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Soil Suffusion under the Dual Threat of Rainfall and Seismic Vibration

Imtiyaz Akbar Najar, Raudhah Ahmadi*, Yunika Kirana Abdul Khalik, Siti Noor Linda Taib, Norsuzailina Binti Mohamed Sutan, Nur Hisyam Bin Ramli

Faculty of Engineering, University of Malaysia Sarawak, Kota Samarahan, Kuching 94300, Malaysia

Corresponding Author Email: araudhah@unimas.my

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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].

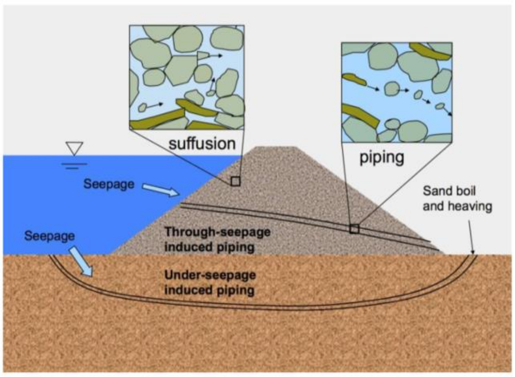

Figure 1. Schematic diagram of suffusion

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.

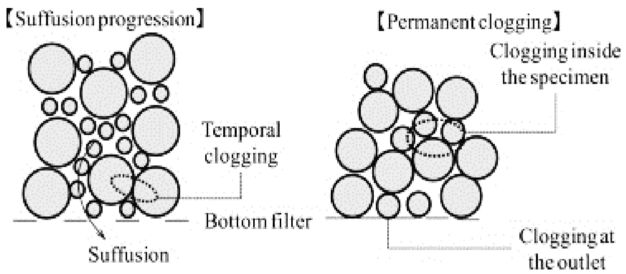

Figure 2. Illustration of factor of suffusion [32]

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