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Toll Road Resilience to Landslide Hazard in Indonesia

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Abstract

Toll roads are critical public infrastructure that drive economic growth and regional development. However, due to Indonesia geographical location which is characterized by its position on the Pacific Ring of Fire, toll roads are vulnerable to natural disasters, particularly landslides. Despite the government's efforts to improve infrastructure resilience, research focused on toll road resilience remains limited. This study aims to develop a methodology to investigate several factors that affecting toll roads resilience to landslide in Indonesia using quantitative approach. The data collected using a Likert scale through a structured questionnaire based on purposive sampling technique. Respondents involved in this research are professionals which have experience in the planning, construction, and management of toll roads. Exploratory Factor Analysis (EFA) is used to uncover and classify the variables into several key factors impacting toll road resilience. In addition to the research methodology, this paper presents a preliminary survey result of the research by determining relevant variables that have been identified from literature. According to the preliminary survey, 18 variables were considered relevant for this research and will be used in the main survey. This research provides a theoretical framework for enhancing toll road resilience in Indonesia by understanding critical factors which influence to toll road resilience to recover from landslide hazard. The results offer practical insights and policy recommendations for improving disaster risk management and infrastructure sustainability.

Keywords
Infrastructure, hazard, landslide, toll road resilience.

1. Introduction

In recent years, infrastructure development in Indonesia has been quite intensive. As an archipelagic country with unique geographical conditions, infrastructure plays a crucial role in supporting connectivity and economic growth. To achieve the vision of "Indonesia Maju 2045" and accelerate economic development, the government has designated infrastructure development as one of its key policies in 2023 (Ministry of Finance of the Republic of Indonesia, 2023). Infrastructure development is a fundamental pillar in ensuring equitable national progress. Reliable infrastructure not only drives economic growth but also influences other key aspects of development, including education, social welfare, regional accessibility, and the distribution of goods. To accelerate infrastructure development, the government has allocated substantial state spending and implemented various policies to enhance progress. In the 2023 budget year, the Ministry of Public Works and Housing (PUPR) received funding for five major programs, with the largest allocation—IDR 86.5 trillion or 47.55% of the total budget—dedicated to the connectivity infrastructure program (PUPR, 2023).

One critical type of infrastructure is toll roads, which fall under the category of transportation infrastructure. In urban systems, essential infrastructure such as buildings, transportation networks, and energy and water systems play a vital role in maintaining social functions. Damage to this infrastructure can deteriorate urban conditions and disrupt economic activities (Yang et al., 2022). The construction of toll roads as a key element in the economy plays an important role in driving medium and long-term economic growth. For example, the construction of the Tangerang-Merak toll road has contributed significantly to the regional income of Banten Province. In the third quarter of 2013, this toll road contributed around 5.7% to the economic growth of this province (Anggraini 2024). This shows that the construction of toll roads is a strategic step to improve connectivity, which can indirectly have a positive impact on economic growth.

Indonesia's geographical location at the convergence of the Eurasian, Indo-Australian, and Pacific plates places it within a volcanic belt, making it highly susceptible to natural disasters such as volcanic eruptions, floods, earthquakes, and landslides. These disasters frequently cause severe damage to buildings and physical infrastructure. Additionally, global warming and climate change have intensified the frequency and severity of natural disasters, including floods, earthquakes, droughts, and tornadoes (Agustin & Adi, 2021). The increasing frequency of these disasters has made transportation infrastructure more vulnerable to disruptions (Nipa et al., 2023). Indonesia has recorded 44,233 disasters, with 7,437 of them being landslides. In 2023, there were 427 landslides, 183 of which occurred on Java Island. These events affected 362,277 people, resulted in 3,198 fatalities, and caused significant damage to homes, educational and healthcare facilities, places of worship, and other public infrastructure (BNPB, 2024). According to PUPR (2023), landslide occurrences in Indonesia have been on the rise from 2012 to 2022. Landslides and floods are among the most frequent disasters in the country. Based on disaster trends from 2014 to 2023, wet hydrometeorological disasters—such as floods, landslides, and extreme weather—are the most prevalent, followed by dry hydrometeorological disasters such as forest and land fires. However, in terms of fatalities and missing persons, landslides remain the deadliest disaster, claiming 144 lives, followed by floods, extreme weather, volcanic eruptions, and droughts (BNPB, 2023).

From January to July 2024, landslides were the disaster with the highest occurrence in Indonesia, with 252 incidents, followed by floods with 248 incidents (BNPB, 2024). According to news reports, the disasters that often occur on toll roads are floods and landslides. However, landslides have a greater impact on toll road operations. Landslides on toll roads can cause lane closures and temporary suspension of toll road operations. In 2022, a landslide occurred on the Pandaan-Malang Toll Road KM 78-79, causing the toll road to not function optimally, only one lane was open in each direction (detikJatim 2024). Landslide material covering the toll road had to be cleared using heavy equipment, which took several days. In addition, on February 26, 2023, the shoulder of the Purwakarta Toll Road experienced a 15-meter landslide due to heavy rain (Sinulingga 2024). As a result, residents' activities and tourist flows are disrupted because vehicles have to take turns crossing. In 2020, landslides also occurred on the Purbaleunyi KM 118 Toll Road (Iqbal 2024). The impact of landslides on toll roads not only causes material losses but also affects people's lives. When landslides disrupt toll road operations, their effectiveness decreases because they cannot function optimally. Toll roads, which are designed as alternative routes for fast and efficient travel (Jasamarga 2023), experience decreased performance when disasters cause delays and increased congestion on national roads. This disruption not only reduces the main benefits of toll roads but also has a negative impact on people's mobility and economic activities.

From a sustainability perspective, disruption to toll road operations reduces its role in achieving equitable development and regional development (PUPR 2023). Toll road closures or disruptions hamper the flow of goods and services, causing delays in the supply chain. This results in increased logistics costs and prices of goods on the market, which ultimately harms consumers. Disruptions in accessibility and connectivity between regions also affect economic development in the affected areas. Significant economic losses can occur due to delayed delivery of goods, causing the manufacturing industry, trade, and service sectors to experience decreased production and income due to delays in the distribution of raw materials and finished products. Sustainable development is an urgent global agenda to ensure social, economic and environmental welfare for current and future generations. Resilient infrastructure development is one of the main pillars in achieving the 2030 Sustainable Development Goals (SDGs). According to Peraturan Presiden (2017), the Indonesian government is integrating national development programs with the 2030 Sustainable Development Goals (SDGs) by preparing a "Sustainable Development Action Plan".

To reduce the impact of landslides on toll roads, the application of the resilience concept is very important as a disaster preparedness measure. Resilience can be increased through actions taken before and after a disaster occurs. The resilience of toll roads to natural disasters is increasingly urgent given the increasing frequency and intensity of disasters triggered by climate change. This resilience not only aims to protect large investments in toll road construction but also to ensure that the transportation network remains operational and supports rapid recovery after a disaster. This is in line with SDG 9 (Industry, Innovation and Infrastructure), which emphasizes the importance of quality and resilient infrastructure, and SDG 11 (Sustainable Cities and Communities), which highlights the need for inclusive, safe, resilient and sustainable cities and human settlements (Department of Economic and Social Affairs 2024).

In recent years, researchers and national and international organizations have emphasized the importance of resilience compared to recovery measures (Wan et al. 2017), and this concept is gaining popularity. Resilience ensures that a system can withstand disasters, both expected and unexpected, by minimizing damage (Nipa et al. 2023). Repairing and upgrading critical urban infrastructure has great potential to make cities more resilient (Yang et al. 2022). According to Jia et al. (2023) resilience refers to the ability of a system to withstand and recover from external disasters. In civil engineering, resilience refers to the ability of a system to withstand or recover from disasters such as earthquakes, floods, landslides, and explosions (Jia et al. 2023). Resilience assessment is a popular and commonly used method to understand complex resilient systems and their properties and characteristics. Resilience assessment frameworks are often indicator-based. Resilience assessment reflects characteristics that are important for risk and disaster prevention (Yang et al. 2021). Indicators are assessed based on their ability to describe infrastructure in the face of disturbances or shocks and to support stakeholders in decision making (Yang et al. 2022).

Research on resilience in Indonesia is still in early-stage phase. For example, research on urban resilience in Surabaya assesses infrastructure resilience to hazards (Fauzan 2018), research by Ciptaningrum evaluates urban areas from a social aspect, namely social resilience in dealing with flood disasters due to climate change in Gresik (Ciptaningrum 2017). These studies are generally indicator-based. Other research conducted by Agustin and Adi (2021) measures the level of resilience of a city based on earthquake simulations. Most research on resilience in Indonesia discusses the resilience of a city in general and does not focus on one particular type of infrastructure such as toll roads. Research on the resilience of toll roads to landslides in Indonesia is still limited, although its urgency is very high. The resilience of toll road infrastructure not only affects transportation and economic efficiency but also the safety and welfare of the community. Damage to toll roads due to landslides can disrupt the distribution of goods and services, cause significant economic losses, and hinder accessibility to affected areas.

Based on previous research, the resilience of an infrastructure is influenced by various factors. This paper aims to present a methodology to identify factors that influence the resilience of toll roads in Indonesia to landslides to realize sustainable infrastructure in Indonesia. By using an indicator-based approach and involving experts in the field, this study is expected to provide comprehensive insights and practical solutions to improve the resilience of toll roads. The results of this study will contribute to the formulation of more effective policies and the implementation of best practices in the development of resilient infrastructure. This, in turn, supports the sustainable development agenda in Indonesia, ensuring that critical infrastructure such as toll roads can continue to operate safely and efficiently despite the threat of natural disasters.

2. Literature Review
2.1 Resilience
According to UNISDR (2009) as cited in Ciptaningrum (2017), resilience is the ability of a system, community, or society affected by a hazard to resist, absorb, accommodate, and recover quickly and efficiently from its impact, including the preservation and restoration of essential structures and functions. Yang et al. (2022) defines resilience as the capacity to maintain functionality despite disruptions. Meanwhile, Jia et al. (2021) describes resilience as a system's ability to withstand and recover from external disasters. In the context of civil engineering, resilience refers to the ability of a system to endure or recover from disasters such as earthquakes, floods, landslides, and explosions.
Based on these definitions, it can be concluded that resilience is a broad concept, whereas this study specifically focuses on infrastructure resilience, which is one aspect of resilience. Over time, disaster risk management has evolved from merely emergency response to proactive efforts aimed at enhancing resilience at the individual, community, national, regional, and global levels. Strengthening infrastructure resilience is considered more efficient than rehabilitation or recovery efforts. According to Pamungkas (2013), disaster risk management encompasses several key concepts, including resilience, vulnerability, and adaptation. While these concepts are interrelated, they are distinct from one another. Resilience is viewed as a characteristic of a community's dynamic system in responding to hazards, where its nature is both systemic and time-dependent. Adaptation, on the other hand, refers to actions taken by stakeholders to minimize the impact of disasters. Resilience, however, is the outcome of actions implemented to reduce disaster risk (Fauzan, 2018).

2.2 Toll Road Resilience
In the context of infrastructure, particularly highways, resilience refers to a system's ability to maintain operations in the face of adverse events such as natural disasters, accidents, or terrorist attacks. Infrastructure resilience is defined as the capacity of a system or network to sustain its performance despite unexpected external disturbances (Fauzan, 2018). Resilience is characterized by the ability to preserve a system's essential functions even when certain components are compromised due to unforeseen circumstances. A major challenge in infrastructure resilience is the rapid decline in performance following a disaster. A well-prepared city must be able to withstand such disruptions by providing essential facilities, including emergency response systems and adaptive learning mechanisms, as key physical responses after a disaster. This encompasses robustness, effective contingency planning (redundancy), and the capacity to restore services and functions swiftly after disruptions (rapid recovery) (Wan et al., 2018).

Highway resilience specifically refers to the ability to continue operating despite unexpected events, mitigate impacts, and implement effective crisis response and recovery efforts (Liao et al., 2018). According to Nipa et al. (2023), highway resilience is the ability to withstand disruptions while maintaining core structures and functions and recovering performance after a disaster. In essence, highway resilience can be understood as the capability to sustain operations despite unforeseen challenges. Several factors influencing toll road resilience have been identified in the literature, as summarized in Table 1.

Table 1. Factor Influence to Toll Road Resilience

No	Variable	Source	Definition
1	Total Length of Disrupted Roads	Nipa et al. 2023; Nipa and Kermanshachi 2022; Sun et al. 2020; Ganin et al. 2019	A shorter length of damaged road minimizes delay times and reduces the overall impact of connectivity disruptions.
2	Number of Lanes	Nipa et al. 2023; Nipa and Kermanshachi 2022; Sun et al. 2020	Having multiple lanes provides the opportunity to make one lane a reversible lane to ensure vehicle mobility.
3	Number of Alternative Roads	Nipa et al. 2023; Nipa and Kermanshachi 2022; Sun et al. 2020	A greater number of alternative routes enhances network redundancy, enabling the system to function more effectively after a disaster.
4	Distance of Intersections from Landslide-Affected Areas	Nipa et al. 2023; Nipa and Kermanshachi 2022; Sun et al. 2020	The intensity of the disaster impact will decrease as the distance of the intersection from the landslide centre increases because a disrupted intersection will cause a longer delay.

No	Variable	Source	Definition
5	Availability of Previous Landslide Disaster Data on Toll Roads	Nipa et al. 2023; Nipa and Kermanshachi 2022; Besinovic 2017	Historical data will allow to predict the level of disruption and hence help in better preparation for disaster management.
6	Access to Landslide Disaster Data	Nipa et al. 2023; Nipa and Kermanshachi 2022	Ease of access to disaster data will help in the preparedness and recovery phase.
7	Availability of Emergency Response Equipment	Nipa et al. 2023; Nipa and Kermanshachi 2022; Sun et al. 2020; Liao et al. 2018	Having sufficient emergency response equipment supplies can help in recovery activities.
8	Access to Required Resources	Nipa et al. 2023; Nipa and Kermanshachi 2022; Wan et al. 2018	The ability to acquire and use resources such as machinery, materials and people, quickly and efficiently to restore the functionality of the affected road, will make the system more resilient.
9	Employee Knowledge of Resilience	Nipa et al. 2023	People with the right knowledge about resilience can be very helpful in management and will have the will to improve the resilience of toll roads to disasters.
10	Availability of Learning Media on Toll Road Resilience	Nipa et al. 2023; Nipa and Kermanshachi 2022; Nipa et al. 2023; Wan et al. 2018	Availability of a platform to provide education to improve knowledge about toll road resilience.
11	Frequency of Toll Road Resilience Evaluations	Nipa et al. 2023	The frequency of regular evaluations will help in implementing the right resilience practices and help in preparedness
12	Length of Delays Occurred	Nipa et al. 2023; Nipa and Kermanshachi 2022; Sun et al, 2020; Ganin et al 2019	The lesser the difference between normal and post-disaster travel times, the more efficient the network will be in accommodating and managing traffic
13	Previous Disaster Experiences	Nipa et al. 2023; Nipa and Kermanshachi 2022; Wan et al. 2018	Experience gained in handling toll roads during disasters will be more efficient in handling and responding to future disasters.
14	Level of Damage	Nipa et al. 2023; Ganin et al. 2019; Sun et al. 2020	The severity of damage to toll road infrastructure damaged by landslides.
15	Time to Start Reconstruction Work	Nipa et al. 2023; Nipa and Kermanshachi. 2022; Ganin et al. 2019	How quickly repair projects are started after a disaster or disruption occurs.
16	Routine Evaluation of Emergency Response Systems	Nipa et al. 2023; Liao et al. 2018; Sun et al. 2020	The process of regular evaluation of the system used to respond to emergencies.
17	Availability of Emergency Funds	Nipa et al. 2023; Nipa and Kermanshachi 2022; Liao et al. 2018	Availability of financial resources that can be used immediately for emergency response when a disaster occurs.

The concept of resilience is often defined using four key principles, known as the 4Rs: robustness, redundancy, resourcefulness, and rapidity. According to O'Rourke (2024), one essential aspect of highway infrastructure resilience is redundancy, which ensures the availability of alternative options, decisions, and replacements within the system in the event of a disaster. To enhance post-disaster infrastructure resilience, cities must implement strategies that prepare communities, employees, and disaster management systems, including planning measures to reduce stress during crises. This preparedness facilitates a smoother transition from the response phase to the recovery phase. These resilience principles serve as a foundation for guiding the design, operations, and policies related to disaster management and infrastructure development. Specifically, the resilience of highways is characterized by the 4Rs framework—robustness, redundancy, resourcefulness, and rapidity (Jia and Zhan, 2023).

1. Robustness: The ability to withstand impact without experiencing serious damage or failure.
2. Redundancy: The availability of alternatives or backups if one part of the system fails.

3. Resourcefulness: The ability to identify problems, set priorities, and mobilize the necessary resources.
4. Rapidity / Rapid Recovery: The ability to recover quickly after a disruption, minimizing downtime and negative impacts.

3. Methods

3.1 Research Types and Respondents

This study uses a quantitative method with a population consisting of individuals involved in the planning, construction, and management of toll roads in Indonesia. Purposive Sampling technique is proposed as there is quite limited professional that have knowledge or experience related to toll road resilience. Targeted respondents consist of contractors, consultants, and toll road business entities, with criteria including knowledge and experience in toll road design, construction, and maintenance, as well as expertise in disaster preparation, response, and recovery strategies. Respondents also include those who have the authority to make decisions related to infrastructure, safety, and disaster management that consisted of business entities, service providers, and consultants.

3.2 Data Analysis

The main data analysis used in this research is Exploratory Factor Analysis (EFA). EFA is used to group variables that influence toll road resistance to landslides. However, descriptive analysis is also proposed to understand better the data. In addition to that, Cronbach Alpha parameter is used to ensure the data reliability. The following are several steps to analyse data using EFA (Anggraini 2017). The first stage before factor analysis is to determine the variables that are eligible for further analysis. The feasibility of the data is tested using the KMO test, which is considered feasible if the minimum value reaches 0.5. In addition, the Bartlett Test of Sphericity statistical test is carried out to test the hypothesis that the variables are not correlated with each other in a population. A variable meets the Bartlett test if its significance value is below 0.1.

The MSA examination aims to determine whether the variables used can be analysed using the EFA method. If the MSA value = 1, the variable can be predicted very well and the analysis can be continued. If the MSA value ≥ 0.5, the variable can still be predicted and analysed further. However, if the MSA value <0.5, the variable cannot be predicted and is not suitable for further analysis. The determination of extraction in this study uses eigenvalues. Eigenvalues are used to determine the total variation associated with a factor and are maintained if the value is more than 1, indicating that the value formed is better than the initial variable (Rohman 2017). The number of factors taken is based on the cumulative amount of variation that has been achieved. If the cumulative value of the percentage of variance is sufficient (more than half of the total variance of the initial variable), then factor extraction can be stopped. Factor rotation is conducted to facilitate interpretation and simplify factors, so that factors will be grouped according to the constructs that form them. Determination of factor groups is based on the highest value of the comparison factor. Interpretation is the process of naming the formed factors. The name of the factor must be in accordance with the variable that has the greatest factor dominance. Although factor naming is subjective, some factors may not be named if they do not have a distinctive or significant variable.

4. Data Collection

A preliminary survey was conducted to evaluate the relevance of the research variables by consulting seven experts with extensive experience—most having over ten years in toll road operations and academia. A total of 17 variables identified through literature studies on resilience and toll roads, as presented in Table 1, were assessed. The experts rated the relevance of each variable using a 1-5 Likert scale, where 1 represented "Strongly Irrelevant" and 5 represented "Highly Relevant." The preliminary questionnaire results were analyzed using the mean score method, with a cut-off value of three (3) to determine variable relevance (Rohman 2017). Variables with a mean score below three were excluded from the main survey.

5. Results and Discussion

In addition to the methodology, this paper presents a preliminary survey result of the research by determining relevant variables that have been identified from literature. Based on the preliminary survey, 18 variables were considered relevant for this research and will be used in the main survey. Two variables were eliminated while three other variables were suggested by the experts interviewed. Mean score analysis ranked the variables from the most to the least relevant, and the results are summarized in Table 2. The respondents generally agreed with the provided variables, with some disagreements regarding specific variables. The mean scores from the analysis ranged between

3.00 and 4.86, while the standard deviation values ranged from 0.38 to 0.90, indicating consensus among respondents regarding the variables' relevance. However, two variables, number of lanes and number of alternative roads, had mean scores of 2.86, which is below the cut-off value of 3. These variables were considered irrelevant and were excluded from further analysis.

Table 2. Preliminary Survey Results

Code	Factors Influence to Toll Road Resilience	Mean	Standard Deviation	Remarks
X20	Risk Management Implementation	4.86	0.38	Relevant
X7	Availability of Emergency Response Equipment	4.71	0.49	Relevant
X13	Previous Disaster Experiences	4.71	0.49	Relevant
X19	Quality of Road Pavement	4.71	0.49	Relevant
X16	Routine Evaluation of Emergency Response Systems	4.57	0.53	Relevant
X17	Availability of Emergency Funds	4.57	0.53	Relevant
X18	Road Pavement Design	4.57	0.79	Relevant
X8	Access to Required Resources	4.43	0.79	Relevant
X11	Frequency of Toll Road Resilience Evaluations	4.43	0.53	Relevant
X12	Length of Delays Occurred	4.43	0.53	Relevant
X5	Availability of Previous Landslide Disaster Data on Toll Roads	4.29	0.49	Relevant
X6	Access to Landslide Disaster Data	4.29	0.49	Relevant
X9	Employee Knowledge of Resilience	4.29	0.49	Relevant
X10	Availability of Learning Media on Toll Road Resilience	4.29	0.49	Relevant
X14	Level of Damage	4.29	0.76	Relevant
X15	Time to Start Reconstruction Work	4.29	0.76	Relevant
X1	Total Length of Disrupted Roads	4.14	0.38	Relevant
X4	Distance of Intersections from Landslide-Affected Areas	3.00	0.82	Relevant
X2	***Number of Lanes***	***2.86***	***0.90***	***Irrelevant***
X3	***Number of Alternative Roads***	***2.86***	***0.69***	***Irrelevant***

According to the results, it can be concluded that the 18 variables proposed in this study are relevant and can be used in the main questionnaire. The main questionnaire in this study employs a Likert scale to acquire respondents' opinions from toll road practitioner in Indonesia.

6. Conclusion

This paper proposes a methodology to investigate factors that influence toll road resilience in Indonesia about landslide hazard. The methodology consists of systematic and integrative literature reviews to understand research gaps and developing research methods to answer the research questions. Literature review has been conducted to explore the concept of infrastructure resilience, resilience principles. Research gap has been identified as an opportunity to examine what factors influence the resilience of toll roads in Indonesia. Based on the literature review conducted, 17 variables are identified as the factors that influence toll road resilience. Exploratory Factor Analysis (EFA) technique is chosen as a research tool to understand underlying factors that influence toll road resilience concept. This paper also presented 18 research variables which were considered relevant for the main survey. This study is expected can provide significant contributions to the understanding and improvement of toll road resilience in Indonesia to improve sustainable development practice in Indonesia by ensuring that toll road infrastructure can operate safely and efficiently even when facing the threat of natural disasters.

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Biographies

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