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Geotechnical Engineering of Lateral Soil Movement and Subsidence in Bojong Koneng, Bogor Regency

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clay shale; lateral soil movement; land subsidence; disaster mitigation; geotechnical engineering; slope stability

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Abstract

Bojong Koneng Village, Babakan Madang District, Bogor Regency, is highly susceptible to lateral ground movement and potential land subsidence due to weathered clay shale, hilly topography, high rainfall, and expanding built-up areas. This study aimed to identify the factors controlling ground instability, establish a conceptual model of ground movement mechanisms, and propose an integrated geotechnical mitigation strategy. A descriptive-analytical approach was employed using secondary geological, soil, topographic, hydrological, land-use, ground movement hazard, and surface deformation data, supplemented by visual field observations. Electrical resistivity tomography (ERT) data indicated a low-resistivity zone at approximately 8–15 m depth, potentially associated with clay-rich, weathered, and water-saturated materials within the Jatiluhur Formation. Ground movement susceptibility was classified into four categories, with high-hazard zones predominantly concentrated in the eastern and southern areas. Surface deformation was categorized as low, moderate, high, and very high, with the highest deformation rates exceeding 60 mm/year in the eastern and southeastern areas. The proposed conceptual mechanism involved rainfall infiltration, increased pore water pressure, reduced effective stress, and progressive deterioration of weathered clay shale shear strength, potentially leading to slope creep and translational landslides. Recommended mitigation options included improved surface and subsurface drainage, soil nailing, shotcrete reinforcement, polymer–calcite precipitation (PCP), gabion retaining structures, and an early warning system (EWS). These measures require site-specific geotechnical investigations and engineering validation before implementation.

INTRODUCTION

Bogor Regency has experienced recurring hydrometeorological and geological hazards that have disrupted residential areas and infrastructure (Putri et al., 2023; Vincent et al., 2025). Disaster records cited in this study documented 66 events between January 1 and June 22, 2026, comprising 17 floods, 30 extreme weather events, 18 landslides, and one drought. These records highlight the importance of examining the interactions among topographic conditions, geological characteristics, rainfall patterns, and infrastructure exposure in disaster-prone areas (Assyidiqi et al., 2025; Vincent et al., 2025).

Bojong Koneng Village, located in Babakan Madang District, represents a particularly relevant case because recurring ground movements have affected roads, residential buildings, and public facilities. Historical records presented in this study documented ground movement events associated with land-use changes in 1982 and 2007, extensive infrastructure damage in September 2022, renewed ground movement in March 2025, and subsequent occurrences in 2026 (Bogor Regency Regional Disaster Management Agency, 2022, 2025). The September 2022 event reportedly affected more than 270 buildings and caused road cracks extending approximately one kilometer, indicating widespread ground instability rather than isolated slope failures (Center for Volcanology and Geological Hazard Mitigation, 2022).

The geological characteristics of the study area provide a plausible explanation for its persistent ground instability. The Jatiluhur Formation comprises sedimentary rock units, including fine-grained materials that may exhibit clay shale characteristics under certain geological conditions (Effendi et al., 1998). Repeated wetting and drying cycles can induce slaking, progressive weathering, and deterioration of shear strength, thereby increasing susceptibility to slope instability (Misbahudin & Pardede, 2023; Misbahudin et al., 2023; Misbahudin, 2023; Yogaswara & Alatas, 2022). In the rapidly developing hilly terrain of the Sentul area, the geotechnical behavior of these weathered materials is particularly important where natural and modified slopes support residential buildings, transportation infrastructure, and other engineered structures, because the strength of weak and sheared rock masses differs markedly from that of intact rock (Hoek & Brown, 1997; Hoek et al., 1998).

Geological susceptibility may be further intensified by slope geometry and hydrological processes. Moderate to steep slopes increase the downslope component of gravitational forces, while rainfall infiltration through fractures and discontinuities may promote groundwater accumulation above relatively low-permeability clay-rich layers. Increased pore water pressure reduces effective stress and available shear resistance, potentially accelerating slope creep, translational sliding, and differential ground displacement (Fata et al., 2022; Pelascini et al., 2022). These interconnected processes indicate that observed surface damage should be evaluated in conjunction with subsurface geological conditions, groundwater behavior, and slope deformation mechanisms (Pratiwi et al., 2022; Priatna & Istiadi, 2021).

Previous geological mapping, disaster assessments, and geophysical investigations have provided valuable information regarding ground instability in the study area. However, the available evidence remains fragmented across geological records, disaster reports, geophysical interpretations, and surface deformation assessments (Pratama & Misbahudin, 2025; Rosyidy et al., 2021; Sari et al., 2024). Consequently, an integrated conceptual framework linking lithological characteristics, topographic conditions, rainfall infiltration, land-use changes, ground movement susceptibility, surface deformation, and infrastructure exposure to appropriate geotechnical mitigation strategies remains insufficiently established. This research gap highlights the need for a comprehensive synthesis of existing evidence to support preliminary assessments of ground instability and mitigation priorities without replacing detailed site-specific geotechnical investigations.

The urgency of developing an integrated mitigation framework was further demonstrated by the March 2025 ground movement event, which reportedly caused severe damage to 67 residential units and displaced 168 residents from 43 households (Bogor Regency Regional Disaster Management Agency, 2025). Mitigation measures focused exclusively on repairing visible structural damage may fail to address the underlying geological and hydrological processes responsible for recurring ground deformation. Therefore, integrating surface and subsurface drainage, slope stabilization, land-use management, and ground movement monitoring may provide a more systematic approach to identifying priority intervention areas, supporting further geotechnical investigations, and reducing potential risks to communities and

infrastructure (Federal Highway Administration, 2015; Situmorang et al., 2025; Yuniawan et al., 2022).

Accordingly, this study aimed to characterize the available geological, geotechnical, topographic, hydrological, land-use, and surface deformation evidence in Bojong Koneng Village; qualitatively assess ground movement hazards, vulnerability, and infrastructure exposure; develop a conceptual model of the mechanisms contributing to ground instability; and evaluate potential integrated geotechnical mitigation strategies. The principal contribution of this study lies in establishing an evidence-based conceptual framework that integrates geological and geophysical information with hazard characteristics and infrastructure exposure to support the prioritization of slope stabilization, drainage improvement, and ground movement monitoring measures. Nevertheless, the proposed mitigation strategies require further validation through detailed field investigations, geotechnical testing, groundwater monitoring, slope stability analyses, and site-specific engineering design before implementation.

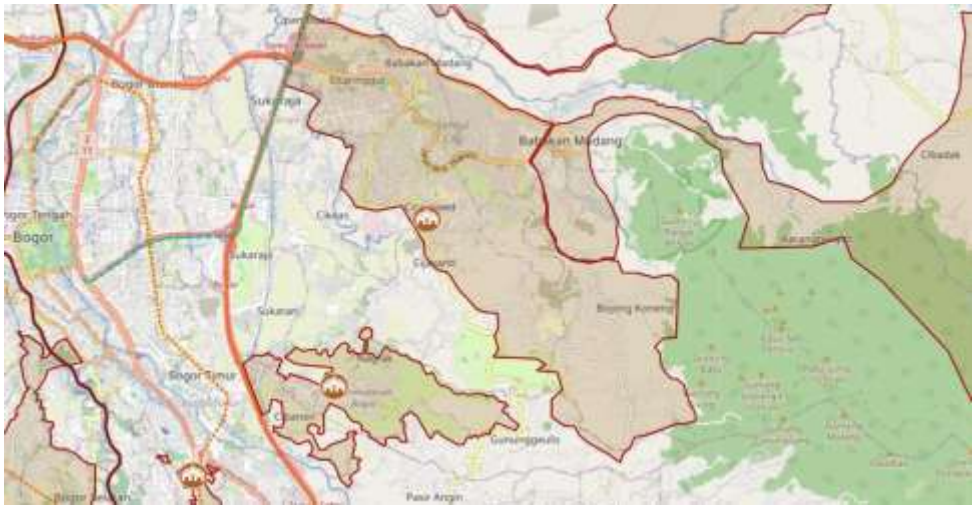


Figure 1. Study Location of Bojong Koneng Village, Babakan Madang District, Bogor Regency. Source: KFMAP by Knight Frank.

Table 1. Track Record of Land Movement Events and Related Disasters

Year/Time	Events	Main impact
1982 and 2007	Land shifts related to land use change	Indicates recurrent occurrences in hilly areas.
September 2022	Massive land movement in Kampung Curug	The main road was cracked for about 1 km; >270 buildings were affected; hundreds of residents were displaced.
March 3, 2025	Soil movement in Curug Village due to high-intensity rain	67 units of houses were severely damaged; 168 people (43 families) were displaced.
February 2026	Flash floods and landslides	Mud and stone materials blocked access and disrupted the drainage system of the area.
April 2026	Follow-up soil movement in Kampung Pasir Ipis	Cracks/damage to houses, sinking, and disconnection of concrete road bodies.

Source: Attribution requires author verification.

METHOD

This study employed a descriptive-analytical approach integrating secondary data analysis, visual field observations, and qualitative hazard–vulnerability–exposure (HVE) assessment.

The study focused on ground movement conditions in Bojong Koneng, Bogor Regency. Secondary data were obtained from geological maps, landslide susceptibility and hazard maps, rainfall records, including Tropical Rainfall Measuring Mission (TRMM) data, previous geotechnical investigation reports, published studies on the Jatiluhur Formation, and historical disaster records. Existing geotechnical parameters were extracted from secondary sources and used to support the interpretation of ground instability mechanisms.

Data collection involved reviewing relevant geological and geotechnical documents, examining spatial and historical disaster records, and conducting visual field observations. Field observations focused on slope morphology, exposed weathered materials, ground and road cracking, indications of slope creep, and visible groundwater seepage. The collected information was used to assess the consistency between documented geological conditions and observed surface instability. No additional subsurface investigations or laboratory geotechnical tests were conducted.

Data analysis examined the interactions among lithological characteristics, weathering processes, slope gradients, rainfall infiltration, land-use conditions, and surface deformation to develop a conceptual model of ground instability. The qualitative HVE assessment evaluated geological hazards, the vulnerability of buildings and infrastructure, and the exposure of populations and physical assets. Based on these findings, potential mitigation measures, including surface and subsurface drainage, soil nailing, shotcrete reinforcement, polymer–calcite precipitation (PCP), gabion retaining structures, and an early warning system (EWS), were evaluated according to the identified instability mechanisms and site constraints. The proposed measures were formulated as preliminary recommendations requiring further geotechnical investigation and site-specific engineering validation.

RESULTS AND DISCUSSION

Geological and Hydrogeological Conditions

Physiographically, Bojong Koneng is a Bogor Zone characterized by hilly to mountainous morphology and geological structures that develop due to tectonic deformation. Based on the Bogor Sheet Geological Map, the research area is influenced by the Jatiluhur Formation, andesite, breccia and Lava of Mount Kencana–Mount Limo, as well as alluvium deposits. The Jatiluhur Formation is composed of, among others, clay rock, marl, and quartz sandstone inserts. These fine-grained layers have relatively low permeability and become important when interacting with more permeable layers.

In wet tropical conditions, weathering is intensive. The weathering material of the Jatiluhur Formation develops into clay shale that is sensitive to changes in moisture content. Cracks and discontinuity fields can function as infiltration pathways as well as weak zones. The results of Electrical Resistivity Tomography (ERT) and Vertical Electrical Sounding (VES) investigations show that the zone of low resistivity is less than 10 Ωm which develops at a depth of about 8–15 m. These zones are interpreted as clay rocks, limestones, and water-saturated marl from the Jatiluhur Formation and correlate with the suspected slip field in contact with the weathering material with the clay layer.

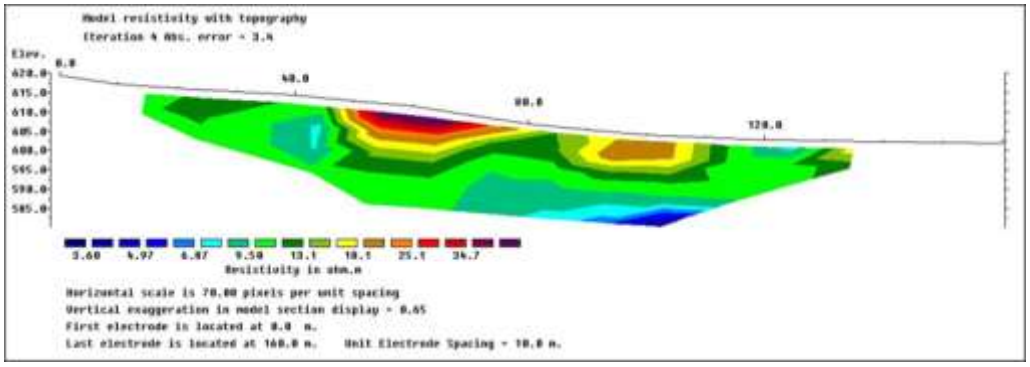


Figure 2. Cross-section of 2D Resistivity of ERT Inversion Results.
Source: Original image attribution requires author verification.

Hydrogeological conditions are an important triggering factor. Rainwater that enters through cracks and pores of the material moves towards a layer with lower permeability. The accumulation of water in the contact zone increases the pore-water pressure, lowers the effective stress, and subsequently decreases the shear resistance. This mechanism explains why changes in hydrological conditions can accelerate deformation in clay shale materials.

Physical Conditions and Controlling Factors

The study area is dominated by moderate to steep slopes, with a slope that in observation and topographic synthesis is around 15°–30°. The geometry of the slope increases the component of the driving force. Surface soil types generally develop from weathering sedimentary rocks and have relatively high clay fractions, so their plasticity and compressibility tend to be large and sensitive to changes in water content. The development of settlements, cultivated land, and infrastructure also changes vegetation cover, load distribution, and surface flow patterns.

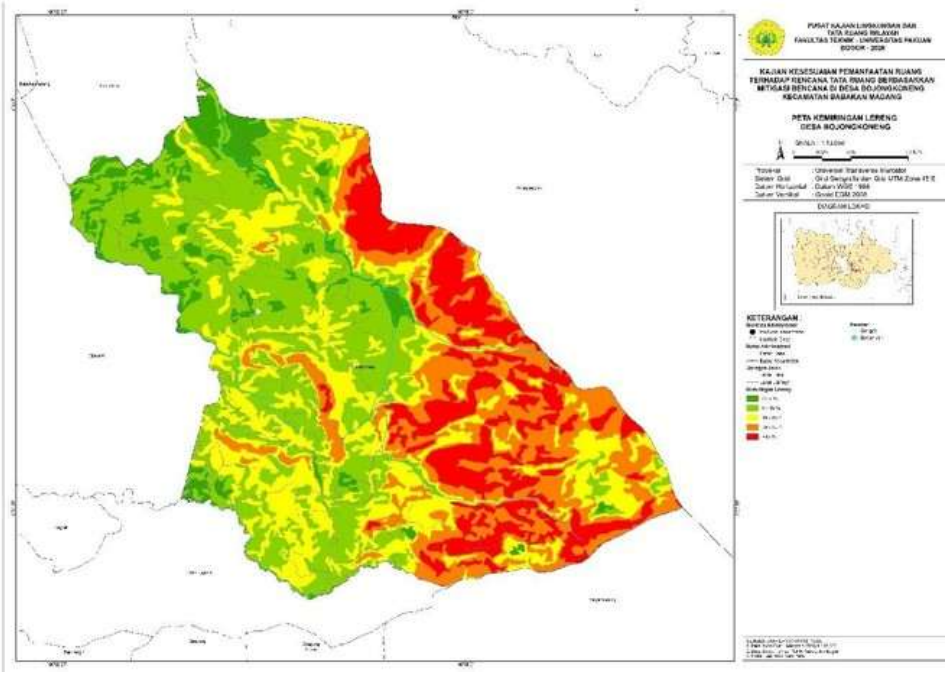


Figure 3. Map of the slope of Bojong Koneng Village.
Source: Original image attribution requires author verification.

Table 2. Synthesis of Controlling Factors for Soil Movement in Bojong Koneng Village

Parameters	Analysis Results	Geotechnical Implications	Influence
Geology	Clay *shale* formation	Weathering, slaking, low shear strength	Very high
Soil type	Finely structured soil	High plasticity, low permeability	Height
Slope slope	Medium–steep	Increase propulsion force	Very high
Rainfall	3,500–4,000 mm/year on the BIG map	Infiltration and increased pore water pressure	Very high
Land use	Settlements and cultivated land	Loads and hydrological changes increase vulnerability	Medium–high
Land suitability	Some areas are not suitable for development	Requires control of space utilization	Height

Source: Processed study data, 2026.

The synthesis shows that soil movement is not controlled by a single parameter. Geology plays a role as a basic factor that controls the properties of materials; soil type becomes a deformation medium; slope gradient increases the driving force; rainfall and infiltration are triggering factors; while land use changes can speed up the process. The interaction of these factors becomes the basis for determining mitigation priority zones.

Hazards, Risks, and Surface Deformation

The hazard zoning map used in the study, which was compiled using the *Frequency Ratio* (FR) method, divides the Bojong Koneng area into four classes: very low, low, medium, and high. The high danger zone is concentrated mainly in the east to south and is associated with relatively steep slopes, weathering materials above the Jatiluhur Formation, and hydrological conditions that support water accumulation. The distribution of high danger zones is also related to the inventory of landslide events and road corridors and river valleys.

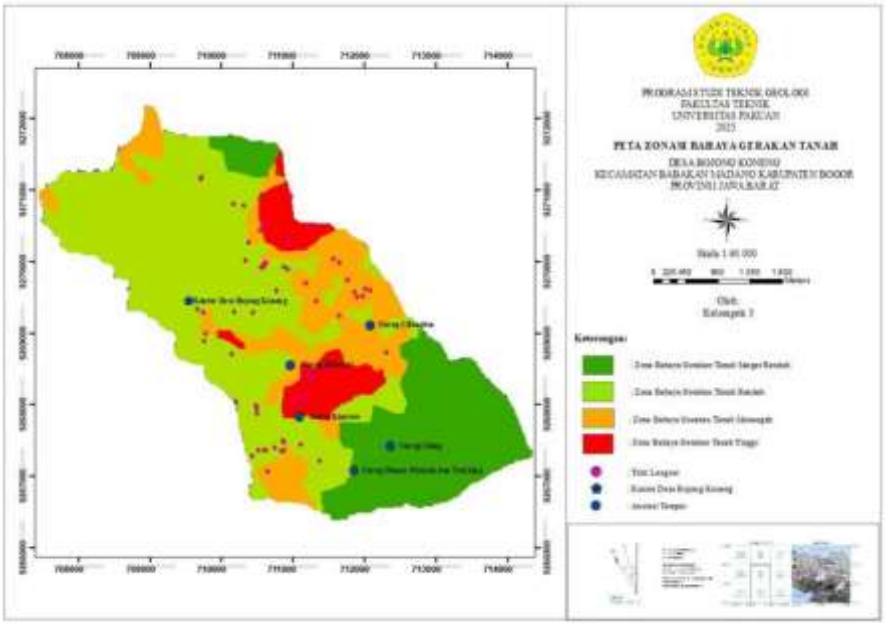


Figure 4. Zoning Map of Soil Movement Hazards in Bojong Koneng Village Based on the Frequency Ratio (FR) Method.

Source: Original image attribution requires author verification.

Table 3. Risk Analysis Based on Hazard–Vulnerability–Exposure (HVE)

Components	Analysis Results	Level
Hazard	Jatiluhur / *clay shale* formation, moderate–steep slopes, and high rainfall	Height
Vulnerability	Settlements, roads, taluds, utilities, and buildings are in a condition prone to deformation	Height
Exposure	Infrastructure and settlements are in the zone prone to land movement	Height
Risk	The interaction of *hazard, vulnerability,* and *exposure* results in the risk of high ground movements	Height

Source: Processed study data, 2026.

The results of the HVE analysis qualitatively show a high level of risk. These findings not only reflect the potential geological hazards, but also the existence of exposed objects. Thus, mitigation strategies need to combine handling sources of instability, infrastructure protection, controlling space utilization, and community preparedness.

The interpretation of surface deformation divides the region into four classes, namely low (0–10 mm/year), medium (10–30 mm/year), high (30–60 mm/year), and very high (>60 mm/year). Very high zones are concentrated in the eastern and southeastern parts and are associated with steep to very steep slopes. These zones are a priority for monitoring and mitigation because they show greater deformation activity and the potential to develop into landslides and differential settlements.

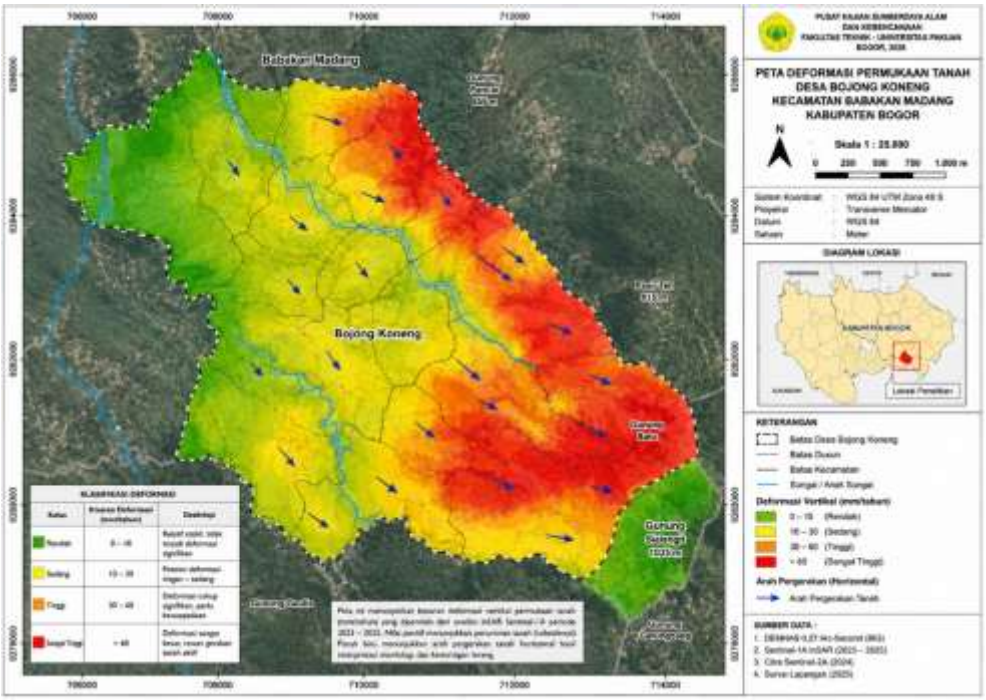


Figure 5. Map of Soil Deformation of Bojong Koneng Village.
Source: Original image attribution requires author verification.

Conceptual Mechanisms of Soil Movement

The mechanism of soil movement is compiled based on geological synthesis, hydrogeology, topography, soil conditions, disaster track record, and surface deformation. The initial stage begins with rainwater infiltration through cracks and pores of weathering material. The water then moves towards the clay layer of the Jatiluhur Formation which is relatively

impermeable, so that water accumulates at the contact limit. Increased pore water pressure decreases the effective stress and shear strength. In clay shale materials, the wetting–drying cycle accelerates the slaking so that cohesion and internal friction angle can decrease.

After the holding capacity decreases, the soil mass on the slope begins to undergo slow deformation in the form of soil creep. Field indicators associated with this process include road cracks, surface cracks, slopes of trees or utility poles, foundation shifts, and building damage. If saturated conditions and rain triggers increase, deformation can develop into translational landslides. Horizontal and vertical deformations also form positive feedback because surface cracks can enlarge the infiltration path and accelerate the next process.

Table 4. Synthesis of Soil Movement Controlling Factors in Bojong Koneng Village

Method	Main functions	Compatibility	Implementation notes
Geology	Jatiluhur Formation (*Clay Shale*)	Weathering, slaking, low shear strength	Very High
Soil Type	Finely structured soil	High plasticity, low permeability	Height
Slope Slope	Medium - steep	Increased thrust force	Very High
Rainfall	3500 – 4000 mm/year	Infiltration and increased pore water pressure	Very High
Land Use	Existing residential areas	Reduces slope stability due to load	Medium – High

Source: Processed study data, 2026.

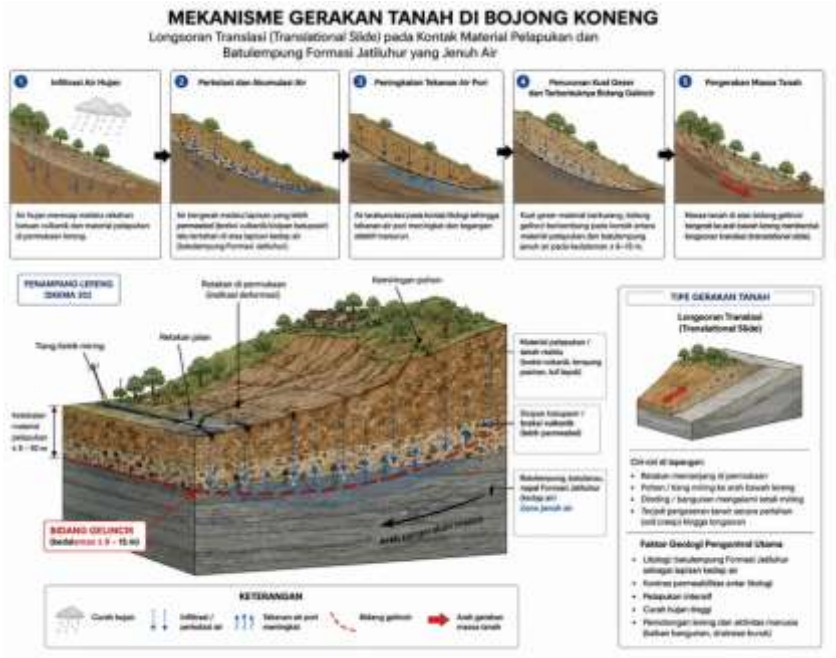


Figure 6. Conceptual Model of Soil Movement Mechanism in Bojong Koneng.
Source: Original image attribution requires author verification.

Integrated Geotechnical Engineering Mitigation Strategy

The selection of mitigation was carried out through the synthesis of geological characteristics, geomorphology, hydrology, disaster track record, built-up area conditions, and deformation mechanisms. Since the study is conceptual and has not been supported by detailed geotechnical investigations, the proposed method is an initial recommendation that must be validated through investigation, stability analysis, and technical design before implementation.

Table 5. Summary of Selection of Mitigation Alternatives

Method	Main functions	Compatibility	Implementation notes
Drainage	Reduces infiltration, runoff, and pore water pressure	Highly suitable	Initial priority; need maintenance and safe outlets.
Soil nailing	Increases internal resistance and limits deformation	Conform	Suitable for existing slopes; need slippage field data and soil parameters.
Shotcrete	Protects surfaces from erosion, raveling, and weathering	Conform	Not a single method; it must be integrated with drainage and reinforcement.
PCP	Improves the bonding and mechanical properties of the material	Quite appropriate	It still requires laboratory tests and trial sections on clay shale.
Gabion retaining wall	Resists lateral pressure while providing drainage pathways	Highly suitable	Requires space and geotextile/drainage detailing.
EWS	Detects changes in conditions and provides *lead time*	Highly suitable	Requires representative sensors, calibration, communication, and response SOPs.

Source: Processed study data, 2026.

Drainage is placed as the first layer because water is the main trigger for increased pore-water pressure and clay shale degradation. Systems can be in the form of surface channels, interceptor drains, subhorizontal drainage, and safe outlets. Water control does not eliminate the need for reinforcement because deformation at the site has been progressive.

Soil nailing was chosen because it can be applied to existing slopes with relatively small geometric changes. Steel rods work as an internal reinforcement element that increases resistance and limits deformation. Design parameters such as nail length, distance, installation angle, tensile capacity, and pull resistance must be determined based on geotechnical investigations. *Shotcrete* serves primarily as a surface protection against weathering, erosion, and the release of superficial materials. Its use must be equipped with drainage so that water is not trapped behind the coating.

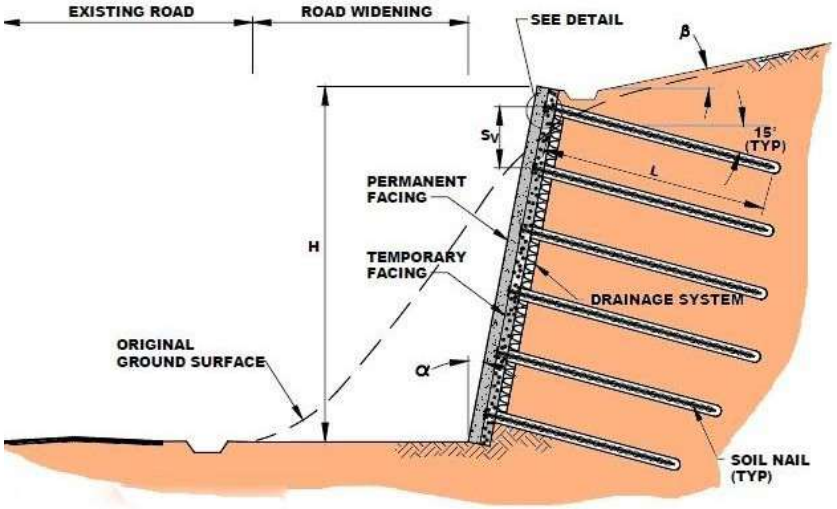


Figure 7. Conceptual Scheme of Soil Nailing on Slopes.
Source: Original image attribution requires author verification.

PCP is positioned as a material repair technology, not as a substitute for drainage or reinforcement. Conceptually, PCP is aimed at improving interparticle bonding, shear strength, rigidity, and reducing permeability. However, the Rev 2 study confirms that its application to clay shale still requires validation through geotechnical investigations, laboratory tests, and *trial sections*. *Gabion retaining walls are* relevant for locations that require flexible retaining elements and have high drainage demands; their implementation needs to consider geotextiles, granular coatings, drainage pipes, and foundation conditions.

EWS complements structural mitigation with monitoring of rainfall, soil movement, slope gradient, cracks, groundwater levels, and CCTV visual verification. Sensor data is sent to the monitoring center to determine the status of the condition and disseminate alerts. An example conceptual schema divides the status into Normal, Alert, and Alert. The operational threshold used at the implementation stage should be established based on local data and calibration results, rather than directly adopting the value of the conceptual example.

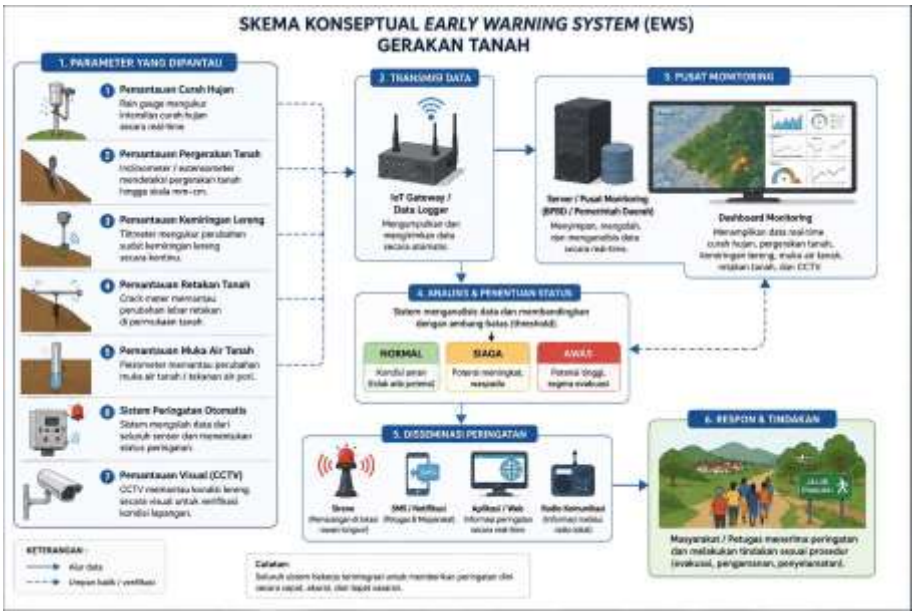


Figure 8. Conceptual scheme of the Early Warning System (EWS) of ground movement.
Source: Original image attribution requires author verification.

Implications of Space Mitigation and Management

The results of the study show that mitigation is not enough to be carried out through one safety building. The first priority is water control through a drainage system that follows the natural flow direction, equipped with safe outlets and periodic maintenance. In high to very high deformation zones, slope reinforcement needs to be determined based on the results of geotechnical investigations, while areas with low land suitability need to be restricted by heavy construction development. This approach is in line with the development direction in Rev 2 which divides the area into maintained, conditionally developed, and restricted zones.

Monitoring needs to be prioritized in deformation zones of >60 mm/year and locations that have indications of cracks, foundation shifts, or road damage. Instruments such as inclinometers, piezometers, settlement markers, tilt meters, rain gauges, and visual monitoring can be used gradually as needed. Monitoring results should be linked to response mechanisms and EWS so that deformation information can be followed up before it develops into a larger failure.

Table 6. Logical Sequence of Integrated Mitigation Implementation

Stages	Intervention	Purpose
1	Surface and subsurface drainage	Reduces infiltration, saturation, and pore water pressure.
2	*Soil nailing* / slope reinforcement	Increases internal resistance and limits deformation.
3	*Shotcrete* /surface or gabion protection at the appropriate location	Reduces erosion, weathering, and the impact of local deformation.
4	PCP in areas that meet the test results	Improve the mechanical properties of materials locally.
5	EWS and monitoring	Detects changes in conditions and provides response time.

Source: Processed study data, 2026.

CONCLUSION

Bojong Koneng Village exhibited high susceptibility to lateral ground movement and landslides due to the combined effects of weathered clay shale associated with the Jatiluhur Formation, hilly topography, high rainfall, fine-grained soil characteristics, and land-use changes. Electrical resistivity tomography (ERT) interpretations identified a low-resistivity zone at approximately 8–15 m depth, potentially associated with water-saturated, clay-rich materials and a suspected slip surface. The qualitative hazard–vulnerability–exposure (HVE) assessment indicated elevated ground movement risk where geological hazards coincided with vulnerable settlements and exposed infrastructure.

The proposed conceptual model suggested that rainfall infiltration and groundwater accumulation along lithological contacts increased pore water pressure, reduced effective stress and shear strength, and contributed to progressive slope creep and potentially translational landslides. Areas exhibiting very high surface deformation rates (exceeding 60 mm/year), particularly in the eastern and southeastern portions of the study area, were identified as priorities for further investigation, monitoring, and mitigation.

The preliminary mitigation assessment identified an integrated approach involving surface and subsurface drainage to manage water infiltration and groundwater pressure, soil nailing for slope reinforcement, shotcrete for surface protection, polymer–calcite precipitation (PCP) as a potential ground improvement technique requiring further validation, gabion retaining structures where geotechnically appropriate, and an early warning system (EWS) to support monitoring and disaster preparedness. These measures should be evaluated collectively based on site-specific geological, hydrological, and geotechnical conditions rather than implemented independently. The study contributed a conceptual ground movement model and preliminary mitigation framework to support geotechnical risk management in Bojong Koneng. Future research should include detailed subsurface investigations, geotechnical laboratory testing, groundwater monitoring, and quantitative slope stability analyses to verify potential slip surface geometry, material properties, groundwater responses, and ground displacement rates before developing detailed engineering designs.

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CONFLICT OF INTEREST

The author states that this research was conducted without any commercial or financial relationship that can be interpreted as a potential conflict of interest.

AUTHOR'S CONTRIBUTION

The author fully contributes to the formulation of the main idea, collects library data, analyzes and interprets the primary text of the figure, and prepares the manuscript. All authors have agreed on the final version of the manuscript.

GENERATIVE ARTIFICIAL INTELLIGENCE USAGE STATEMENT

The author states that generative artificial intelligence (AI) was used in the preparation of this manuscript. The author acknowledges the use of generative AI to help improve language clarity and improve the grammatical structure of the manuscript. The use is done in compliance with the applicable ethical guidelines regarding the use and disclosure of generative AI in scientific research. Each author has made substantial intellectual contributions to this work. The entire manuscript content has been carefully reviewed to ensure its accuracy, and the author is solely responsible for the integrity and final content of the manuscript.

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