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Soil Suffusion under the Dual Threat of Rainfall and Seismic Vibration

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ABSTRACT

This paper employs the systematic literature review (SLR) methodology to investigate the combined effects of seismic vibrations and rainfall on soil suffusion, a process leading to soil instability. Earthquake activity can accelerate soil liquefaction, exacerbating suffusion, while heavy rainfall can increase soil weight, inducing instability. Consequently, the repercussions of seismic activity and rainfall on suffusion may induce further damage and instability to civil infrastructure. The review reveals that the compound impact of rainfall and seismic vibrations can precipitate severe damage and instability, primarily through two mechanisms. First, earthquakes can catalyze soil liquefaction, inciting soil movement and amplifying the suffusion process. Second, heavy rainfall can saturate the soil, augmenting its weight and rendering it unstable, thereby inducing suffusion. However, the review also reveals a significant gap in understanding and mitigating suffusion triggered by simultaneous rainfall and seismic activity. Current techniques for identifying and mitigating such suffusion are inadequate, highlighting the need for further research. This review posits that the interaction of rainfall and seismic vibrations as a catalyst for soil suffusion demands additional scrutiny. It provides a comprehensive understanding of suffusion and the impact of rainfall and seismic vibrations on suffusive soils, serving as a basis for future studies on this important issue.

1. INTRODUCTION

1.1 Interactions of suffusion with rainfall and seismic activity

Suffusion phenomenon observed in soils, is characterized by the displacement of soil particles catalyzed by increased pore water pressure [1, 2]. This process may precipitate soil erosion and sinkhole formation [3]. The interplay of rainfall and seismic activity significantly influences the suffusion dynamics within soils. Rainfall can exacerbate soil saturation and elevate pore water pressure, rendering the soil susceptible to liquefaction [4, 5].

Conversely, seismic waves may instigate soil particle displacement, thereby fostering instability [5-13]. The synergistic effects of these two factors can provoke substantial damage to structures and landscapes [14, 15]. Consequently, elucidating the impact of the concurrent events of rainfall and seismic activity on soil suffusion is paramount, given its implications on engineering practices, construction protocols, and natural hazard planning.

1.2 Suffusion as a mechanism of internal erosion

Internal erosion, a common occurrence in embankment cores or dam foundations, has been implicated in numerous embankment dam failures globally [16]. This erosion encompasses four distinct mechanisms: suffusion, backward erosion, contact erosion, and concentrated leak erosion [2-4]. Suffusion, a critical mechanism of internal erosion, induces selective erosion and the gradual displacement of fine soil particles through the gaps formed by coarser particles during seepage flow [5, 6] as depicted in Figure 1. This process can provoke erosion and instability in sloped surfaces and foundations, rendering it an essential consideration within construction and earthwork projects [4, 7].

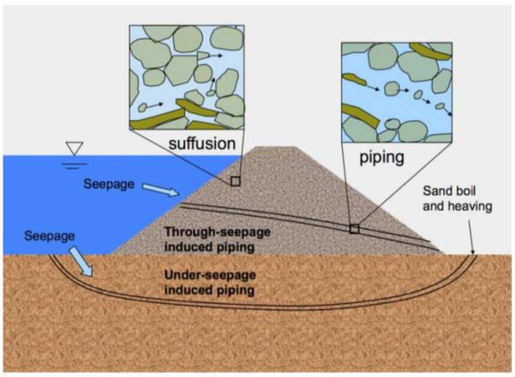

Figure 1. Schematic diagram of suffusion

Hydraulic structures including dams, dikes, levees, and landslide dams constructed from soils exhibiting significant particle size disparities are particularly vulnerable to suffusion-induced degradation and failure. These structures bear substantial loads and often experience horizontal seepage flow through the soil mass, both of which enhance the risk of suffusion-related complications [1, 4, 8-16].

Moreover, the hydraulic properties of soils prone to suffusion may alter in response to the erosion and repositioning of minuscule soil particles [2, 17-19]. Consequently, suffusion poses a significant threat to hydraulic geo-structures built from gap-graded cohesionless soils, potentially leading to their degradation or catastrophic failure [1, 17, 20-22]. Many researchers have been particularly interested in the proliferation of gap-graded cohesionless soils such as [2, 20, 23-26].

2. BACKGROUND

2.1 Suffusion in sandy gravel and its deviation from conventional hypothesis

In sandy gravel, Skempton and Brogan [24] discovered that the failure hydraulic gradient of suffusion was much lower than that predicted by the conventional hypothesis. The soil structure, composed of larger gravel particles, bears the majority of the overburden weight, while the smaller sand particles play a lesser role in transmitting loads. Numerous studies examining suffusion have already been conducted by a multitude of researchers. The experiments revealed that soil particle size distribution was one of the factors influencing suffusion features [20, 25-30] seepage flow direction [31, 32], hydraulic gradient [14, 33-36], fines content (FC, i.e., the mass ratio of fine particles to total weight of the soil specimen; [2, 17, 37-39] and others, hydraulic loading history [29, 40].

2.2 Importance of considering rainfall and seismic activity in structural design and natural hazards

The combined effect of rainfall and seismic waves on suffusion of soil can lead to increased soil instability and erosion. Rainfall can cause soil saturation and increase the pore water pressure in the soil, making it more prone to liquefaction and erosion [4, 5]. Seismic waves can cause soil particle displacement, leading to soil compaction and further instability. The interaction of these two factors can cause significant damage to structures built on the soil and to the surrounding terrain. The illustration of factor of suffusion is shown in Figure 2.

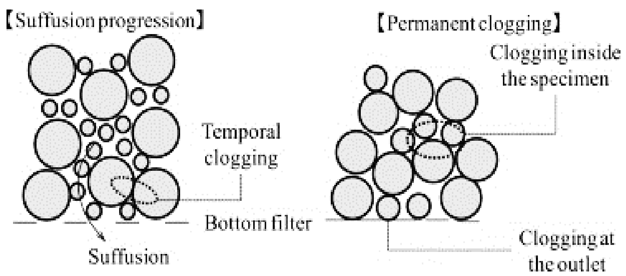

Figure 2. Illustration of factor of suffusion [32]

It is therefore important to consider the potential impact of combined rainfall and seismic activity when designing structures and planning for natural hazards. This requires an understanding of the mechanics of suffusion and the ways in which rainfall and seismic activity can affect soil stability. In this context, researfch and analysis of the effects of combined rainfall and seismic activity on suffusion of soil can inform engineering and construction practices and natural hazard planning, helping to minimize potential damage and risk to life and property.

2.3 Stress impact on suffusion behavior and seepage orientation

The majority of these investigations conducted vertical seepage flow tests without taking into account external tension. The soil in hydraulic geo-structures is constantly under pressure from the weight above it, and water often seeps through it horizontally. Stress impact on suffusion behaviour has recently drawn increasing attention [3, 19, 29, 36, 41-46]. Experimental studies revealed that stress states had a substantial impact on the hydraulic gradients of initiation and failure [47, 48]. It should be emphasized that the seepage orientation in the majority of these tests was still vertical, which differs significantly from engineering practice. According to Richards and Reddy [49], Pachideh and Majdeddin [50], and Salehi Sadaghiani and Witt [51], the direction of seepage flow had a substantial impact on the suffusion behaviour. Landslides that are caused by earthquakes have been researched as a significant class of geological disasters in seismic zones [45-49]. However, numerous field investigations on earthquake damage reveal that, rather than being caused by just seismic load, slope instability is a result of a sequence of ripple effects generated by earthquakes [50-53]. The rainfall brought on by earthquakes has occasionally been recorded to cause slope instability. Following the 1999 Taiwan earthquake, the extent of landslides due to heavy rains grew to three times the amount of landslides directly resulting from the earthquake [14]. Following the 2008 Wenchuan Earthquake, the high seismic intensity region of Beichuan experienced the heaviest rainfall, amounting to 250–350 mm, which triggered more landslide activity and a significant number of new landslides [54, 55].

To investigate the dynamic response and failure features of slopes, theoretical analysis has been done by several researchers [56-59]. Although slope stability assessment theories are developing, the mechanism of slope instability under complicated external stresses is still unclear. To examine the causes and failure mechanisms of landslides as well as to discuss the stage failure features of slopes under shaking table conditions, shaking table model tests were carried out [60-62]. Slope stability is particularly vulnerable to the demanding danger of seismic activity and the ensuing rainfall. The aftermath of an earthquake can have an impact on precipitation due to the altered stress levels and fault lines [63-67]. The seismic shockwave from the earthquake also contributes by releasing energy into the air, leading to air vibrations and an increase in condensation particles. This, combined with potential landslides, can result in a higher concentration of dust and particles in the air, which act as seeds for water droplets to form [68-70]. Over time, these collisions between water vapor molecules can lead to heavy rainfall [71, 72]. Following the Kobe earthquake in Japan on January 17, 1995, rainfall caused numerous small-scale landslides from May through October [73].

2.4 Challenges in numerical simulation and pore pressure development

Another major factor that causes slope instability is heavy rain [65-67]. Landslides occur when rainwater infiltrates the ground, causing the water table to rise and weakening the rock and soil in the slope [74-76]. This process, known as the transition from unsaturated to saturate soil, results in changes to the physical and mechanical properties of the slope and reduces its stability. This change is crucial for maintaining the stability of the slope [77-82]. The study by Chen et al. [83] is a specific research that evaluates the stability of a slope subjected to the combined effects of seismic activity and subsequent rainfall. The study likely includes the following aspects: analysis of the effects of seismic activity on the soil and the potential for liquefaction, evaluation of the impact of subsequent rainfall on the stability of the slope, taking into account factors such as saturation and erosion, analysis of the combined effects of seismic activity and subsequent rainfall on the stability of the slope, use of numerical modeling and/or physical experiments to simulate the conditions of the slope, propose stability assessment methods that take into account the combined effects of seismic activity and subsequent rainfall. It is important to note that this is a specific study, and the findings may not be generalizable to all soil types, conditions, or slopes. It is always recommended to conduct a site specific investigation and analysis of the area to find the best solution.

Iwata et al. [84] and Huang and Xiong [85] studied a large number of real-world slope instability cases with the help of numerical simulation, but the accuracy of the calculations is typically severely constrained by the lack of information regarding the development of the pore pressure, particularly the dynamic pore water pressure brought on by earthquakes. The aim of this study is to provide an overview of the research into the characteristics of suffusion, which is a type of horizontal seepage, in gap-graded cohesionless soils that are subjected to controlled vertical stress [86]. In addition, the aim of this study is to deliver a literature review in order to make it easy for researchers to study suffusion of soil, its impacts due to earthquakes and rainfall, solving approaches and prevention and mitigation procedures.

3. OBJECTIVE OF THE STUDY

The main purpose of this paper is to provide a comprehensive, in-depth and clear understanding through a review of the internal instability, i.e., suffusion of the soil, and the effects of rainfall and seismic vibrations on suffusion and to summarize the key findings of the previous research and studies. The paper also highlights the significance of the topic and the importance of understanding the effects of combined rainfall and seismic vibration on internal erosion and provides recommendations for the future research. The findings of this review have implications for engineering and construction practices, natural hazard planning, and the design built on slopes. On the basis of this review paper, a future research gap has been analyzed on the topic suffusion of soil incorporated with soil-structure interaction in the moderate seismic region.

4. MECHANISM OF SUFFUSION

4.1 Internal erosion (suffusion)

Internal erosion, also known as suffusion, is a type of soil erosion that occurs when water infiltrates into the soil and causes the soil particles to be carried away, leading to voids and cavities within the soil [22, 87-89] which is illustrated in Figure 3. This type of erosion is often associated with combined rainfall and seismic vibrations, which can cause the soil to become saturated and increase the water pressure within the soil [83]. The water pressure causes soil particles to be dislodged and carried away, leading to the formation of voids and cavities within the soil [90-92]. Over time, these voids and cavities can grow and cause the soil to become unstable, leading to the failure of soils and the structures on soil [18, 67, 73].

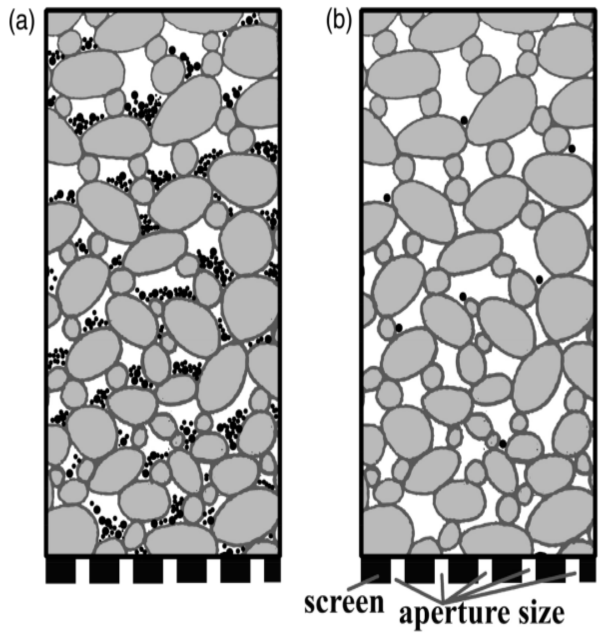

Figure 3. An illustration of the formation of an internal filter during the washout of soil particles is depicted in two stages: (a) before the flow of water and (b) after the flow of water. In the illustration, the gray particles represent the main soil structure and the black dots represent the finest particles [87]

4.2 Illustration of suffusion mechanisms

The exact mechanisms of suffusion are complex and depend on various factors such as the type of soil, the intensity and frequency of rainfall and seismic vibrations, the water content of the soil, and the soil structure [29, 37, 74, 75]. In general, suffusion occurs as a result of the combined effects of rainfall and seismic vibrations, which can cause changes in the water pressure within the soil, leading to the displacement and movement of soil particles [67, 70].

The key mechanisms of suffusion shown in Figure 4 has been summarized as follows:

i. Infiltration of water into the soil: Rainfall can cause water to infiltrate into the soil, leading to an increase in the water content of the soil [67, 76].
ii. Saturation of the soil: When the soil becomes saturated, the water pressure within the soil increases, leading to changes in the water content of the soil [15, 44].
iii. Displacement and movement of soil particles: The increased water pressure can cause soil particles to be dislodged and carried away, leading to the formation of voids and cavities within the soil shown in Figure 5 [59, 92-94].
iv. Formation of voids and cavities: The displacement of soil particles can lead to the formation of voids and cavities within the soil, which can cause the soil to become unstable [21, 93, 94].

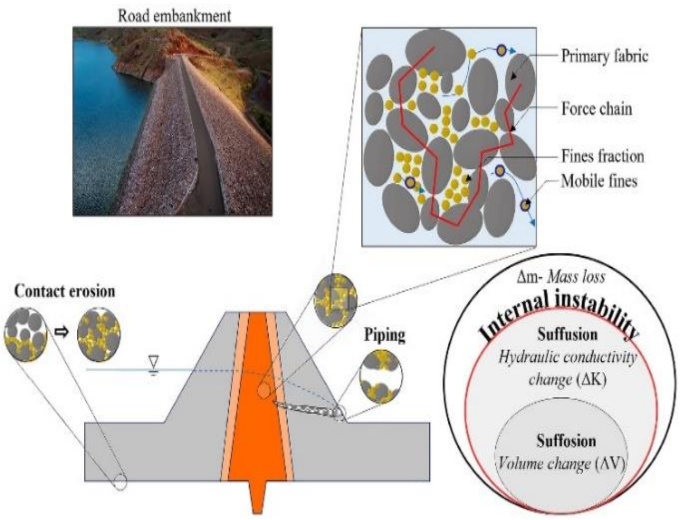

Figure 4. An illustration of internal instability and potential internal erosion mechanisms [90]

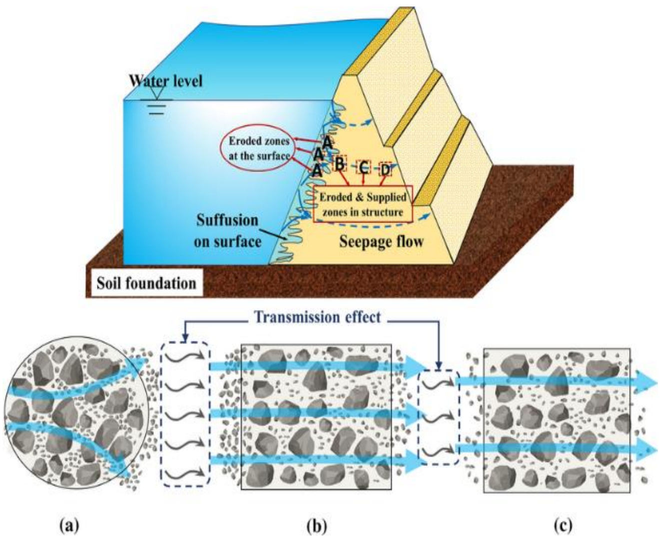

Figure 5. Schematic diagram of the transmission effect of suffusion: (a) Zone A on the fluid-solid surface (multidirection of fines transport); (b) Zone B; (c) Zone C (fewer eroded fines than Zone B due to reduction in hydraulic gradient) [94]

4.3 Factors inflencing suffusion

The rate and extent of suffusion in soil is influenced by several factors, including soil texture, porosity, permeability, and the presence of organic matter and other materials that can affect water movement. Understanding these factors and how they influence suffusion is important for soil conservation, for the management of land for agriculture, forestry, and other uses, and for the understanding of hydrologic processes in the subsurface [95-97]. Based on the above review, mechanism of suffusion involves the flow of water from areas of high water potential to areas of low water potential through the soil matrix. The water potential is determined by both water pressure and the presence of solutes, such as salts, that can create osmotic gradients. Water moves through the soil by diffusing through the soil pores and filling up the spaces between soil particles. As water moves into the soil, it displaces the air, which can cause soil compaction and decreased permeability. Over time, repeated suffusion can lead to the formation of larger pores and the development of a soil structure that is more conducive to water flow.

5. RAINFALL AND SEISMIC VIBRATION

5.1 Rainfall: Impact on soil saturation and erosion

Rainfall can cause soil saturation, which increases the pore water pressure and makes the soil more susceptible to liquefaction. When soil is saturated, the water can seep into the soil pores and increase the pore water pressure, reducing the effective stress on the soil particles. This can result in soil particle displacement and erosion, particularly if the soil has a low shear strength [70, 78-80]. Rainfall can also increase the risk of soil erosion through the action of runoff and water flow, which can cause soil particles to be carried away by the water [97].

5.2 Seismic vibration: Soil particle displacement and compaction

Seismic vibration can cause soil particle displacement and compaction, leading to soil instability. Seismic waves can produce vibrations that result in soil particle movement, which can cause soil compaction and a reduction in porosity [98]. This can result in increased soil density, reduced permeability, and reduced soil shear strength [49]. Seismic waves can also cause soil liquefaction, which can result in soil particle displacement and instability [99]. When seismic waves interact with soil, they can cause soil particles to move relative to one another, which can cause soil compaction and a reduction in soil permeability [100].

5.3 Combined effects: Increased soil instability and erosion

The combined effects of rainfall and seismic vibration on suffusion can result in increased soil instability and erosion. Rainfall can cause soil saturation and increase the pore water pressure in the soil, making it more prone to liquefaction and erosion [83]. Seismic waves can cause soil particle displacement, leading to soil compaction and further instability [101-103]. The interaction of these two factors can cause significant damage to structures built on the soil and to the surrounding terrain [102-108].

It is important to consider the potential impact of combined rainfall and seismic activity when designing structures and planning for natural hazards [102, 104-106]. This requires an understanding of the mechanics of suffusion and the ways in which rainfall and seismic activity can affect soil stability [67, 70, 86]. In this context, research and analysis of the effects of combined rainfall and seismic activity on suffusion of soil can inform engineering and construction practices and natural hazard planning, helping to minimize potential damage and risk to life and property [100].

6. METHODS OF FINDING SUFFUSION

This review is discussing the use of numerical models to study seepage flow through embankments, dikes, and soil foundations. It states that numerical models have proven to be effective in this regard and can be used to assess the internal stability of soils with a specific grain size distribution (GSD) [106, 109-115]. It is also noted that the effectiveness of the numerical model in this regard depends on the use of an appropriate model for particle mobility within the soil matrix. It has proven effective to use numerical models to examine seepage flow via embankments, dikes, and soil foundations. Numerical models may be able to assess the internal stability of soils with a specific GSD if an appropriate model for particle mobility within the soil matrix is used [23, 33, 37, 91, 92].

The various numerical and experimental studies [4, 8, 15, 31, 39, 44, 79, 95-97, 98-101] that have been conducted in order to understand the mechanisms behind suffusion. It notes that most of these studies have been macroscopic in nature and operate under the assumption that soil movement is a continuous process. However, more recent granular system studies (such as those using Discrete Element Method (DEM) models and computational fluid dynamics, CFD+DEM models) have begun to demonstrate the ability to support this notion. The passage also notes that these studies have provided detailed information about the suspension, collision, and spin of particles, but they still appear to be unrelated to internal structure fracture or large movement (based on regime transition study). Despite this, macroscopic research on suffusion remains popular, particularly when focusing on engineering procedures.

Studies aimed at understanding suffusion, the movement of soil through porous materials, have been conducted through numerical simulations (CFD) and experiments [24, 91-93]. The majority of these studies were macroscopic and based on the assumption that soil movement is a continuous process, which has yet to be proven through particle-level investigation. However, later granular system studies using DEM models [96, 97] and CFD+DEM models [116] have demonstrated the ability to support this idea by characterizing particle suspension, collision, and spin. Despite this, the relationship between particle behavior and the larger-scale movement and internal structure fracture of soil remains unclear [117]. Nevertheless, macroscopic research on suffusion remains a widely studied area, particularly in the context of engineering procedures [7, 94-99, 118].

7. MITIGATION AND PREVENTION

Preventing and mitigating internal erosion, also known as suffusion, is an important aspect of geotechnical engineering, particularly in areas prone to natural hazards such as earthquakes and heavy rainfall. There are several strategies and techniques used to prevent and mitigate internal erosion, including: soil stabilization and reinforcement, design of drainage systems, geotechnical engineering techniques, site assessment and monitoring, stabilization of slopes, vegetation management and design of cut and fill slopes and so on.

One approach is the use of geotechnical engineering techniques to stabilize and reinforce soil. This can be achieved through the use of geosynthetics and geotextiles, such as geogrids and geocomposites, which provide additional tensile strength and stability to soil [119]. Geosynthetic-reinforced soil walls can also be used to stabilize slopes and prevent internal erosion [120-124]. Another approach is the design and implementation of effective drainage systems. This can help to reduce the buildup of water pressure within soil, which can contribute to internal erosion. The use of drain pipes, permeable geosynthetic materials, and other drainage solutions can help to improve soil stability and prevent internal erosion [87, 101, 113, 117].

In addition to these geotechnical engineering techniques, vegetation management can also play a role in preventing internal erosion. Proper vegetation cover can help to reduce runoff and improve soil stability, while vegetation conservation practices can help to promote infiltration and reduce erosion. The design of cut and fill slopes can also play a role in preventing internal erosion. Proper grading and the implementation of effective erosion control measures, such as retaining walls, can help to stabilize slopes and prevent internal erosion [87, 102-106].

In conclusion, the combined effects of rainfall and seismic vibrations on internal erosion can be prevented and mitigated through the use of geotechnical engineering techniques, such as soil stabilization and reinforcement, and the design of effective drainage systems. Proper vegetation management and the design of cut and fill slopes can also play a role in preventing internal erosion.

8. CASE STUDIES

These are the few case studies stated in Table 1 that have been conducted by the researchers on the combined effects of rainfall and seismic vibration on suffusion of soil. They highlight the importance of considering the potential impact of combined rainfall and seismic activity in the design of structures and natural hazard planning, and the need for further research to better understand the mechanisms of suffusion and the ways in which rainfall and seismic activity can affect soil stability. These studies demonstrate the need for further research on the combined effects of rainfall and seismic vibration on suffusion of soil, and highlight the importance of considering these factors in the design and planning of structures in areas prone to natural hazards.

8.1 Summary of case studies

The studies summarized in Table 1 examined the combined effects of rainfall and seismic loadings on slope stability, soil erosion, suffusion, and soil instability. The findings indicated that the combination of seepage and moisture content increased the likelihood of soil instability and liquefaction. Factors such as soil friction angle, hydraulic gradient, and fines content influenced slope stability, while suffusion led to decreased soil strength. Post-earthquake rainfall intensified landslide vulnerability, and fines migration had both positive and negative impacts on slope stability. These studies emphasize the importance of considering multiple factors and their interactions when assessing the stability and behavior of slopes under rainfall and seismic conditions.

Table 1. Case studies on combined effects of rainfall and seismic loadings

S.no.	Author and Year	Research Contribution	Methodology	Results
1	Develioglu and Pulat [124]	Experimental study on suffusion under multiple seepages and its impact on undrained mechanical responses of gap-graded soil	This study used experimental setup to investigate the multiple seepage induced suffusion and effects of mechanical responses of unstable soil.	The results highlighted that the seepage and moisture content increased the likelihood of soil instability and liquefaction, compared to either factor alone.
2	Avesani Neto et al. [125]	Numerical modelling of interactions of rainfall and earthquakes on slope stability analysis	This study used numerical modeling to investigate the effects of rainfall on soil erosion and slope stability during earthquakes.	The numerical analysis results show that under similar slope conditions, soil friction angle has a stronger impact on slope stability compared to soil cohesion. The observed failure surface for biaxial seismic shaking differs from that observed for uniaxial seismic shaking. The effects of multi-axial seismic shaking must be taken into account when analysing the slope's failure mode. Seismic shaking after rainwater infiltration leads to a low factor of safety and changes the slope's failure mode. The factor of safety steadily decreased with the biaxial seismic shaking and post-rainwater infiltration seismic shaking of the slope.
3	Chen et al. [83]	Stability evaluation of slope subjected to seismic effect combined with consequent rainfall	This study used numerical modelling to investigate the effects of seepage on suffusion.	The results showed that the combination of rainfall and seismic vibration increased the likelihood of soil instability and liquefaction, compared to either factor alone.
4	Cao et al. [99]	Dynamic response and dynamic failure mode of the slope subjected to earthquake and rainfall	This study used experimental setup to investigate the impact of seismic vibration and rainfall on soil stability by using the shaking table and the mechanism of suffusion.	The results showed that the combination of rainfall and seismic vibration increased the likelihood of soil instability and cracking shearing slippage and cracking shearing crushing.
5	Ke and Takahashi [53]	Experimental investigations on suffusion characteristics and its mechanical consequences on saturated cohesionless soil	This study used experimental setup to investigate the impact of moisture content on suffusion of saturated cohesionless soil and the mechanism of suffusion.	The test outcomes showed that as suffusion progresses, the hydraulic gradient decreases and hydraulic conductivity improves. Significant amounts of fines are eroded and result in contractive volumetric strain. Greater effective confining pressure leads to a smaller extent of suffusion. With a higher initial fines content, more fines are eroded. The monotonic compression tests indicate that suffusion causes a decrease in soil strength during the major stage of drained shearing.
6	Ogbobe et al. [126]	Post-earthquake rainfall-triggered slope stability analysis in the Lushan area	This study used the SINMAP model, the discrete element method based model and the GIS platform in order to investigate the soil instability, which leads to slope failures.	The findings offered a fresh perspective on the spatial spread and attributes of landslides caused by post-earthquake rainfall in the region. A rise in rainfall intensity leads to a substantial rise in the area that is vulnerable to instability.
7	Mandloi et al. [127]	Numerical investigation of rainfall-induced fines migration and its influences on slope stability	This study used numerical modelling to investigate the intrinsic mechanisms of slope failures by using the finite element method.	The findings indicate that the migration of fines can lead to both positive and negative outcomes, depending on whether they escape or get trapped in narrow pores. It is recommended that more focus should be given to slopes prone to internal erosion as their stability assessment cannot be accurately determined using conventional techniques.

9. DISCUSSION AND CONCLUSION

The systematic literature review provides valuable insights into the phenomenon of internal erosion, specifically suffusion, in the context of combined rainfall and seismic vibrations. The findings highlight the significant impact of earthquakes and rainfall on soil instability and the potential for suffusion. It is evident that geophysical techniques can aid in understanding internal soil instability, while earthquakes can lead to soil liquefaction and exacerbate suffusion. This review emphasizes the long-term nature of suffusion, occurring over decades, and the potential for structural collapse during earthquakes. The study also underscores the importance of crack formation, tension stress, and pore water pressure in slope instability. The findings of this review underscore the need for comprehensive considerations and measures when designing and constructing infrastructure in vulnerable areas, taking into account the complex interactions between earthquakes and rainfall.

9.1 Key findings

From the systematic literature review, following points have been understood which are listed below:

i. Internal erosion, also known as suffusion, is a significant issue that can occur when soil is subjected to combined rainfall and seismic vibrations.
ii. Geophysical techniques such as electrical resistivity tomography, vertical electrical sounding can be applied in order to understand the internal instability of soil.
iii. Earthquakes can cause soil liquefaction, which occurs when soil loses its strength and stiffness and behaves like a liquid. This can lead to soil movement and instability, and can exacerbate suffusion.
iv. Rainfall can also have an impact on suffusion as it can increase the amount of water present in the soil, making it more susceptible to movement. Heavy or prolonged rainfall can saturate the soil and increase the weight on the soil, which can cause it to become unstable and lead to suffusion. Additionally, rainfall can also cause erosion, which can further weaken slopes and increase the risk of suffusion. In summary, earthquakes and rainfall can both contribute to soil movement and instability, and can exacerbate suffusion, which can lead to erosion and other issues in slopes and foundations.
v. Increase in rainfall, increases the moisture content of soil, which increases the hydraulic head in soil slopes, hence results the transportation of finer particles with the seepage flow.
vi. Due to seepage, the fine particles flow with the water and create voids in the soil which is said to be the suffusion. This suffusion is a long term process which takes decades to occur. When an earthquake occur, the suffusive soil will undergo in settlement which may cause a big collapse of structure.
vii. High displacement rates are typically found in the less-consolidated soils and debris under seismic strain. Tension fractures and a reduction in tensile strength are brought on by topographic amplification, which increases tension stress at the peak.
viii. Cracks make it easier for rainfall to seep in after an earthquake, which slows down the release of extra pore water pressure. The ultimate causes of slope instability are soil weakness brought on by seismic loads and a decrease in the rate at which pore water pressure dissipates.
ix. The significance of this topic lies in the fact that internal erosion can lead to soil instability and failure of slopes and other structures, which can have serious consequences for human safety and infrastructure. It is therefore important to understand the effects of combined rainfall and seismic vibration on internal erosion in order to prevent and mitigate this type of erosion.

9.2 Recommendations for future research

Based on the review, it is recommended that future research should focus on improving our understanding of the mechanisms of internal erosion by employing the advance methodologies and developing new techniques to prevent and mitigate this type of erosion. Additionally, research should also focus on the development of reliable and effective methods for monitoring and predicting the onset of internal erosion, so that preventive measures can be taken in a timely manner. The combined effects of earthquakes and rainfall on suffusion of soil can be complex and can lead to significant damage and instability. During an earthquake, the ground can shake violently, causing soil liquefaction and leading to soil movement and instability. If heavy rainfall occurs at the same time or in the aftermath of an earthquake, the saturated soil can become even more susceptible to movement, leading to increased suffusion. Additionally, the heavy rainfall can cause erosion, further weakening slopes and increasing the risk of suffusion.

9.3 Summary and concluding remarks

If an earthquake occurs in an area that is already saturated with water from heavy rainfall, it can cause the soil to lose even more strength, leading to even more soil movement and instability. This can lead to severe damage to bridges, buildings, roads, and other infrastructure and can be extremely dangerous for people. In summary, the combined effects of earthquakes and rainfall on suffusion of soil can lead to severe damage and instability, and can exacerbate the risks associated with each individual event. Considering the complex interactions between earthquakes and rainfall, it is important to account for both hazards when designing and constructing infrastructure in at-risk areas. By doing so, we can reduce the risks associated with suffusion, minimize damage, and enhance the resilience of our built environment.

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