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Integrated GIS Mapping and Laboratory Investigation of Soil Piping

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Abstract

Internal erosion in soils, particularly in the form of soil piping, is a critical geotechnical problem that can lead to severe instability of slopes, embankments, and earth structures. Soil piping is a progressive process in which seepage water removes fine soil particles, forming underground tunnels that gradually develop into continuous pipes and weaken the soil mass. This phenomenon is commonly initiated under conditions of high hydraulic gradient and in loose, silty, or poorly graded soils, with erosion typically beginning at the downstream side and advancing upstream. This project presents an integrated approach combining laboratory investigation and Geographic Information System (GIS) mapping to study internal erosion due to soil piping. Laboratory experiments are conducted using a permeability-type apparatus to simulate seepage conditions and evaluate the susceptibility of different soil samples to piping based on their basic engineering properties. The experimental results are then integrated with spatial data using GIS techniques to map zones vulnerable to internal erosion. The GIS-based analysis helps visualise the spatial variation of soil properties and identify areas prone to piping failure. The integrated methodology enhances the understanding of soil piping mechanisms and provides a practical tool for predicting internal erosion-prone zones. The outcomes of this study are expected to support better planning, design, and mitigation strategies for geotechnical and hydraulic structures by combining experimental evidence with spatial analysis.

Keywords: Soil piping, Internal erosion, Seepage, Hydraulic gradient, Permeability, Laboratory investigation, GIS mapping, Soil stability.

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1. Introduction

The Internal erosion is one of the most critical causes of failure in earth structures such as embankments, slopes, levees, and earth dams. Among the various forms of internal erosion, soil piping is a progressive and concealed process in which seepage water gradually removes fine soil particles from within the soil mass, leading to the formation of subsurface channels or pipes. Although the process initiates slowly and is often difficult to detect at early stages, sustained seepage under favorable hydraulic conditions causes these channels to enlarge over time. As piping progresses, a continuous erosion path develops, resulting in a significant reduction in soil strength and stability, which can ultimately trigger sudden and catastrophic structural failure.

Soil piping is more likely to occur in loose, silty, or poorly graded soils subjected to high hydraulic gradients. The initiation of piping generally starts at the downstream side of a soil mass, where seepage water exits and carries fine particles with it, and then progresses upstream toward the source of water. Due to its internal nature, soil piping often remains undetected until advanced stages, making it a serious concern in geotechnical engineering and slope stability assessment.

Figure 1: Soil Piping

In recent years, the integration of laboratory testing with Geographic Information System (GIS) techniques has emerged as an effective approach for understanding and predicting geotechnical hazards. Laboratory studies help in evaluating the basic engineering properties of soils and their susceptibility to piping under controlled seepage conditions, while GIS enables the spatial analysis and visualization of soil characteristics over a study area. By integrating experimental results with GIS mapping, vulnerable zones can be identified more accurately.

This project, titled Integrated GIS Mapping and Laboratory Study of Internal Erosion, aims to investigate the mechanism of soil piping through laboratory experiments and to develop GIS-based maps for identifying areas prone to internal erosion. The combined approach provides a comprehensive understanding of soil piping behavior and supports effective planning and mitigation strategies for geotechnical and infrastructure projects.

1.2 Objectives of the Study

- To investigate the behavior of soil piping using soil samples collected from Kuranchery.
- To analyze how soil properties affect piping susceptibility.
- To map and interpret the results in QGIS to identify high-risk piping zones.
- To conduct laboratory experiments to observe the initiation and development of soil piping.
- To identify the critical hydraulic gradient at which internal erosion begins.
- To assess the relationship between soil properties and piping susceptibility.

1.3 Scope of the Study

The scope of this project includes the laboratory investigation of soil piping using a permeability-type apparatus to evaluate the susceptibility of different soils to internal erosion. It also involves integrating experimental results with GIS techniques to map and identify zones vulnerable to soil piping. The study supports improved prediction, planning, and mitigation of internal erosion problems in geotechnical and earth structure projects.

- Study soil properties to understand susceptibility to piping.
- Conduct laboratory piping tests for assessment of soil behaviour.
- Identify areas at risk of soil piping using collected data.
- Map vulnerable zones using GIS for spatial analysis.

- Support safe infrastructure planning and soil management strategies.

2. Materials And Methods

2.1 Materials Used

The various materials used in the experimental program are described below.

2.1.1 Soil

The soil material used for the laboratory study of internal erosion and soil piping was collected from Kuranchery, representing the natural soil conditions of the study area. The sample was obtained from an undisturbed location to avoid surface disturbances and organic contamination, ensuring that the soil behavior observed in the laboratory closely reflects field conditions.

The soil predominantly consists of fine-grained particles with a significant proportion of silt and sand, which makes it vulnerable to internal erosion under seepage forces. Such soil types are known to allow the migration of fine particles when subjected to continuous water flow, leading to the initiation of soil piping.

This soil material was selected to study the response of locally available soils to seepage-induced stresses and to understand their susceptibility to internal erosion and piping. The observations derived from this study are relevant for assessing erosion-related stability issues in similar soil conditions.

Figure 2: Kuranchery Soil

2.1.2 QGIS Software

QGIS is a free and open-source Geographic Information System (GIS) software widely used for the creation, analysis, and visualization of spatial data. Its user-friendly interface and powerful analytical tools make it suitable for geotechnical and environmental studies involving spatial variability.

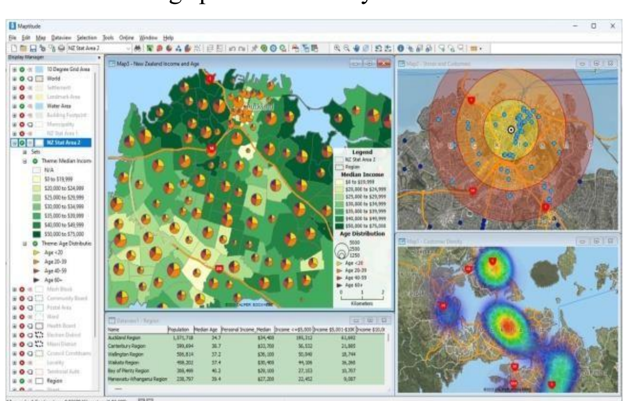

Figure 3: QGIS Software

In this study, QGIS was employed to map the study area along with relevant soil characteristics obtained from laboratory investigations and secondary data sources. The software enabled the integration of soil properties with spatial layers, allowing effective visualization of their distribution across the area.

Through spatial analysis in QGIS, zones susceptible to internal erosion and soil piping were identified and represented in map form. This GIS-based approach enhances the understanding of spatial patterns of soil vulnerability and supports better assessment and decision-making related to erosion-prone areas.

2.2 Experimental Setup

The experimental procedure is designed to study the behavior of different soils under controlled seepage conditions and to evaluate their susceptibility to internal erosion and soil piping. In this setup, water is supplied from a water tank and allowed to enter the system at the base of the soil-filled well or plastic mould. The soil sample is placed inside the mould and compacted to the required density to ensure uniformity. Water is then allowed to flow upward through the soil mass, creating seepage forces that act against the natural equilibrium of the soil particles.

As water moves upward through the soil, it generates hydraulic pressure and seepage forces that tend to lift and displace fine soil particles. When the hydraulic gradient increases beyond a certain limit, the forces exerted by the flowing water overcome the resisting forces between soil particles, leading to the initiation of internal erosion. This process disturbs the internal structure of the soil, causing rearrangement of particles and the formation of small voids and preferential flow paths within the soil mass.

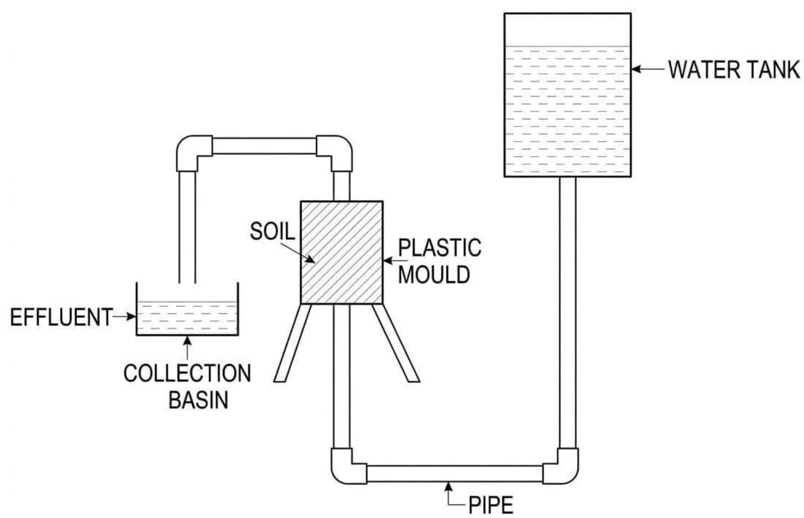

Figure 4: Experimental Setup

The seepage water, along with any eroded fine particles, exits from the top of the well in the form of effluent. The flow rate is carefully controlled using valves to maintain consistent hydraulic conditions throughout the test. A fixed and predetermined time interval is selected for each soil sample, during which the effluent is collected in a collection basin. Observations are made on the clarity, turbidity, and quantity of effluent, as these characteristics provide valuable indications of the onset and progression of soil piping.

As the test continues, soils that are more susceptible to piping are expected to show increased turbidity in the effluent due to greater loss of fine particles. In some cases, a sudden increase in discharge may be observed, indicating the formation of a continuous pipe within the soil sample. This change also reflects an increase in permeability caused by internal erosion and structural disturbance of the soil mass. Conversely, soils with better gradation and higher resistance may show minimal particle loss and relatively stable flow conditions.

The effluent collected from each soil sample is further analyzed to assess the extent of erosion and to compare the behavior of different soils. Based on these observations and measurements, the properties and piping susceptibility of soils collected from the Kuranchiri area are evaluated. This experimental procedure provides a clear understanding how seepage-induced forces influence soil stability and helps in identifying soils that are vulnerable to internal erosion and piping under hydraulic loading.

3. Literature Review

T.C. Pierson (1982) conducted an experimental investigation using a Hele-Shaw analogue, consisting of Perspex plates, hydraulic oil, and a soil pipe chamber. The study aimed to analyze how soil pipes affect slope stability under varying conditions. The findings revealed that closed soil pipes tend to increase pore water pressure, which can trigger landslides by reducing soil strength. In contrast, open pipes act as drainage pathways, reducing internal water pressure and thereby enhancing slope stability. This research highlighted the dual role of soil pipes either stabilising or destabilizing slopes—depending on their configuration and connectivity.

G.V. Wilson, J.L. Neiber, R.C. Siddle, G.A. Fox (2013) This research reviewed a wide range of field data, laboratory experiments, and analytical/numerical models to understand the mechanisms of internal erosion caused by soil pipeflow. The authors examined how soil pipes influence the hydraulic behaviour of slopes, often acting as conduits for water flow that can lead to internal erosion and gully formation. They found that soil pipes may both stabilize and destabilize slopes depending on hydrological and soil conditions. The study also highlighted that modeling soil pipeflow remains a complex challenge, as it involves dynamic interactions between soil structure, hydraulic conductivity, and erosion processes. The authors emphasised the need for further research to improve predictive models and mitigation strategies for slope failure due to internal erosion.

Yank Yang, Reiko Kuwano (2018) This experimental study focused on understanding how piping erosion alters the mechanical behavior of Toyoura sand. The researchers utilized glucose pipes, Toyoura sand, and de-aired water to simulate subsurface erosion under controlled laboratory conditions. The objective was to experimentally reproduce piping erosion and observe its impact on soil stiffness, shear strength, and shear band formation. The findings demonstrated that volumetric strain increased by 25–30% as the glucose proportion dissolved, indicating significant structural weakening. Approximately 80% of the glucose volume was successfully eroded, leading to noticeable formation of voids and shear bands. The study concluded that piping erosion considerably reduces soil strength, contributing to slope instability and deformation, even under small hydraulic gradients.

Narges Karimnejad, Adel Sepehr, Jean Poesen, Ali Hassnali (2021)This global-scale study used comprehensive datasets such as SOC SIC (Soil Organic Carbon and Soil Inorganic Carbon), SoilGrids, WoSIS samples, and the RUSLE erosion model, among others, to analyze soil carbon translocation due to erosion. The main objective was to quantify the movement of soil carbon at a global level and identify the key environmental and anthropogenic drivers influencing it. The results revealed that global soil erosion mobilises approximately 1.01 petagrams (Pg) of carbon annually, including 894.8 teragrams (Tg) of SOC and 107.1 Tg of SIC. The study further found that SOC decreases with increasing aridity, while SIC increases under similar conditions. Agricultural lands were found to lose substantially more carbon than natural vegetation areas. Topography, land use, and aridity emerged as the dominant controls on global soil carbon movement. This research underscores the urgent need to include erosion induced carbon fluxes in global carbon cycle models to improve climate change predictions.

Fangli Wei, Anhui Wang, Lizhi Jia, Yuanyuan Huang (2022) This study assessed how vegetation restoration efforts influence soil erosion dynamics across China under the back drop of increasing climate extremes. The research relied on datasets including ERA5-Land (1980–2020), NAEADEM 30 m land-use data, National soil survey, and CHLUCC Landsatimagery. The main objective was to evaluate how vegetation restoration mitigates soil erosion and to determine whether such benefits persist under intensifying rainfall events. The results showed that vegetation restoration has successfully reduced erosion rates across much of China. However, extreme rainfall events, which are becoming more frequent under climate change, are partially offsetting these gains. The study highlighted that while restoration remains an effective erosion control strategy, increasing rainfall intensity and short-duration storms continue to pose significant risks. Overall, it emphasised the importance of integrating vegetation management with adaptive water and soil conservation strategies to enhance long-term erosion resilience.

Xiaohua Zeng, Yusheng Tian, Jun Zhai, Wenyi Sun, Jun Li (2023) This research inte grated UAV (Unmanned Aerial Vehicle) remote sensing, pedological analysis, and geophysical tools to develop an improved method for detecting and analyzing soil piping. The materials and instruments used included a UAV camera model, hydrometer and core sampling methods, pH meters, and geophysical mapping tools. The objective was to establish an integrated approach for accurate detection, mapping, and monitoring of subsurface erosion features such as hidden pipes and cavities. The study found that UAV imagery and digital elevation models (DEMs) effectively identified surface cracks, depressions, and subsidence zones caused by piping. Ad ditionally, Ground Resistivity Analysis (GRA) and Electrical Resistivity Tomography (ERT) successfully revealed hidden voids and pipe networks beneath the surface. This combination of remote sensing and geophysical data offers a cost-effective and non-invasive solution for understanding the extent and risks of soil piping in vulnerable landscapes.

Rosar-Chavoya, J.L. Gandoli (2017) This study utilized field observations, sediment analysis, and geomorphological surveys to analyze the occurrence of soil piping in tropical regions. The authors emphasised the contribution of GIS tools like QGIS in mapping and assessing gully development and subsurface erosion. The results indicated that soil piping significantly drives subsurface erosion, leading to the enlargement of gullies and weakening of slope materials. Consequently, this process promotes mass wasting and land degradation. The study underscores the importance of integrating GIS-based spatial analysis with field data to understand complex erosion dynamics.

Shafat Khan, Khalid Mohiuddin (2020) This comparative study assessed ArcGIS 10.5.1 and QGIS 2.18 in terms of cost, licensing, technical support, and functionality for spatial planning and environmental research. The authors concluded that both software platforms have significant potential for GIS-based studies, but the choice depends on the organization's requirements and staff expertise. While ArcGIS provides a more comprehensive suite of proprietary tools, QGIS—being open-source—is more accessible and cost-effective, and in many cases, can effectively replace ArcGIS. The study highlighted the growing role of opensource GIS in research and professional applications, particularly in developing countries where budget constraints exist.

4. Expected Result and Discussion

The expected results suggest that weak and piping-prone soils can be effectively identified based on their physical characteristics such as loose fabric, higher silt or fine sand content, poor gradation, and higher void ratios, which make them more vulnerable to internal erosion under seepage conditions. Laboratory testing is expected to determine distinct critical hydraulic gradients for each soil sample, with lower values observed in soils of lower density and cohesion, indicating early initiation of piping. A strong relationship is anticipated between basic soil properties—grain size distribution, permeability, compaction state, and uniformity coefficients—and piping behaviour, where uniformly graded soils are more susceptible compared to well-graded or denser soils. Observations during the experiment are expected to show that piping initiates at the downstream exit face due to higher hydraulic gradients and gradually progresses upstream, forming visible erosion channels and continuous pipes accompanied by soil particle migration. As piping develops, significant changes in soil structure are expected, including loosening of the soil mass, development of internal voids, and an increase in permeability, which further accelerates erosion and instability. The use of QGIS software is expected to integrate laboratory results with spatial data to generate thematic maps identifying soil characteristics and piping susceptibility zones, enabling visualization of high-risk areas and demonstrating the effectiveness of combining laboratory investigation and GIS-based mapping for predicting and managing internal erosion and soil piping hazards.

5. Conclusion

The study successfully identified soils that are weak and more susceptible to internal erosion and soil piping through a combination of laboratory experimentation and spatial analysis. The results clearly indicate that soil piping is strongly influenced by basic soil properties such as grain size distribution, gradation, density, and permeability. Soils with loose structure, higher fine content, and poor gradation were found to be more vulnerable to internal erosion under seepage conditions, emphasising the importance of proper soil characterisation in evaluating piping susceptibility.

Laboratory experiments confirmed the hydraulic conditions under which soil piping initiates and progresses. Controlled seepage tests demonstrated that piping generally begins at the downstream end of the soil sample, where the exit hydraulic gradient is highest. Initial erosion was characterised by the movement of fine particles, which gradually developed into continuous erosion channels as seepage intensity increased. These observations validate the role of sustained hydraulic loading in triggering and accelerating internal erosion and piping failure.

A key outcome of the study was the determination of critical hydraulic gradient values for each soil sample. The critical hydraulic gradient represents the threshold condition at which soil particles begin to detach and internal erosion initiates. Significant variation in critical hydraulic gradients was observed among different soil samples, highlighting the influence of soil type and gradation. Uniformly graded and loosely compacted soils exhibited lower critical hydraulic gradients, indicating a higher susceptibility to piping, while well-graded and denser soils showed greater resistance to internal erosion.

The piping tests also revealed clear changes in soil structure during the erosion process. Progressive removal of fine particles led to loosening of the soil mass and the formation of internal voids and preferential flow paths. These structural changes resulted in a noticeable increase in permeability as piping progressed, allowing greater seepage flow and further accelerating erosion. This confirms that soil piping is a progressive phenomenon in which initial minor erosion can rapidly evolve into severe instability if unfavorable hydraulic conditions persist.

The application of QGIS software effectively complemented the laboratory findings by enabling spatial mapping of soil characteristics and piping susceptibility. Laboratory results were integrated with spatial data to generate thematic maps identifying weak soil zones and areas of high piping risk. The GIS-based analysis provided a clear visual representation of the spatial variability of soil properties, making it easier to identify and interpret high-risk regions.

Overall, the integration of laboratory investigation with QGIS-based mapping provided a comprehensive understanding of internal erosion and soil piping behavior. The study highlights the importance of combining experimental data with spatial analysis for effective identification, assessment, and management of piping-prone soils. These findings are valuable for geotechnical and hydraulic engineering applications, particularly in the planning, design, and maintenance of structures exposed to seepage-related risks.

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