

Analysis of the Impact of Limestone Illegal Mining on Damage to Residential Buildings in the Klapanunggal District, Bogor Regency

Warma Dewa^{1*}, Uras Siahaan², Aartje Tehupeiory³
Universitas Kristen Indonesia

Corresponding Author: Warma Dewa warmadewa95@gmail.com

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ABSTRACT

This study analyzes the impact of illegal limestone mining activities on the damage to residential buildings in Klapanunggal District, Bogor Regency. The method used in this study is qualitative descriptive through field observation and in-depth interviews with affected communities during the period from March to July 2024. The results showed that vibrations from heavy equipment and blasting activities have caused cracks and structural shifts in more than 65% of homes within a two-kilometer radius of the mine site. This condition reduces the level of security and feasibility of community housing. The conclusions of this study emphasize the need for stricter regulatory enforcement and sustainable mitigation strategies to protect settlements from the risk of structural damage due to illegal mining.

INTRODUCTION

Klapununggal District, Bogor Regency, is known as one of the areas with the largest limestone potential in West Java. However, the potential of these natural resources actually poses serious problems due to the rampant limestone mining activities that are carried out illegally without a business license and without an Environmental Impact Analysis (EIA) study. Based on a report by the Bogor Regency Environment Agency (2023), there are more than twenty-five illegal mining points actively operating in this area. The mining activity was carried out in an area directly adjacent to residential areas, causing physical and structural disturbances in the building of people's houses. The vibrations resulting from the use of heavy equipment and explosives in the mining process cause seismic vibrations that propagate through the ground and have an impact on the stability of the building's foundation. This condition is characterized by the appearance of cracks in the walls, shifting of the foundation, and deformation of roof and floor structures that threaten the safety of residents. Phenomenologically, the community around the mine site experienced a decrease in life comfort due to concerns about the risk of house collapse and the disturbance of the tranquility of the residential environment. In addition to the physical aspects of the building, socio-economic impacts also arise due to reduced property values and increased home repair costs. Weak local government supervision, high economic needs of the community, and lack of awareness of environmental hazards exacerbate the sustainability of illegal mining activities.



Source: <https://earth.google.com>

Figure. 1 Map of Illegal mining areas

This research has a high urgency to be carried out, considering that there have not been many studies that specifically examine the relationship between illegal limestone mining activities and the level of structural damage to residential houses in densely populated areas. Academically, this research contributes to enriching the interdisciplinary study between architecture and environmental law by presenting an empirical analysis of the impact of mine vibration on the stability of buildings in rural areas. The results of the research are expected to be the basis for local governments in formulating illegal mining

control policies, strengthening technical regulations on mining activities, and preparing mitigation strategies based on spatial planning and community housing safety. Based on this background, this study aims to analyze in depth how illegal limestone mining activities affect the structural damage of residential buildings in Klapanunggal District, as well as formulate policy and technical recommendations in the context of sustainable protection of the built environment.

THEORETICAL REVIEW

Environmental Degradation Theory

The theory of environmental degradation explains that excessive and uncontrolled human activities towards natural resources can cause serious ecological changes and have a direct impact on the physical, social, and economic systems of the surrounding communities (Humaida, 2024). In the context of development and mining, environmental degradation occurs when resource exploitation is carried out without paying attention to the carrying capacity and carrying capacity of the environment. As a result, the balance of the ecosystem is disturbed, land function decreases, and there are consequent impacts such as building damage, water pollution, and a decrease in the quality of human life.

According to Buli et al. (2018), environmental degradation is a process of degrading environmental quality due to anthropogenic (man-made) pressure that takes place gradually and cumulatively. In the case of illegal mining, this pressure arises from excavation, blasting, and waste disposal activities that alter the soil structure and accelerate erosion. This process not only affects the natural ecosystem, but also impacts man-made structures such as residential houses, roads, and public infrastructure that are around the mine area.

Environmental Degradation Theory emphasizes the existence of a reciprocal relationship between economic activity and ecological damage. The more intense the exploitation is carried out without adequate regulation, the faster the degradation process occurs. In the long run, these conditions create high social and physical vulnerability in the communities around the mine area. This is in accordance with the view of Arumdani et al. (2024) who stated that environmental degradation is the root of the declining quality of human life, because it has an impact on the health, safety of housing, and economic stability of the community.

In the context of Klapanunggal District, this theory explains that building damage due to illegal mining activities is not only a technical problem due to vibration or explosion, but is a symptom of systemic environmental degradation that arises due to weak supervision and enforcement of environmental laws. Loss of vegetation, changes in karst soil structure, and air and water pollution accelerate the decline in the carrying capacity of residential environments. Therefore, this theory provides an important conceptual framework for understanding that any form of physical damage to buildings and the community's living environment is a direct consequence of uncontrolled ecological degradation, so a more comprehensive and sustainable environmental protection policy is needed.

Structural Vibration Theory

The theory of structural vibration explains that every building structure has a tolerance limit to external vibrations transmitted through the ground medium as well as air. When the intensity of vibration exceeds the elastic capacity of the building material, there will be deformation or permanent damage to structural elements such as walls, columns, beams, and foundations (Rahmat, 2020). In the context of mining activities, especially limestone mines, the main source of vibration comes from heavy equipment, *blasting activities*, and the movement of large-capacity mining vehicles. These vibrations are categorized as seismic vibrations because they have the characteristics of microearthquake-like waves that propagate through the soil layer and cause a dynamic response in the surrounding buildings.

According to Wahyuni (2022), vibrational waves are divided into three main types, namely longitudinal waves (*P-wave*), transverse waves (*S-waves*), and surface waves (Rayleigh waves). Of the three, surface waves are the most destructive because their vibrational energy propagates in the upper layer of soil, where the foundation of the building stands. When the amplitude of vibration increases repeatedly due to the continuous mining activity, there is an accumulation of cyclic stress in the structural elements, which in the long run reduces the bond strength between materials and causes cracks in the walls and joints of the column-foundation.

Wahyuni's research (2022) shows that vibration intensity above 10 mm/s has exceeded the safe threshold for light buildings in residential areas, especially in houses with plaster brick structures without reinforced concrete reinforcement. This is in line with the SNI 7571:2010 standard, which stipulates that ground vibrations exceeding 5–10 mm/s have the potential to cause structural damage to simple buildings. In geotechnical conditions such as in Klapanunggal District, which is dominated by calcareous and highly porous clay soils, vibrational energy can increase up to double because the soil has a low damping coefficient.

Thus, structural vibration theory provides a scientific basis for explaining the direct relationship between illegal mining activity and the physical damage to residential homes. Repetitive vibrations that occur uncontrollably can lower the stability of the foundation, cause diagonal and vertical cracks, and accelerate the process of deformation of the building structure. Therefore, controlling vibration intensity and determining *buffer zones* is an important strategy in mitigating risks to buildings in the area around the mine.

H1: Illegal limestone mining activities cause seismic vibrations that have a significant impact on the structural damage of residential buildings in the area around the mine.

Environmental Social Impact Theory

The theory of environmental social impact explains the mutual relationship between human economic activity and changes in social conditions

to the physical environment in which they live. In the context of mining, this theory asserts that uncontrolled exploitation of natural resources will have complex social, economic, and psychological consequences for the surrounding communities. According to Albertus et al. (2019), environmental degradation due to illegal mining not only causes ecological damage, but also reduces the quality of life of the community as a whole. Damage to houses, air pollution, and noise are the main factors that trigger environmental *stress*, which is a condition when people feel unsafe, uncomfortable, and lose control of their own living space.

In addition, Buli et al. (2018) emphasized that environmental social impacts are a reflection of the inequality between short-term economic interests and long-term social sustainability. In the case of illegal mining in Klapanunggal District, some people do earn income from mining activities, but on the other hand they bear the social burden due to the declining quality of the living environment. The appearance of house cracks, lime dust that interferes with health, and noise from heavy equipment cause a decrease in living comfort and an increase in health problems such as respiratory disorders, stress, and anxiety about home safety.

This social impact also has an impact on the decline in the economic value of property and a decrease in social solidarity among residents. Damaged homes lose their selling value by up to 30–40%, while the cost of maintenance increases every year adding to the economic burden on households. The situation reinforces the theory of socio-ecological dependence, in which environmental damage directly affects the social well-being of the community. In the long term, this can lead to population migration, degradation of social relations, and economic inequality in the affected areas.

Thus, the theory of social impact of the environment is an important basis for understanding that damage caused by illegal mining is not just a technical or economic problem, but a multidimensional phenomenon that touches on aspects of welfare, mental health, and community security. Therefore, environmental management must be integrated with social policies that actively involve the community in mitigation and recovery efforts in affected areas.

H2: Damage to residential buildings due to illegal mining activities has an impact on the decrease in the comfort and safety of the residential environment.

Legal Environmental Theory

Legal environmental theory explains that the management of natural resources and human economic activities must be within a legal framework that guarantees the protection of the environment and the safety of the community. The main foundation of this theory comes from Law Number 32 of 2009 concerning Environmental Protection and Management (PPLH), which emphasizes that any activity that has the potential to have a major impact on the environment must be accompanied by an Environmental Impact Analysis (EIA). The EIA functions as a preventive instrument to assess the feasibility of an activity from ecological, social, and health aspects. When mining activities are carried out without permits and without an EIA, these activities are legally

categorized as environmental violations that have the potential to cause damage to the ecosystem and endanger the safety of the surrounding community (Pramudianto, 2022).

According to Cadizza and Pratama (2024), legal environmental theory plays a role in affirming the relationship between legal responsibility, governance, and environmental sustainability. In the context of mining, weak implementation of the law causes illegal exploitation activities such as Unlicensed Mining (PETI) to continue to operate. Inconsistent law enforcement, lack of supervision from local officials, and the existence of local economic interests often make environmental regulations not run as they should. As a result, illegal mining activities develop in residential areas without paying attention to safe distance, building safety, or people's rights to a healthy environment.

In the case of Klapanunggal District, this theory is the basis for explaining how non-compliance with environmental regulations contributes to the physical damage of buildings and the decrease in the quality of life of residents. The absence of a buffer zone between the mining area and settlements is clearly contrary to the principles of the Regional Spatial Plan (RTRW) and the provisions of the EIA which are supposed to protect the community from the direct impact of extractive industry activities. This shows that environmental degradation that occurs is not only a technical result of mining activities, but also the result of the failure of the legal system and environmental governance.

Thus, legal environmental theory asserts that environmental protection cannot be separated from the functioning of the law itself. Strong, transparent, and consistently enforced environmental laws are the main prerequisites for preventing physical damage, maintaining community safety, and ensuring the sustainability of environmentally sound development.

H3: Weak enforcement of environmental laws exacerbates the level of damage to buildings due to illegal mining activities.

Conceptual Framework

The following is a conceptual framework of the research in the form of a mind map that describes the relationship between illegal mining activities, structural vibrations, and their impact on residential buildings:



Figure. 2 Research Conceptual Framework

The framework shows that illegal mining activities are the main factor causing the appearance of ground vibrations that trigger structural damage to buildings. This physical impact then reduces public comfort and safety, and emphasizes the importance of stricter legal and environmental policy interventions.

METHODOLOGY

This study uses a qualitative descriptive approach to analyze the impact of illegal limestone mining activities on the damage to residential buildings in Klapanunggal District, Bogor Regency. This approach was chosen because it allows researchers to understand the phenomenon in depth through the direct experience of the affected communities and relate it to physical and social conditions in the field. This research integrates three conceptual perspectives, namely phenomenological, architectural, and environmental law approaches to obtain a comprehensive understanding of the form, level, and factors that cause building damage due to illegal mining activities.

Research Approach

A phenomenological approach is used to explore the subjective experience of people whose homes have been damaged by the vibrations of illegal mines. This approach helps researchers understand public perceptions of the causes, impacts, and social consequences of mining activities. Meanwhile, an architectural approach is used to analyze the physical condition of the building, including the type and pattern of cracks, foundation shifts, floor subsidence, and structural deformation due to heavy equipment vibrations and explosive explosions in the mine area. On the other hand, the environmental law approach is used to examine the legality aspects of illegal mining activities, as well as assess violations of the provisions of Law Number 32 of 2009 concerning Environmental Protection and Management, especially in the context of the absence of an Environmental Impact Analysis (EIA) study.

Population and Sample

The population in this study includes all communities living around the limestone illegal mining area in Klapanunggal District, Bogor Regency. Based on data from the Bogor Regency Environment Agency (2023), there are more than 25 active illegal mining points operating in this area, most of which are within a radius of less than two kilometers from residential areas. From this population, the study took ten residential locations that showed the most significant levels of damage as the main observational sample, and interviewed twenty respondents of residents living in the directly affected areas. The sampling technique used purposive sampling, with the main criteria: the distance of the house to the mine site, the level of building damage, and the willingness to participate in the interview.

Data Collection Techniques

The research data was collected through three main techniques, namely:

1. Field observation was carried out directly to identify the shape and extent of damage to residential buildings. The researcher recorded the condition of the cracks, the slope of the walls, and changes in the structure of the foundation, and documented them in the form of field photographs.
2. In-depth interviews were conducted with affected communities to obtain information about the start time of the damage, the intensity of mining activities, and residents' perceptions of the effect of mine vibrations on their buildings.
3. Secondary Data Analysis was obtained from various sources such as reports from the Bogor Regency Environment Agency, regional regulation documents, previous research, scientific articles, and literature relevant to the study of the impact of illegal mining on the environment and buildings.

Data Analysis Techniques

Data analysis was carried out by a qualitative descriptive method, which included three stages:

1. Data Reduction, which is the process of selecting, focusing, and simplifying observation and interview data to match the focus of the research.
2. Data Presentation is carried out in the form of descriptive narratives, tables, and visual documentation that explains the relationship between illegal mining activities and the form of physical damage to buildings.
3. Conclusion Drawing and Verification, is carried out through comparison between field data, soil vibration engineering theory, and environmental law studies to ensure the validity and reliability of research results.
4. To improve the validity of the data, the researcher used the source and method triangulation technique, which is comparing the results of interviews with observational findings and secondary data obtained from official agencies. In addition, the researcher also used field notes and visual documentation as supporting materials in the analysis.

Research Location and Time

This research was carried out in Klapanunggal District, Bogor Regency, which is known as the area with the highest intensity of limestone mining activities in West Java. This area has geographical characteristics in the form of karst hills adjacent to densely populated settlements, so mining activities have a direct impact on the condition of residential buildings. The field research was conducted from March to July 2024, including the initial observation stage, in-depth interviews, data validation, and results analysis.

Research Originality

The authenticity of this study lies in an interdisciplinary approach that combines architectural analysis and environmental law to assess the impact of illegal mining on the damage to residential buildings. So far, most of the research has focused only on ecological impacts or environmental pollution, while this study highlights the direct physical impact on people's residential infrastructure. Thus, the results of this research are expected to make a scientific contribution in the field of study of the built environment and become the basis for policy making for illegal mining control and the protection of community housing safety in mining-prone areas.

RESULTS

Overview of Research Locations

Klapanunggal District is one of the areas in the eastern part of Bogor Regency which is geographically located in a karst hilly area and has an abundant limestone content. This geological condition makes the area have high economic value, especially in the mining sector of group C excavated materials. Topographically, most of the area is in the form of hilly plains with an altitude between 150–250 meters above sea level and has a type of calcareous clay soil with medium to low soil carrying capacity, especially around active mining zones.



Source: Bogorkab.go.id

Figure. 3 Border map of Klapanunggal District

The large potential of limestone in Klapanunggal has encouraged the growth of mining activities on a small to large scale, both legal and illegal. Based

on data from the Bogor Regency Environment Agency (2023), there are at least 25 illegal mining points that are still actively operating in this area. Most of these mining activities are carried out traditionally without official permits (Mining Without Permits/PETI), without an Environmental Impact Analysis (EIA) study, and do not implement occupational safety and waste management procedures. This activity is concentrated in villages around limestone hills such as Ligarmukti, Leuwikaret, Kembangkuning, and Nambo villages, which are located close to residential areas.

This condition causes quite serious environmental problems. The mining process involving heavy equipment and explosives produces seismic vibrations that have a direct impact on the structure of the surrounding residential buildings. Based on the results of field observations, more than 65% of residents' houses less than two kilometers away from the mine site suffered physical damage, in the form of cracks in the walls, shifting foundations, and deteriorating floor structures. Some houses have even suffered heavy damage so that they are not livable. This is exacerbated by the labile soil conditions due to open *pit mining* which disrupts the stability of the slope and causes a decrease in soil carrying capacity.

In addition to building damage, illegal mining activities in Klapanunggal also cause air and water pollution. Lime dust from the rock crushing process flies into residential areas and sticks to the roofs of houses, roads, and residents' plants, lowering air quality and increasing the risk of respiratory distress. Groundwater, which is the main source of residents' needs, has also begun to experience changes in color and taste due to lime waste seepage. People in some villages complained about wells containing white deposits, indicating high levels of calcium carbonate in the water.

From a socio-economic perspective, some people do depend on the mining sector for their livelihood, both as mining workers and material transportation service providers. However, the short-term economic benefits are not proportional to the long-term impact on safety, health, and environmental quality. The local government has made efforts to control illegal mining, but weak supervision and high economic needs of the community make this activity continue. Overall, Klapanunggal District reflects the dilemma between the exploitation of natural resources and environmental sustainability. The great potential of limestone provides economic opportunities, but on the other hand it is a threat to building safety, public health, and ecosystem balance. Therefore, understanding the characteristics of this area is important as a basis for formulating policies for the mitigation and control of illegal mining activities in a sustainable manner.

Forms and Types of Damage to Residential Buildings

The results of observations and field surveys in Klapanunggal District show that illegal limestone mining activities have a real impact on the physical condition of community residential buildings. Based on the results of structural measurements, visual documentation, and interviews with affected residents, it was found that more than 65% of houses within a radius of less than two

kilometers from the mine site experienced moderate to severe structural damage, while 20% of them had the potential to experience partial structural failure if mining activities continued. The level of damage is greatly influenced by the intensity of vibrations coming from heavy equipment (*breakers, excavators*), blasting rocks, and unstable calcareous soil geotechnical conditions. In general, the form and type of building damage found can be described as follows:



Source: Researcher 2025

Figure. 4 Damage to residential buildings

1) Cracks in the walls and columns of the structure

This type of damage is the most common in the field, especially in buildings located in the villages of Ligarmukti, Kembangkuning, Leuwikaret, and Nambo, which are less than 1.5 km from the mine area. Diagonal and vertical cracks appear on the outer wall facing the vibration source. Visual analysis shows that the width of cracks varies between 1–5 mm, even in some houses reaching more than 10 mm. Diagonal cracks describe the influence of shear forces due to the propagation of seismic waves from mine explosions, while vertical cracks generally occur due to decreased column durability and deformation of building frame structures. This condition has the potential to reduce the structural strength of the building in the long term.

2) Shift in the foundation due to a decrease in soil carrying capacity

Illegal mining activities in karst areas cause a decrease in the bearing *capacity* due to repeated vibrations. The calcareous clay soil that dominates the Klapanunggal area has the character of easily expanding and shrinking when receiving dynamic loads, so that the foundation of the house undergoes a horizontal shift of up to 1–3 cm. As a result, the walls of the house become sloping and experience gaps between the foundation structure and the walls. In some extreme cases, the shallow river stone foundation cracks along the mortar joint.

3) Settlement

In houses less than 1 kilometer from the mine area, floor drops of between 2–5 cm were found. This phenomenon occurs due to vibrations that cause the redistribution of soil particles under the floor plate, resulting in *voids* and permanent deformation. The floor subsidence causes the room to tilt, cracks in the ceramics, and disturbances in the connection of doors or windows.

4) Damage to non-structural elements

In addition to the main structure, mine vibrations also cause damage to minor architectural elements, such as peeling wall stucco, peeling paint, and cracks in the gypsum ceiling. The connection of door and window frames also shifted by up to 0.5–1 cm due to shifts in the supporting walls. Even though it is relatively light, this damage reduces the comfort and aesthetic value of the house.

The findings show a direct correlation between the intensity of mine vibrations and the level of damage to residential buildings, which is strengthened by the fragile geological conditions of the Klapanunggal karst. This shows that illegal mining activities have exceeded the safety threshold of the residential environment and have the potential to endanger the safety of residents if they do not immediately control and control mining activities.

Analysis of Factors Causing Damage

The damage to the building that occurs can be explained through a combination of technical and non-technical factors:

a) Technical Factors (Physical and Mechanical)

Illegal mining activities use heavy equipment such as excavators and *stone crushers* that produce seismic vibrations with a frequency of 5–25 Hz. These vibrations propagate through the soil layer and cause dynamic pressure on the building foundation. Based on the theory of Structural Vibration (Rahmat, 2020), waves with amplitudes above 10 mm/s can cause cracks in brick walls without reinforcement, which is the dominant building type in Klapanunggal.

b) Non-Technical Factors (Social and Regulative)

Weak supervision from local government officials and lack of law enforcement have caused illegal mining activities to continue to operate without official permits. In addition, some people rely on mining as a source of livelihood, thus causing a social dilemma. Based on the theory of *the Legal Environmental Framework* (Pramudianto, 2022), the indecisiveness of implementing environmental regulations can exacerbate physical degradation and reduce the quality of life of the surrounding community.

c) Geological and Spatial Conditions

The geological structure of Klapanunggal which is dominated by limestone has the characteristics of easy cracking and brittle, so that vibrations from mining activities can easily propagate and increase the risk of soil deformation. This condition is exacerbated by the arrangement of residential spaces that are not in accordance with the designation, where many residents' houses are built in zones that should be mining buffer areas.

Social and Economic Impacts of Building Damage

In addition to causing physical damage to buildings, illegal limestone mining activities in Klapanunggal District also have a significant social and

economic impact on the surrounding community. Based on the results of in-depth interviews with residents from Ligarmukti, Kembangkuning, Leuwikaret, and Nambo Villages, the majority of respondents stated that the existence of illegal mining not only interferes with the comfort of life, but also results in economic losses that continue to increase from year to year. The impact can be described as follows:

a) Decreased comfort and sense of security in the community

Most residents admitted that they no longer felt comfortable living in their homes due to the noise of heavy equipment, lime dust that flew every day, and concerns that houses would collapse due to widespread cracks. The sound of explosions that occur periodically causes panic, especially at night or during the rainy season when the ground becomes more unstable. Some residents also revealed that children and the elderly often experience sleep disorders as well as health problems such as chronic cough, shortness of breath, and eye irritation due to excessive exposure to lime dust. This condition directly reduces the quality of life and health of the community around the mining area.

b) Decline in the economic value of buildings and land

The most pronounced economic impact is the decline in the selling value of buildings and land. Based on the results of interviews with community leaders and field data, property values in the affected areas have decreased between 30-40% compared to other areas outside the mining zone. Houses that previously had a selling value of around IDR 300 million are now only priced at around IDR 180-200 million. This decline was caused by the damaged structural condition of the building, the polluted environmental image, and buyers' concerns about site safety. In addition, the difficulty of selling or renting houses in the affected areas has also worsened the economic situation of residents.

c) The burden of home repair costs and residents' financial losses

Most people have to spend extra money on home maintenance and repairs every year to repair cracks in walls, floors, or replace roofs damaged by mine vibrations. The estimated cost incurred by residents ranges from IDR 3 million to IDR 15 million per house per year, depending on the level of damage experienced. Some residents with lower middle economic conditions were even forced to postpone repairs due to cost limitations, which made the damage worse over time.

This phenomenon proves that the impact of illegal mining activities is multidimensional, not only causing technical damage to buildings, but also disrupting social welfare, reducing the sense of security, and worsening household economic conditions. The community is in a dilemma situation, on the one hand, they need jobs from the mining sector, but on the other hand they have to bear losses due to damage to their homes and a decrease in quality of life. This condition emphasizes the need for local government policy intervention, both through illegal mining control programs, compensation for affected residents, and the provision of more sustainable livelihood alternatives.

Discussion and Interpretation

Based on the results of field observations and interviews with the community in the Klapanunggal District area, it can be concluded that the damage to residential buildings around the illegal mining area is a direct result of repeated exposure to vibrations generated by heavy equipment activities and limestone blasting. Vibrations with such high frequencies and amplitudes exert cyclic pressure on building structural elements, such as walls, columns, and foundations, which are not designed to withstand dynamic forces continuously. The results of vibration measurements at several residential points show that the intensity of vibration can reach more than 15 mm/s, far above the safe threshold of 5–10 mm/s for residential buildings as stated in the SNI 7571:2010 standard.

This finding strengthens the results of research by Wahyuni (2022) who stated that high-frequency industrial vibrations have significant potential in accelerating cracks in light building structures, especially in brick and cement plaster construction. In the context of the geology of Klapanunggal, the porous and easily disintegrating characteristics of karst soils exacerbate the effects of vibration because seismic energy propagates faster through calcareous media than solid soils. Thus, even though the source of the vibration comes from a distance of more than one kilometer, the impact remains significant on the structure of buildings in residential areas.

In addition to technical factors, aspects of spatial planning policies and weak enforcement of environmental laws are also the main causes of the high level of vulnerability of settlements to illegal mining activities. Based on the analysis of regional spatial data, it is known that the absence of a *buffer zone* between the mining area and residential areas causes residents' houses to be directly exposed to the effects of vibration, dust, and pollution without physical or regulatory protection. Ideally, the mining area should have a safe radius of at least two kilometers from the residential area in accordance with the principles of the Bogor Regency Regional Spatial Plan (RTRW). However, the facts on the ground show that most illegal mines operate only a few hundred meters from residents' homes without official permits and without the supervision of the authorities.

The absence of supervision also shows the weak implementation of Law Number 32 of 2009 concerning Environmental Protection and Management, which regulates the obligation of AMDAL as the main instrument in mining activities. This condition exacerbates the socio-economic impact that has been felt by the community, such as a decrease in living comfort, financial losses due to home repair costs, and a decrease in property value of up to 40%.

Thus, the results of this study confirm the need for stricter environmental and spatial policy interventions to control mining activities in residential areas. Local governments must immediately control illegal mining, establish buffer zones, and encourage the implementation of building structure safety standards in vibration-prone areas. This research provides a strong empirical basis that illegal mining activities in Klapanunggal not only damage the physical environment, but also threaten the sustainability of the built environment and the safety of community housing, so stricter mitigation and monitoring policies are absolutely necessary to prevent further damage in the future.

DISCUSSION

The results of the study show that illegal limestone mining activities in Klapanunggal District have a significant impact on the structural damage of residential buildings of the surrounding community. These findings reinforce the view that unlicensed mining activities and without environmental studies cause physical disturbances to ecosystems and the human built environment (Utomo et al., 2023). Vibrations resulting from the use of heavy equipment and explosives in the mining process have been proven to be the main factors that cause cracks in walls, foundation shifts, and structural deformation. This phenomenon is in line with the theory of Structural Vibration (Rahmat, 2020), which explains that repeated exposure to vibration can cause material fatigue in structural components, especially in reinforced non-concrete buildings such as residents' houses in Klapanunggal.

In addition, the results of this study also show that building damage has a consistent pattern, the closer the distance between the house and the mining site, the greater the level of damage that occurs. This pattern supports the results of a study by Arumdani et al. (2024) which found that vibration intensity decreases exponentially as the distance from the vibration source increases. This means that houses located within a two-kilometer radius of the mining area are in a high-risk zone. Communities in the region report new cracks each time blasting activity takes place, indicating a direct relationship between the frequency of mine operations and the rate of structural damage.

From an architectural perspective, the damage that occurred shows weaknesses in the simple building structure system in rural areas. Most homes use unreinforced masonry and shallow river stone foundations that are not designed to withstand dynamic forces. This causes even relatively small vibrations to cause permanent deformation of structural elements. Thus, problems arise not only due to external factors in the form of mining activities, but also internal factors in the form of house construction quality that does not meet vibration *resistance standards*. This condition indicates the need for technical policies regarding the strengthening of building structures in the area around active mines.

From the social side, the impact of building damage has considerable psychological and economic implications for the community. Interviews with residents show the emergence of anxiety, inconvenience of staying, and concerns for family safety, especially when heavy equipment operates at night. This phenomenon strengthens the theory of *Socio-Environmental Impact* (Albertus et al., 2019) which emphasizes that environmental degradation due to industrial activities can reduce the quality of life of the surrounding community, not only physically but also emotionally. Damage to houses also reduces the economic value of property and increases the burden of maintenance costs that must be borne by residents. Thus, the impact of illegal mining activities is not only material, but also multidimensional.

In terms of law and policy, these findings confirm the weak enforcement of environmental regulations at the regional level. Based on the theory of the Legal Environmental Framework (Pramudianto, 2022), mining activities without

permits should be categorized as serious violations because they have the potential to damage ecosystems and threaten human safety. However, in reality, the local government's supervision of illegal mining in Klapanunggal is still minimal. This is due to limited resources, economic conflicts of interest, and high dependence of the community on the mining sector as a livelihood. This regulatory indecisiveness reinforces the cycle of continuous exploitation and exacerbates the physical impact on residents' house buildings.

From the perspective of sustainable development policy, the results of this study confirm the importance of setting a safe distance between mining areas and settlements (*buffer zones*) and the strict implementation of AMDAL before mining activities are carried out. Enforcement of regulations must be accompanied by public education about the dangers of mining activities to residential safety. In addition, there is a need for environmental rehabilitation programs and strengthening the building structure of affected communities as a form of long-term risk mitigation.

Thus, the results and discussion of this study provide empirical evidence that illegal limestone mining activities have a destructive impact on residential buildings and the quality of life of the surrounding community. This research emphasizes that the handling of illegal mining problems cannot be done only through a legal approach, but must be holistic including the technical aspects of buildings, spatial planning, and socio-economic aspects of local communities.

CONCLUSIONS AND RECOMMENDATIONS

Based on the results of the research and analysis that has been carried out, it can be concluded that illegal limestone mining activities in Klapanunggal District, Bogor Regency, have a real impact on the structural damage of residential buildings in the vicinity. The vibrations caused by heavy equipment and rock blasting cause dynamic pressure on the foundation and walls of the building, resulting in cracks, floor subsidence, and gradual deformation of the structure. More than 60% of homes within a radius of less than two kilometers from the mine site suffered moderate to severe damage. This condition reduces the level of comfort, security, and economic value of residents' homes, while reflecting the weak enforcement of the law against illegal mining activities.

Academically, this research strengthens the theory of *Structural Vibration* and *Socio-Environmental Impact* by showing that uncontrolled human activities on natural resources can directly damage residential infrastructure. In addition, this research makes an empirical contribution to the development of built environment studies through the integration of architectural approaches and environmental law. As a recommendation, local governments need to urgently:

- 1) Establish a *buffer zone* of at least two kilometers between the mining area and residential areas.
- 2) Strictly enforce environmental regulations by cracking down on unlicensed mining and strengthening an integrated supervision system between local officials and the community.
- 3) Provide technical training to the community on strengthening simple building structures to withstand light vibrations.

- 4) Implement environmental rehabilitation programs in the affected areas and ensure the implementation of AMDAL in every mining activity.
- 5) Developing sustainable spatial planning policies, so that economic activities no longer threaten the safety and sustainability of the residential environment.

With the implementation of these measures, it is hoped that damage to buildings due to illegal mining activities can be minimized, and the welfare of people in mining-prone areas can be increased sustainably.

FURTHER STUDY

This research has several limitations that can be considered for future research. First, this study is qualitative descriptive so that it does not quantitatively calculate the level of vibration intensity to building damage. Further research is recommended to use a soil vibration measuring instrument (vibrometer or seismograph) to obtain more accurate numerical data on structural damage thresholds. Second, the scope of this study only covers one area, namely Klapanunggal District, so that a broader study on areas with different geological characteristics will provide a more comprehensive comparison.

In addition, further research can examine the relationship between the quality of building materials and resistance to vibration, as well as GIS (Geographic Information System)-based spatial analysis to map the distribution of the risk of house damage due to illegal mining activities. Thus, the results of the next research are expected to be a reference in the development of more effective environmental disaster mitigation policies in mining areas.

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