When evaluating the stability of engineered slopes, the height of the slopes becomes an essential parameter. Hence, these types of slopes are often known as finite slopes (Ausilio et al., 2000). Slope deformation is the slow but constant change in the form and stability of a slope because of human activity. Cracks, changes in topography, and compromised slope structural integrity are common outcomes of this process. Deformation of slopes could be caused by a variety of natural and man-made processes, including weathering and geological processes. For determining the likelihood of landslides and other slope-related disasters, as well as to develop and execute efficient technical solutions to ensure the stability of slopes and the public's safety, it is essential to detect and comprehend these deformations. Figure 1 (a) shows tension fractures along the slope's rear edge. These cracks range in width from 0.1 to 0.5 meters, have a depth of 2 meters, a significant dip angle is observed. On the left side of the hill, there are surface fractures that are about 220 meters long and 0.1 to 0.2 meters broad. A house's wall has developed shear fractures because of the slope's deformation as illustrated in Figure 1 (b). The cracks observed along the right direction of boundary of the slope extend approximately 25 m, accompanied by shear cracks on the ground in adjacent structures depicted in Figure 1 (c). Notably, at the forefront of the slope, where a portion of the pier intersects, visible cracks of 2~3 cm are apparent between the soil and the pier shown in Figure 1 (d). The absence of deformation cracks on the front edge of the slope led to the determination that the middle and rear sections of the slope experienced cohesive deformation. The sliding zone was not entirely penetrated, indicating that the slope is presently in the creeping slip stage (L. Zhou et al., 2023).

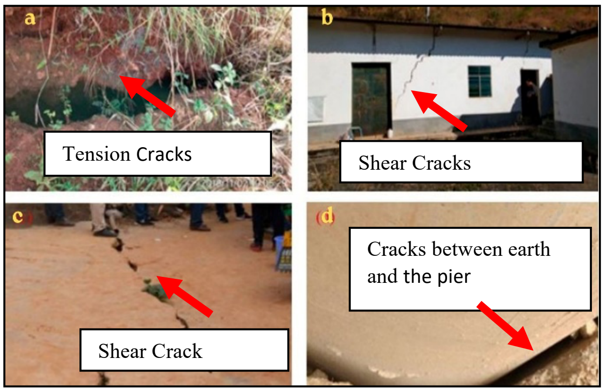

Figure 1 Several types of slope fractures (L. Zhou et al., 2023)

The objective of this paper is to investigate the interplay between rainfall and seismic loading on slope stability, with a particular emphasis on the critical role of earthquakes in triggering the landslides. During earthquakes, the ground shakes intensely, which can cause slopes to become unstable. When the ground shakes, soil, rock, and debris fall off steep slopes, causing landslides. Rock fragments break away from steep slopes due to seismic vibrations. Seismic events cause fast flowing mixtures of water, mud, and debris to surge downhill. Hence an attempt has been done to enhance the understanding of slope deformation mechanisms and to help in developing advanced models to assess and mitigate the risk of slope failure during rainfall induced seismic events based on systematic literature review.

2. RAINFALL PATTERN IN GLOBAL - INDIAN SCENARIO

The rainfall pattern determines the extent of damaged because of slope failure. Several scientific studies have also shown that climate affects rainfall patterns. In North America, Europe, and parts of Asia, extreme rainfall events have intensified in recent years (Trenberth et al., 2014). Water stress has also increased in many regions due to abrupt changes in precipitation patterns, such as the Mediterranean and the southwest (Sheffield et al., 2012). Over the past few decades, global climate changes have been marked by unexpected shifts in temperatures and rainfall patterns. At middle and high latitudes, land precipitation has increased in the Northern Hemisphere except for eastern Asia and also that there has been a decline in land-surface rainfall in the subtropics on average (about 0.3% per decade), although recent years have seen signs of recovery (Dore, 2005). The average monthly rainfall in India in the range of 1989 and 2007 was 99 millimetres, with the monsoon season receiving 330 millimetres and autumn receiving 52 millimetres (Kishore et al., 2016). A 30-year mean rainfall climatology (1981–2010) estimates a mean of 3mm/day of rainfall yearly, which peaks at 7mm/day in monsoon season and decreases to 1 mm/day in October–November (Kishore et al., 2016). The extreme rainfall events over central India have changed significantly over 1951–2000 (Davis et al., 2006). In an analysis of future rainfall patterns, found that as compared to climate range between 1961 to 2000, eastern India would experience an increase of 4% in rainfall amounts in the future. It can be expected that future climate change will significantly affect the rainfall patterns over India, which will impact slope stability (L. Das & Lohar, 2005).

3. EARTHQUAKE PATTERN IN GLOBAL - INDIAN SCENARIO

There have been a number of studies examining the global pattern of earthquakes. Seismic event density and energy flux are symmetrical with respect to the equator, indicating that rotational dynamics influence tectonic processes (Fan et al., 2019). Strong earthquakes are usually triggered by plate movement at tectonic plate boundaries (Starovoit et al., 2019). Earthquake occurrence varies seasonally, particularly in mid latitude intra plate seismic regions, with precipitation correlation (Matsumura, 1986). The study of earthquake patterns in India has revealed that the country is experiencing a variety of seismicity trends. The Himachal Pradesh region experienced an increase in seismic activity before two earthquakes, followed by a period of relative quiet (Paul & Sharma, 2011). In northeast India, earthquake have different mechanisms, including thrust faulting, normal faulting, and strike-slip faulting (Thingbaijam et al., 2008). Forecasting techniques were used to predict future earthquakes in northern India, with some success along the border with Nepal (Mohanty et al., 2016). Earthquakes can be forecast using various methods, such as geological studies or machine learning techniques, or sometimes a combination of both. Techniques like Artificial Neural Networks (ANN) algorithm as well as Support Vector Machines (SVM) are used to analyse seismic data, with some studies achieving prediction accuracies as high as 83% (Asim et al., 2018). The use of deep learning models and hybrid neural networks has also been explored, showing promising results in improving prediction performance. The Relative Intensity (RI) method and Pattern Informatics (PI) method are also used to forecast earthquakes. An RI is used to forecast long-term seismicity in a region. The PI quantifies the change in seismicity rate in the historic seismicity. In the PI method, seismic activity is measured and the spatio-temporal seismicity rate changes are quantified (Mohanty et al., 2016). It is not possible to predict the precise time and location of earthquakes with the PI method. However, it identifies potential hotspots (regions) where earthquakes may occur more frequently in the near future. Based on the number of earthquakes in the past, this technique able to predict Relative Index of future Seismicity.

4. METHODS TO REVIEW LITERATURE

Systematic Review (SR) is conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. SR begins with the identification of records from databases and other sources, followed by the removal of duplicates during the screening phase. The eligibility stage involves assessing records against predefined criteria, leading to the inclusion or exclusion of studies. The final number of studies included is then presented, along with reasons for exclusions. Data extraction and synthesis are the concluding steps, where relevant information is collected from the included studies and analysed to form the reviews findings.

4.1 Eligibility Criteria

The process involves manually reviewing the bibliographies of pertinent articles and reviews, as well as thoroughly examining the remaining documentation. To determine the inclusion or exclusion of studies in this SR, assess their supplementary information and abstracts based on the criteria outlined in Table 1.

Table 1 SR Criteria for Inclusion and Exclusion

Inclusion criteria	Exclusion criteria
I1: The document needs to undergo a peer review.	E1: Papers that do not Centre around the examination of body stress.
I2: The document must be written in English.	E2: Informal literature or non-traditional publications.
I3: There is no specific time frame restriction for publication.	E3: Redundant research and duplicated publications.
I4: The papers should be published in a research journal or as full-article publications.	E4: Doctoral thesis, work-in-progress papers, and project deliverables.

The next step in the review methodology involved the selection of appropriate internet sources and online databases for information gathering. A final search was conducted on June 6th, 2023. The primary databases utilized were Springer, Scopus, and Science Direct.

4.2 Search Strategy

A Systematic Literature Review (SLR) is concentrated on the analysis of slope deformation under the influence of Rainfall and Earthquake, along with the development of a suitable case-base structure for effective case retrieval. During this undertaking, primary databases including Science Direct, IEEE Xplore, Springer, and Scopus are initially consulted for information gathering.

On March 25th, 2023, the most recent search was conducted, employing comprehensive keyword-based database searches to locate pertinent scholarly literature. The search criteria were applied to articles and reviews. The keywords utilized in the search strategy for Scopus and here are detailed in below encompassing multiple variations in spelling. The keywords employed in the search strategy are:

1. Influence of slope deformation on rainfall intensity and duration.
2. Critical threshold of rainfall that triggers slope instability.
3. Influence of seismic activity on slope stability and deformation.
4. Interaction between rainfall induced slope deformations and seismic activity induced slope deformation.

4.3 For Study Scrutiny of Papers

Systematic reviews are rigorous methods for synthesizing available evidence on a specific topic or research question. The process begins with the formulation of a clear research question and the development of inclusion and exclusion criteria. Academic databases, grey literature, and reference lists of relevant articles are essential sources for selecting relevant studies. In order to minimize bias and ensure that all relevant studies are identified, the systematic search process uses predefined search terms and strategies. Study eligibility is determined by applying predetermined criteria to the gathered studies by means of a systematic screening process.

The process for selecting primary studies involves four distinct stages i.e. detection, admissibility, inclusion and multiple screenings.

In the initial phase, the goal is to identify all potentially relevant studies, resulting in 2,958 results from the initial search. A systematic exploration of various databases and sources, including articles from Science Direct, Springer, Scopus, and uncovered conference proceedings. After thorough screening and analysis to eliminate duplicates, a total of 212 studies were identified. Among these, 28% focused on the detection of emotional stress, 17% on scientific viability and consistency, and 33% were exploratory studies on recent science-based applications and innovations.

The second stage involves a preliminary assessment through the screening of titles, keywords, and abstracts. At this point, 2,847 records were excluded due to their failure to meet inclusion criteria, especially regarding the scope of research and optimization topics. Some additional papers are added at later stages which fulfil all the criteria.

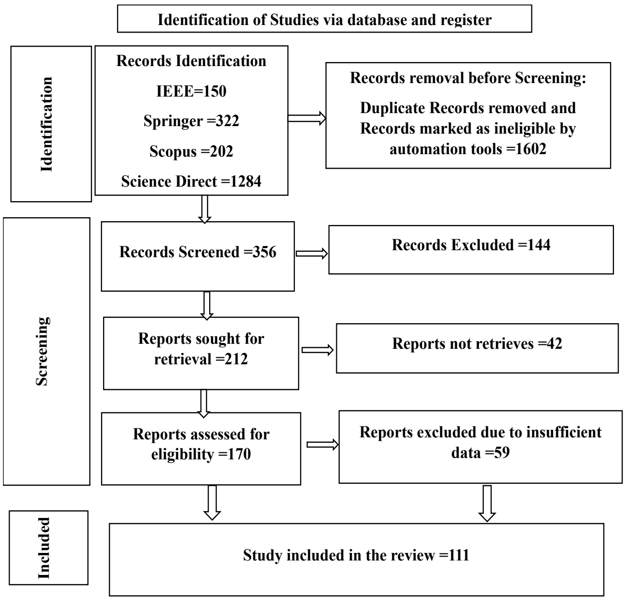

Figure 2 The process of conducting a SR for published articles in databases

An additional objective of these SRs involves establishing an open-source knowledge platform aimed at facilitating forthcoming research endeavours on the subject. This platform is designed to accumulate and analyse pivotal insights derived from past research, summarizing, and comparing these findings while pinpointing emerging issues and limitations stemming from prior work. The study delves into the analysis of slope deformation under the influence of rainfall and earthquakes by evaluating the existing knowledge base in this domain. Formulated during the study's design phase, three primary investigative questions guide the research, and these inquiries are thoroughly examined and assessed throughout the article. The subsequent section outlines these key investigation questions:

RQ1: What is the impact of earthquake-induced forces on slope deformation, and how does this impact differ from deformation caused by rainfall?

RQ2: How do different geological and geotechnical characteristics of slopes influence their response to both rainfall and earthquake-induced deformation?

RQ3: What lessons can be learned from case studies of slope deformation under the dual influence of rainfall and earthquakes, and how can this knowledge inform best practices for slope stability assessment and engineering design?

To initiate the study, an extensive examination of the current literature was undertaken to fulfil the specified objectives. Citation indexing databases such as Sage, Google Scholar, Multidisciplinary Digital Publishing Institute MDPI, Science Direct, IEEE Xplore, and Springer Link were utilized. This exploration encompassed both the academic and wider internet publications to identify relevant papers published within the last decade.

5. REVIEW OF LITERATURE

In this section, the previous studies of several authors on stability of slope as well as deformation analysis subjected to Rainfall and Earthquake are discussed based on deterministic and probabilistic approach. Deterministic approaches in slope stability analysis assume fixed values for input parameters, providing a single factor of safety. However, these approaches may oversimplify the complexities and uncertainties inherent in geotechnical conditions. In contrast, probabilistic approaches acknowledge and incorporate variability by treating input parameters as probability distribution. For quick assessment of slope stability under rainfall and earthquake, some important literature is tabulated in Table 2.

5.1 Factors Influencing Slope Deformations

In slope failures, gravity and shear stresses cause downward movements of material beyond its strength. The various factors influencing slope stability are water content, shear strength parameter, field density, slope geometry, seismic loading, rainfall intensity etc. Slopes are affected by water in two different ways. Firstly, ground water or aquifers below the surface generate porewater pressure, and secondly, rainwater infiltration flows along the slopes, creating water pressure along the slopes. An important geotechnical parameter that affects slope stability is soil's shear strength parameter. It is comprised of cohesion and friction angles. Friction is a force that resists movement between two surfaces. The bond between particles causes cohesion. Deformation is minimal with a high cohesion and friction angle. Slope stability is also affected by density. However, its effect is more pronounced in mine waste dumps, depending on how the waste is deposited, graded, and loaded. Shear strength can be increased by a relatively small increase in density (Y. Wang et al., 2021). Height and angle of slope are another most important parameters of slope geometry that affect stability. The critical height of a slope depends on its shear strength, density, and bearing capacity. When a slope is steeper, slope stability generally decreases. Due to the increased weight within the slope, the shear stress increases as the slope height increases. Mass and slope angle are also factors that influence shear stress. Tangential stress increases with increasing slope angle, which results in an increase in shear stress, reducing the slope stability (Komadja et al., 2021). During seismic waves that pass-through rock or soil, stress is added, which can lead to fracturing. Intensity of rainfall at the beginning of a rainfall period affects the rate of reduction in FOS (Suradi & Fourie, 2014).

5.2 Evaluation of Slope Stability and Deformation Caused by Rainfall

Slope deformation studies subjected to rainfall have been investigated in several papers based on deterministic and probabilistic approach.

5.2.1 Deterministic Approach

During rainfall, rainwater infiltrates into the unsaturated zone of a slope, decreasing matric suction and consequently decreasing soil shear strength (Ishihara & Yasuda, 1990). Various studies emphasis role of vegetation on rainfall induced slope stability such as Eab et al. concludes that vegetation, especially vetiver grass with its deep root system, can stabilize soil slopes effectively as rainwater infiltration is reduced, the groundwater table rises slower, and soil shear strength is enhanced, which together minimize deformations and prevent slope failure (Eab et al., 2014) . Vegetation offers a natural, cost-effective method for slope protection in areas that experience intense and prolonged rainfall. Researcher (Sarma et al., 2015) applied three physically based models to evaluate landslide triggering areas in the Guwahati region. These models were found to be capable of identifying places prone to landslides and generating data matching with reality. Various researchers validated vetiver grass root systems ability to reinforce soil slopes against rainfall-induced landslides using centrifuge and numerical simulations. Soil shear strength increases when the roots reduce rainwater infiltration and delay groundwater table response, and reduce rainwater infiltration (Likitlersuang et al., 2017). Researcher (Rahardjo et al., 2018) investigated stress and pore-water pressure variations within and behind the Geo Barrier system (GBS) wall following rainfall. There is a greater effect of rainfall infiltration on the horizontal pressure at the top of the GBS wall than on the vertical pressure. In an experimental flume setting, retrogressive landslides were explained by researcher (Kim et al., 2018) showed that sequential slope failures occurred following the infiltration of 80 mm/h rainfall, starting at the toes of the slope and slowly moving to the crest. If the retaining walls were not designed and constructed properly, slope movement did not stop, instead it delivered an extra backfill load, which made the slope unstable. Ngo et al. investigated the effectiveness of a Geosynthetic Cementitious Composite Mat (GCCM) in stabilizing sandy slopes under high seepage conditions, showing that GCCM significantly reduces slope deformation compared to non-stabilized slopes (Ngo et al., 2019). By utilizing a fully coupled finite-element modelling code, various researcher (Ali et al., 2021) examined slope behaviour under various range of rainfall intensities and angle of slopes. They find that the slope deformation increases with increasing rainfall duration and slope angle, and that the matric suction decreases with increasing rainfall intensity and depth and also concludes that the soil nailing technique can effectively reduce the horizontal deformation and increase the stability of the slope by developing axial forces in the nails. In Kerala, two slopes affected by landslides and their failure mechanisms were studied (Das et al., 2022a). Based on the results of their analysis, the slopes were not stable at the time when the water table reached ground. Various researcher (Dhanai et al., 2022) investigated the change in pore water pressure and slope stability due to rainfall infiltration in different hill slopes in India, and concluded that slopes may fail under projected precipitation estimates due to climate change. Considering the variability of soil properties, using an indoor model test and FEM simulation, Sun et al. investigated the stability of a slope affected by rainfall (Y. Sun et al., 2022). In their study, they found that the phreatic line, water head, seepage depth, and pore water pressure of the slope increased with rain intensity and duration, but the FOS and shear strength decreased. Xu et al. investigates the response of unsaturated slopes to post-earthquake rainfall using numerical modelling and finite element analysis (J. Xu et al., 2022b). The analysis shows that the earthquake significantly affects the slip surface of the slope, leading to more severe landslides. Layek et al. analysed the stability of mine waste dump slopes under rainfall conditions and found that the slope was more stable under rainfall compared to seismic conditions (Layek et al., 2022). Ongpaporn et al. found that bioengineered slopes with pioneer plants and rubber trees had a lower FOS than natural ecosystems, highlighting the importance of vegetation type in slope stability (Ongpaporn et al., 2022). A study of geosynthetic cementitious composite mats (GCCM) was conducted to investigate their effectiveness in reinforcing soil slopes. Based on centrifuge tests under seepage and rainfall conditions, the GCCM demonstrated its potential as a reliable method of slope reinforcement by reducing slope displacement and delaying the increment in pore water pressure during rainfall (Ngo et al., 2022). Researcher studied the impact of rainfall on slope stability in Kota Belud, Malaysia, and found that the FOS of the slope decreased after 24 hours of rainfall but increased after 48 hours (Rosly et al., 2023). Kumar et al. investigated three-dimensional slope stability analysis using the LEM and the Bishop simplified method (BSM) for different soil types, slope heights, and slope angles. They concluded that the safety factor increases with the decrease of slope height and angle, and the 3-dimensional safety factor is generally 10-20% higher than the 2-dimensional safety factor for the same problem (S. Kumar et al., 2023).

5.2.2 Probabilistic Approach

An actual site study was carried out to investigated slope failure in Hong Kong, where the pore water pressure at failure and the reliability of a redesigned slope are estimated probabilistically, using Monte Carlo simulation and statistical distributions of input parameters (El-Ramly et al., 2005). Zhang et al. adopted Green–Ampt model and the infinite slope model to evaluate the infiltration process and the FOS of the slope, and conducted parametric studies to investigate the effects of rainfall intensity, duration, pattern, and soil properties on the failure probability and the failure time of the slope (J. Zhang et al., 2014). Considering the variability of hydraulic conductivity in the context of rainfall infiltration and redistribution, Dou et al. presented a probabilistic approach to slope stability analysis. The Monte Carlo Simulation method is used to generate random number sequences of hydraulic conductivity following a log-normal distribution. The Green-Ampt model and the infinite-slope stability model are combined to establish the closed form of the limit state function (Dou et al., 2014). Nguyen et al. investigated the impact of spatial variability in shear strength parameters of the soil on the probability of landslides induced by rainfall, using a probabilistic analysis framework by presenting an actual site study of a slope having sandstone in Japan, highlighting the importance of considering non-homogeneous soil profiles in slope stability assessments. Their study emphasizes the efficiency of probabilistic analysis in identifying potential failure surfaces due to spatial variability in soil shear strength under various rainfall intensity conditions (Nguyen et al., 2017). Researcher also introduces a probabilistic approach to account for the spatial variability of root cohesion and its effects on slope stability analysis (Nguyen et al., 2019). Nguyen et al. examined how unsaturated soil slope stability is affected by soil property variability during rainfall infiltration. Based on random field theory and probabilistic methods, their observation shows that slope stability is affected by variations in pore water pressure and friction angle (Nguyen & Likitlersuang, 2019). An evaluation of rainfall-induced landslides was conducted (Y. S. Yang & Yeh, 2019) using both a fuzzy point estimate method and a local FOS equation. They applied the method to loam and silt slopes and analyses the harmful effects of rainfall infiltration, suction stress, and parameter correlation on the slope stability and probability of failure. Chakraborty and Dey reviewed different approaches including approximate methods and Monte Carlo simulation-based approaches. They also concluded that geotechnical engineering has yet to pay adequate attention to stability assessment of reinforced natural slopes based on probability (Chakraborty & Dey, 2022). To assess the probability of failure on rainfall-induced shallow landslides at slope scale, researcher combined a fuzzy point estimation method with a physical model. They applied their framework to a practical hillslope in Chiayi County, Taiwan, where they measure the soil hydraulic and mechanical properties, the local FOS, and the failure probability under various rainfall patterns and found that their framework can effectively predict the slope stability (Y. S. Yang et al., 2022). A multivariate Monte Carlo simulation method was applied to generate gridded rainstorms based on historical data, and a slope-stability numerical model to simulate the safety factors and failure time steps of shallow landslides at various locations and soil depths (X. J. Wang et al., 2023). Nada et al. explored the effectiveness of machine learning models in predicting landslides caused by rainfall events along the Bandipojohra to Gurez Highway in J&K, India. Random Forest and Logistic Regression models were used to find the optimal parameters for landslide prediction (Nanda et al., 2023). (Ering & Babu, 2016) proposed a novel machine learning method for rainfall-induced slope failure, which explicitly models the rainfall triggering mechanism and reduces randomness in soil strength and hydraulic properties. Youssef et al. highlighted the potential of Spiking neural networks (SNN) optimization as a powerful tool for natural hazard assessment and mitigation, as well as a general framework for developing fully interpretable AI models for various applications (Youssef & Bathrellos, 2023).

5.3 Evaluation of Slope Stability and Deformation Caused by Earthquake

Slope deformation studies subjected to earthquake have been investigated in several papers based on deterministic and probabilistic approach.

5.3.1 Deterministic Approach

Pseudo-static approach includes the numerical estimation of slope displacement, the use of the upper bound technique for calculating yield acceleration, the consideration of earthquake loading, and the importance of overall displacement accumulation during an earthquake (Ling et al., 1999). There is a need to treat seismic forces in a realistic manner, considering that ground acceleration in earthquakes is not monotonically increasing in one direction but alternating in direction (Simatupang & Ohtsuka, 2001). Alonso et al. analysed the behaviour of a slope in Italy, made of weathered over consolidated clays, and the influence of rainfall on its deformation and safety using a finite-element model that can handle saturated and unsaturated flow and mechanical interaction due to suction changes. They compare the model results with field measurements of pore-water pressures and displacements and concluded that the heterogeneity of soil permeability and strength, and the rainfall record greatly affect stability of slope (Alonso et al., 2014). The slope stability was assessed using a nonlinear failure criterion (Li, 2007) using a finite element analysis. Additionally, he computed and compared stability numbers based on different seismic coefficients that account for earthquake effects using pseudo-static considerations. Choudhury et al. investigated seismic stability in a generalized earth slope, employing limit equilibrium analysis to assess dynamic safety. Results indicate that higher soil friction angles enhance safety, while steeper slopes and increased seismic accelerations reduce dynamic safety, potentially causing slope instability (Choudhury et al., 2007). By considering the stiffness and deformation of materials and geosynthetics, researchers developed a numerical procedure to evaluate seismic slope stability. When the cumulative plastic displacement of a vertical slope reaches a critical value, the slope fails (Lu et al., 2014). An ambient noise measurement and spectral analysis are used to investigate soils that liquefied in Northern Thailand as a consequence of an earthquake (Mase et al., 2018a). Their study provides valuable insight into seismological hazard assessments and informs mitigation strategies for earthquake-prone areas by understanding the dynamic behaviour of soils during earthquakes. A study by Wang et al. examined how earthquake duration affected the failure process and displacement of the failed soil mass, and compared the displacement of the toe obtained from FEM with the displacement obtained from Newmark's simplified model. It has been demonstrated that Eulerian-based Finite Element modelling techniques have been successfully used to simulate large-scale landslides in clays that are sensitive to earthquake loading (C. Wang et al., 2019). In recent studies various physical model tests and numerical model studies have been conducted to analyse the seismic behaviour of reinforced soil retaining walls. The inclusion of reinforcing material, such as biaxial geogrid, reduces horizontal displacement in reinforced soil walls (Murali Krishna &

Bhattacharjee, 2019). The study conducted by Mase et al. found that during the Tarlay Earthquake, the significant duration of ground motion was 24 seconds, indicating vulnerability of low-medium story buildings within the frequency range of 1.82 to 2.1 Hz (Mase et al., 2018b). A study is conducted by Qodri et al. to determine Bangkok's subsoils seismic vulnerability to earthquakes triggered by the three Pagodas Fault which emphasizes the need for seismic design considerations in structural development (Qodri et al., 2021). The liquefaction risk in Northern Thailand using seismic ground response analysis is investigated (Mase & Likitlersuang, 2021) and concluded that liquefaction could occur at investigated locations in Northern Thailand during the Mw 6.1 Mae Lao Earthquake. Using three-dimensional finite element analysis, Petchkaew et al. investigated the seismic stability of unsupported excavations under pseudo static seismic forces in cohesive-frictional soil. Introducing a dimensionless stability number based on excavation aspect ratio, depth ratio, soil friction angle, and earthquake acceleration coefficient and examined their effects on excavation failure mechanisms for the first time. Additionally, a case study shows that the proposed stability number can be used to assess the seismic risk associated with such excavations (Petchkaew et al., 2023). Using finite element analysis and empirical methods, Mase et al. reveals high liquefaction potential during seismic events in the Izumio sands in Osaka, Japan (Mase et al., 2022). Das et al. concluded that the displacement-based method is more reliable than the pseudo static method for estimating seismic slope stability, and that the Newmark sliding block method can be used to calculate permanent displacements of slopes under seismic loading (T. Das et al., 2022b). Rahman et al. conducted a numerical analysis using the Coupled Eulerian-Lagrangian (CEL) technique in ABAQUS/Explicit to investigate seismic landslides in a Kerala hill slope. Findings reveal that the CEL method aligns closely with traditional Lagrangian Finite Element Method (LFEM) when assessing the post-failure behaviour of the slope under seismic conditions (Rahman & Jaksa, 2022). A lack of literature on strength reduction techniques to analyse seismic slope stability is reported, so more effort needs to be put into developing these techniques. Further, new design charts should be prepared to account for soil heterogeneity when considering seismic slope stability (Boruah & Chakraborty, 2022). Hong-in et al. presented an equation for predicting seismic stability numbers is provided which shows that horizontal seismic accelerations have a significant impact on failure mechanisms on three dimensional slopes. A seismic stability number is introduced by the author that depends on the slope length ratio, depth factor, inclination of slope, and the seismic acceleration coefficient in horizontal direction (Hong-in et al., 2023).As a part of the investigation on the seismic stability of vertical circular excavations in cohesive-frictional soil by Petchkaew et al. a finite element analysis (3D) was performed. Several dimensionless variables play a role in the calculation of the dimensionless seismic stability number, including the excavated height ratio, the soil's effective friction angle, and the horizontal earthquake acceleration coefficient (Petchkaew et al., 2022).

5.3.2 Probabilistic Approach

Johari et al. discussed uncertainty and reliability analysis applied to slope stability, as well as the use of neural networks and particle swarm optimization algorithms in slope stability analysis. They presented different methods for calculating the stability of slopes, such as Bishop's equation and the methods of slices (Johari & Mousavi, 2014). Researcher presented design aids for probabilistic seismic slope stability analysis and design, which consider the spatial variability of soil properties and concludes that as long as spatial variability is adequately considered, the probabilistic seismic slope stability design aids presented provide an effective alternative to computer-based analyses (Jesse Burgess et al., 2018). During the Tarlay Earthquake of 2011 in Northern Thailand, resonance effects likely contributed to structural damage as per findings from Mase et al., particularly in low-medium story buildings, due to significant ground motion parameter (Mase et al., 2021) Now a days Researcher are, investigated earthquake attenuation models and Tanapalungkorn et al. recommends NGA-West2 to predict ground motion in Northern Thailand, impacting seismic design standards (Tanapalungkorn et al., 2020). Mase et al. investigated liquefaction potential in the Thailand-Myanmar border area following the 2011 Tarlay earthquake and confirms that shallow sand layers were highly susceptible to liquefaction, aligning with empirical predictions (Mase et al., 2020). Gharrawi et al. explored the use of Monte Carlo simulation to assess the stability of finite slopes under earthquake loading. The authors consider various factors in their analysis, including soil properties, slope geometry, and seismic parameters. The outcome of this research can be used in real-world engineering problem to improve the safety as well as the stability of slopes subjected to earthquake loading (Al-Gharrawi & Abdul-Husain, 2020). Boruah and Chakraborty investigated that Factor of safety (FOS) values begin to fall sharply upon seismic impact and also several prediction models have been created utilizing Multiple Non-Linear Regression (MNLR) and Multiple Linear Regression (MLR). The model's performance is evaluated by comparing anticipated FOS values to those from 10 real-world scenarios. The findings show that MNLR's FOS forecasts are accurate (Boruah & Chakraborty, 2023). An approach for predicting soil liquefaction potential in Bengkulu City based on seismic activity and soil conditions is proposed by Mase et al. which correlates kinetic energy density with liquefaction, providing engineers and planners in earthquake-prone areas to better understand soil behaviour during earthquakes (Mase et al., 2023).

5.4 Evaluation Stability and Deformation of Slope Caused by Combined Effect of Rainfall and Earthquake

Slope deformation studies subjected to combined effect of earthquake have been investigated in several papers based on deterministic and probabilistic approach.

5.4.1 Deterministic Approach

The FOS obtained with analysing seismic shaking after rainfall seepage is 70% of the FOS obtained when only analysing rainfall seepage. This highlights the importance of considering the combined effect of rainfall seepage and seismic shaking for slope stability (C.-Y. Chen & Wu, 2019). Using LEM and FEM, Chen et al. investigated the effects of dynamic load on slope behaviour under earthquake loading and heavy rainfall in Southwest China. Based on their findings, it appears that slope instability is ultimately caused by permanent structural damage as a result of earthquakes or ground motions, as well as secondary damage as a result of heavy rainfalls (Y. L. Chen et al., 2020). Using finite difference methods, Zhang et al. solve the dynamic response problem of reinforced flexible Earth slopes affected by earthquakes and rainfall. They developed a numerical model to estimate pore pressure and tensile stress distributions in reinforcement under earthquake and rainfall scenarios (X. Zhang et al., 2020). Researcher studied mudflow-like landslides that are induced by earthquakes and rainfall and developed a formula to determine sliding distance, which can be used to prevent and control them (Pu et al., 2021). Researcher investigated a landslide located along Bâsca Rozilei river had a factor of safety in the range of 1.17–1.32, with static displacements of 0.4–4 m and dynamic displacements up to 8–60 m. In addition, the groundwater (GW) effect reduces the factor of safety and increases displacement (V. Kumar et al., 2021). Ren et al. examine the deformation and stability of the Zhoujiashan landslide in the context of rainfall and earthquakes (J. Ren et al., 2023). In Tianshui, China, under 0.1-g and 0.3-g seismic conditions, they found that the slope deforms and decreases in safety, but the landslide does not suffer overall damage; however, under 0.6-g seismic conditions, the slope liquefies, resulting in overall damage and deformation. The effect of earthquakes and rainfall coupling on slope stability is much greater than that of either factor individually, and the slope toe is always the most unstable factor regardless of the coupling conditions (Qu et al., 2023).

5.4.2 Probabilistic Approach

Utilizing various models and techniques, numerous studies have analysed the likelihood of slope instability and potential risks. Nguyen et al. offered a model that could evaluate the yearly risks of landslides caused by earthquakes and rainfall. The simulation module assessed the likelihood of slope failure caused by rain and earthquake employing two distinct approaches: a Newmark displacement model and a pseudo-static model developed in the uncertainty-analysis module using the Monte Carlo simulation technique and the model abled to generates a unified map presenting a range of annual landslide probabilities at specific confidence levels and provides a reliable forecasting tool for understanding and preparing for the combined impact of rainfall and earthquakes on landslide occurrences (Nguyen & Kim, 2020). Ji et al. did a probabilistic investigations of rotating sliding mass collapse using Newmark's sliding block theory, with an extension to calculate the rotational displacement when history of horizontal ground acceleration is known (Jian et al., 2020). Khan and Wang examined the rock fill dam's upstream and downstream slopes at the Nauseri Dam site for dynamic deformation and finally predict the upstream and downstream slope displacements based on probabilistic techniques (Khan & Wang, 2023). Samm et al. rigorously evaluated earthquake and rainfall- induced landslide hazards in the Kutupalong Rohingya camp, considering topographic, soil, and contributing factors and using Peak Ground Acceleration (PGA) and rainfall intensities for various return periods, employing Monte-Carlo simulation and direct estimation methods. The findings, validated against field data, demonstrate high accuracy (more than 85%) in identifying landslide-prone areas (Samm-A et al., 2023). Yu et al. employed the Newmark sliding block model alongside reliability analysis, utilizing both the Monte Carlo simulation and Latin hypercube sampling methodologies during their investigation into slope stability amidst rainfall and earthquake scenarios (Yu et al., 2023). Using a robust quasi-Monte Carlo simulation and a conditional random field (CRF) to simulate soil variability, estimate slope failure probability and generate the horizontal and vertical stochastic ground motion (Chao, 2023).

5.5 Research Development of Slope Stability Analysis

The study of slope stability is a major research area that aims to prevent natural hazards such as landslides. A variety of FEM and LEM methods are used to analyse slope stability. It is important to note that this research field has experienced a significant growth over the last few decades. Today, optimization techniques, machine learning techniques, etc., have been applied to analyse slope stability, achieving high accuracy in classifying slopes as stable, marginally stable, or unstable, as well as predicting the factor of safety (FOS). To assess geotechnical reliability of hypothetical slopes with drained and undrained soil conditions, Nguyen et al. combined finite element limit analysis with random field copulas which evident that copula selection results in significant variations in slope failure probabilities (Nguyen et al., 2022). Probabilistic analysis of passive trapdoors in c-ϕ soil, is carried out by Nguyen et al. considering multivariate cross-correlated random fields and their effect on the failure behaviour and design failure probability (Nguyen et al., 2023). A study on the undrained stability of braced excavations in clay, is carried out by focusing on the probabilistic analysis using random adaptive finite element limit analysis (RAFELA) and Monte Carlo simulations and concludes that considering the spatial variability of soil strength can significantly affect the probability of design failure for braced excavations (Tanapalungkorn et al., 2023). A timeline diagram of slope stability analysis methods and development is prepared in Figure 3 to help visualize the study quickly.

6. IMPLICATIONS AND RECOMMENDATIONS FOR SLOPE DESIGN AND MANAGEMENT & CHALLENGES OF THE EXISTING RESEARCH

Deformation of slopes due to rainfall and earthquake can effectively be avoided and mitigated by implementing certain recommendations and implications that are discovered through comparison and findings. These recommendations and implications cover a wide range of areas such as identifying crucial parameters and scenarios, choosing adequate models and methods, and evaluating the slope's overall performance and vulnerability. It's vital to take these into consideration when deciding how to manage and design slopes. With proper implementation of these measures and strategies, slope damage can clearly be minimized. Several studies have drawn and proposed implications and recommendations for slope design and management based on their analysis results and conclusions. For example, stability analysis of slopes under precipitation and earthquakes should consider the effects of precipitation infiltration, seismic inertia and pore pressure dissipation, and that slope design should consider the combined effects of precipitation and earthquakes rather than the individual effects of each factor (Jian et al., 2020). It is recommended that dynamic analysis rather than quasi-static analysis should be used for slope stability analysis under the coupling effect of precipitation and earthquakes, and slope management should focus on the slope foot that is prone to instability (Khan & Wang, 2023).

One of the limitations and challenges of existing research is the lack of comprehensive data and validation, which may affect the accuracy and reliability of slope deformation analysis during rainfall and earthquakes. Data and validation are critical for the calibration and validation of methods and models and for the evaluation and comparison of results and conclusions. However, data and validation are often sparse, incomplete or inconsistent due to the difficulties and uncertainties in measuring, monitoring and interpreting slope parameters and loading conditions, particularly under the coupled effects of rainfall and earthquakes. Many studies have proposed techniques and strategies to reduce complexity and improve the performance of models and algorithms, using different methods and theories such as, the Latin hypercube sampling technique and the response surface method were used to simplify and accelerate their reliability analysis and the Newmark sliding block model for slope stability evaluation under rainfall and landslides. Sample size and computational costs were reduced, while maintaining the precision and accuracy of the results. Adaptive Metropolis algorithm and parallel computing techniques used in the Markov chain Monte Carlo method to optimize and accelerate their Bayesian inference and estimate the slope risk in landslide and rainfall. A final limitation and challenge of existing research is the integration and communication of results and recommendations, which may affect the usefulness and utility of slope deformation analysis under rainfall and landslides. Integrating and communicating the results and recommendations have been suggested by a number of studies, with various methodologies and tools being employed. Various researcher used finite element model as well as Newmark sliding block model to introduce the reliability-based design approach for slopes subjected to rainfall and earthquake. The researchers superimposed the probability failure curves on the slope displacement graphs under different scenarios and issued a set of slope design charts and tables. In addition, various researcher tried to developed the risk-based management plan for slopes that are affected by both rainfall and earthquake using their finite element mode along with the risk analysis framework. They presented expected loss information as well as probability of occurrence details on different slopes under given conditions, also they recommended mitigations measures in order to safeguard slope risks.

7. CRITICAL CONCLUSIONS & RECOMMENDATIONS

In conclusion, the comprehensive analysis of slope stability deformation subjected to both rainfall and earthquake loading has provided valuable insights into the slope stability. The study integrated geotechnical and seismic data to assess the dynamic response of slopes, revealing nuanced interactions between these two influential factors. The findings reveal significance of considering both rainfall and earthquake in slope stability assessments, particularly in regions prone to these environmental challenges. Among all the factors that cause or worsen slope deformations, the rainfall and earthquake are the most influential ones. When these two events combined together, they will greatly lower the stability and safety of slopes. Slope deformation analysis under joint rainfall and earthquake is a tough job due to various issues such as rain intensity and duration, magnitude and frequency of an earthquake, soil properties and structure, initial and final boundary conditions. This review article critically highlights the salient works on rainfall-induced and seismic slope stability analyses, along with their sequential evolution of the research area and its future scope. The research's underscore the intricate interplay between rainfall and earthquakes on slope stability, revealing that the simultaneous occurrence of these two factors significantly exacerbates vulnerable slope deformations. It highlights the necessity for a holistic approach to assessing slope stability in vulnerable areas, considering the dynamic nature of these environmental influences. The paper also charts the progression of research in this domain and suggests future explorations into advanced predictive models using robust optimization and machine learning techniques along with developing early warning system as well as developing real time monitoring system.

Infiltration of rainwater reduces shear strength, increases slope failure risk, and causes groundwater to rise. Various Studies shows rainfall intensity, duration, soil properties, and slope angles significantly contribute to slope stability. Slopes saturate rapidly under high rainfall intensity, decreasing safety factors and increasing damage risk. Natural frequencies close to seismic wave frequencies exhibit resonance. Resonance can cause ground shaking, potentially leading to liquefaction in loose and water-saturated soils which result slope failure. Rainfall following seismic activity reduces seepage velocity, increasing slope stability over time by decreasing pore water pressure, as observed in the several studies on clay slopes. Deformations caused by earthquakes can result in brittle fractures and shear failures, which differ from deformations caused by rain, which weaken soil strength gradually, which facilitates deformation. Due to increased pore water pressure, clay-rich slopes are more vulnerable to rainfall-induced landslides. Coarse-grained slopes are more vulnerable to earthquake-induced liquefaction. The structural geology characteristics of a slope such as bedding planes, influence seismic response and progressive failure under earthquakes. In studies like those conducted in Kavalappara, India, or in volcanic soils in Japan, dual hazards such as earthquakes and rainfall are commonly seen together. Real-time monitoring of data is very necessary to predict slope stability. Anti-slide piles and anchor bolts are effective to enhance slope stability. The combination of time response analysis and traditional methods like pseudo static analysis can provide a comprehensive understanding of slope failure during an earthquake.

In this study, some important critical findings were discovered:

1. Researchers have used deterministic and probabilistic approaches for analysing the simultaneous effects of Rainfall and Earthquake on slope stability. More research has been conducted in the past few decades using deterministic approaches, but recent research has shifted to a probabilistic approach. Since slope stability is a complex phenomenon, probabilistic methods are more applicable here since they can quantitatively describe any scenario where slopes can deform and result in substantial consequences. The development and application of probabilistic methods for slope deformation analysis under rainfall and earthquakes have accrued a lot of attention in recent years.
2. The majority of studies consider rainfall and earthquake effects separately in slope stability analyses. While in practice, it is not uncommon for earthquakes and rain to occur simultaneously. Only a few literatures have considered both influencing factors together. Future research should consider two factors simultaneously to simulate actual practical conditions.
3. In the last few decades, more research has been conducted on slope stability based primarily on FOS, but the actual deformation behaviour of soil has been neglected. Recent studies have changed that trend and emphasized deformation studies as well. It would be beneficial to conduct more research on slope deformation analysis.
4. In addition to advancing knowledge in this field, there is a need of practical implications for designing effective slope management and mitigation strategies in areas susceptible to heavy rainfall and seismic events, which will ultimately contributing to enhanced resilience in geotechnical engineering practices. The future scope involves refining predictive models and developing real-time monitoring systems for enhanced assessment and management of slope deformation under combined influences of rainfall and earthquakes.

Some important recommendations were suggested as follows:

1. Integration of coupling effects of rainfall precipitation and seismic activity in slope stability assessments is very necessary, especially in regions prone to these environmental challenges. Slopes should be design by considering the combined effects of rainfall and earthquakes, rather than evaluating each factor in isolation.
2. Selection of materials and construction techniques are such that they can act as partial resilient to the effects of both water infiltration and seismic activity. This may include the use of geosynthetics, proper compaction, and the selection of appropriate vegetation for bioengineering solutions. Similarly, by Implementation of effective drainage systems to manage surface water and groundwater flow, reducing pore water pressure and the risk of slope failure.
3. Installation of monitoring systems will be helpful which can provide real-time data on slope conditions, allowing for early detection of potential failures and timely interventions.

Some limitations of this research area were mentioned as follows:

1. Reliable field data on soil properties, rainfall patterns, and seismic activity is essential for accurate analysis. However, such data may be scarce or incomplete, especially in remote areas.
2. Most models are developed for specific scales and may not be applicable to all kind of slope. This can limit the generalizability of the results.

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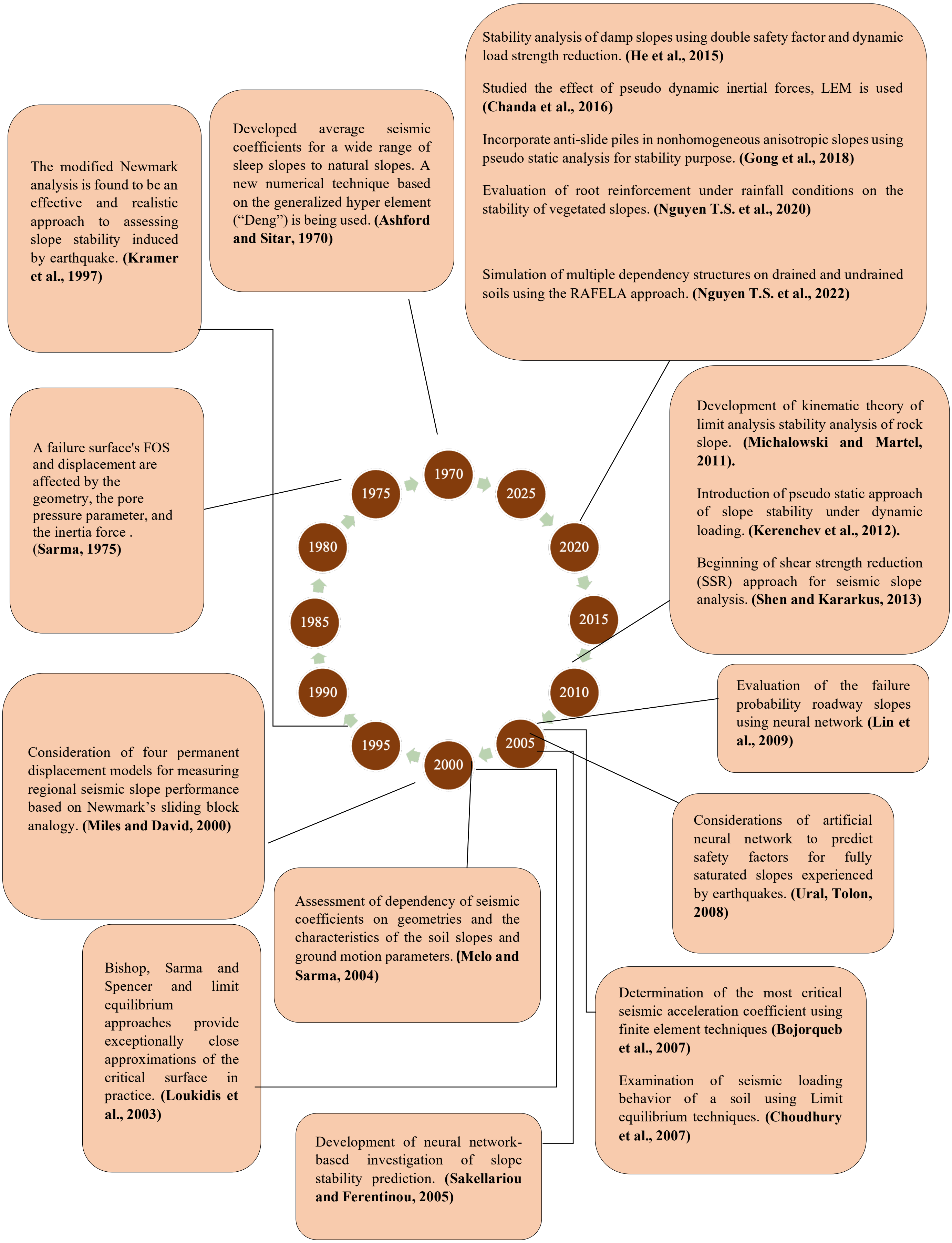
9. CONFLICTS OF INTEREST/COMPETING INTERESTS

The author(s) declare that there is no conflict of interest.

10. DATA AVAILABILITY STATEMENT

All data, models, and code generated or used during the study appear in the submitted article.



Stability analysis of damp slopes using double safety factor and dynamic load strength reduction. **(He et al., 2015)**

Studied the effect of pseudo dynamic inertial forces, LEM is used **(Chanda et al., 2016)**

Incorporate anti-slide piles in nonhomogeneous anisotropic slopes using pseudo static analysis for stability purpose. **(Gong et al., 2018)**

Evaluation of root reinforcement under rainfall conditions on the stability of vegetated slopes. **(Nguyen T.S. et al., 2020)**

Simulation of multiple dependency structures on drained and undrained soils using the RAFELA approach. **(Nguyen T.S. et al., 2022)**

The modified Newmark analysis is found to be an effective and realistic approach to assessing slope stability induced by earthquake. **(Kramer et al., 1997)**

Developed average seismic coefficients for a wide range of sleep slopes to natural slopes. A new numerical technique based on the generalized hyper element ("Deng") is being used. **(Ashford and Sitar, 1970)**

A failure surface's FOS and displacement are affected by the geometry, the pore pressure parameter, and the inertia force . **(Sarma, 1975)**

Development of kinematic theory of limit analysis stability analysis of rock slope. **(Michalowski and Martel, 2011).**

Introduction of pseudo static approach of slope stability under dynamic loading. **(Kerenchev et al., 2012).**

Beginning of shear strength reduction (SSR) approach for seismic slope analysis. **(Shen and Kararkus, 2013)**

Evaluation of the failure probability roadway slopes using neural network **(Lin et al., 2009)**

Consideration of four permanent displacement models for measuring regional seismic slope performance based on Newmark's sliding block analogy. **(Miles and David, 2000)**

Considerations of artificial neural network to predict safety factors for fully saturated slopes experienced by earthquakes. **(Ural, Tolon, 2008)**

Assessment of dependency of seismic coefficients on geometries and the characteristics of the soil slopes and ground motion parameters. **(Melo and Sarma, 2004)**

Bishop, Sarma and Spencer and limit equilibrium approaches provide exceptionally close approximations of the critical surface in practice. **(Loukidis et al., 2003)**

Determination of the most critical seismic acceleration coefficient using finite element techniques **(Bojorqueb et al., 2007)**

Examination of seismic loading behavior of a soil using Limit equilibrium techniques. **(Choudhury et al., 2007)**

Development of neural network-based investigation of slope stability prediction. **(Sakellariou and Ferentinou, 2005)**

Figure 3 Development of slope stability analysis research for last few decades

Table 2 Summary table of some important existing literature on slope stability analysis subjected to Rain & Earthquakes

Authors	Category of Approaches	Methods Used	Key Parameters Used	Key summary	Limitation
Likitlersuang et al., 2019	Deterministic	Limit equilibrium methods & Centrifuge modelling	Hydraulic conductivity, Rooting depth, Rainfall intensity, Pore water pressure	Centrifuge tests showed that the existence of root fibres increases soil strength and reduces rainfall infiltration rate, leading to delayed slope failure.	The study focused on the effects of vegetation roots on slope stability under specific conditions, limiting the generalizability of the findings.
Nguyen et al., 2019	Probabilistic	Random finite element method.	Soil water characteristic curve parameters, Saturated hydraulic conductivity, effective friction angle.	The random field of the effective friction angle is the most important parameter for probabilistic stability analysis in unsaturated soil slope stability.	Focuses on the effect of spatial variability of soil properties on slope stability during rainfall infiltration but not earthquake effects.
Rosly et al., 2023	Deterministic	Limit equilibrium method.	Rainfall intensity. coefficient of volume compressibility, Hydraulic conductivity.	The FOS of the slope model decreased by around 27 to 33% after 24 hours of rainfall, but increased by around 3% after 48 hours.	The study did not consider the long-term assessment of rainfall on slope stability beyond 72 hours.
Nanda et al., 2023	Probabilistic	Random Forest (RF) and Logistic Regression (LR).	Rainfall, antecedent rainfall, Distance to road, river, fault.	Logistic Regression model outperformed Random Forest model for landslide prediction.	Logistic Regression model showed better efficacy in landslide prediction, but there is always a margin for error in predictive models, emphasizing the need for continuous refinement and validation.
Hong-in et al., 2023	Deterministic	Finite element limit analysis (FELA).	Slope length ratio, depth factor, horizontal seismic acceleration coefficient. slope inclination.	Examined the impacts of horizontal seismic acceleration coefficient on the mechanisms of 3D slope failures based on FELA.	The research is based on pseudo-static seismic loading conditions, which may not fully capture the dynamic behaviour of slopes during actual seismic event.
Gharrawi & Husain, 2020	Probabilistic	Monte Carlo simulation combined with FEM	Soil properties such as unit weight, angle of internal friction, cohesion, seismic accelerations (vertical and horizontal) etc	Deterministic methods underestimate safety factors, highlighting the importance of probabilistic approaches for safe and economic slope design.	The study did not consider the potential impact of other factors beyond soil properties and seismic accelerations on slope stability analysis.
Ren et al., 2023	Deterministic	Shaking table tests, and FEM	Saturated permeability coefficient, residual moisture content, damping ratio, effective cohesion, friction angle, poisson's ratio, PGAH	During the earthquake, the slope deformed and liquefied at the sliding surface, ultimately causing slope damage.	The study did not consider the potential impact of vegetation cover or other slope stabilization measures.
Samm-A et al., 2023	Probabilistic	Monte-Carlo simulation, Direct estimation methods	Bulk density, cohesion, friction angle, hydraulic conductivity, Rainfall intensity, PGAH	With over 85% accuracy, Monte-Carlo simulations and direct estimation methods are used to compute factors of safety, which are validated against field investigation-based landslide inventories.	Limited consideration of uncertainties in soil physical property parameters

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