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Climate Change Risk and the Performance of Road Infrastructure Projects

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ABSTRACT

Climate change is one of the factors contributing to the increased intensity of rainfall. Unpredictable weather patterns pose a major risk that can affect project schedules and costs. With the rise of extreme rainfall due to climate change, the risk to infrastructure project performance is also expected to escalate. This study aims to evaluate the performance of road infrastructure projects in response to climate change risks and to identify appropriate risk response measures for medium-high risks that predominantly affect costs and timelines. The research adopts a qualitative method by distributing questionnaires targeted at contractor and consultant companies involved in road infrastructure projects in Bireuen Regency. Data analysis employs the Severity Index method, aiming to categorize probability (P) and impact (I). The findings reveal that climate change risks such as flooding, extreme temperatures, and heavy traffic loads in Bireuen Regency significantly affect road infrastructure performance. Physical damage, material degradation, functionality disruptions, and increased maintenance costs emerge as critical issues that require immediate attention. Long-term solutions include the implementation of adaptive technologies, the use of more climate-resistant materials, and enhanced preventive road quality monitoring to mitigate the impacts of climate change in the future.

Keywords: Climate Change, Project Performance, Contractors

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INTRODUCTION

Construction projects are a series of activities related to the development of infrastructure (Gido et all, 2018). These projects are time-consuming and complex, often leading to uncertainties on-site that pose various risks during project implementation (Heagney, J. 2016). Risks are unexpected events that may occur and can hinder the achievement of project goals, including cost, time, and quality. According to Moi et all (2021), risks can arise at any stage of a construction project: planning, design, construction, and operational or maintenance phases. Climate change is one of the factors contributing to increased rainfall intensity. Unpredictable weather is a major risk that can affect project schedules and costs (Rahardian, 2020; Marzoughi et all, 2018; Ballesteros F., et all, 2017). With the growing severity of extreme weather conditions over the years, their impact on infrastructure project implementation continues to increase (Gaarder, J.E., et all, 2024; Rashid, Y. 2020).

Climate change significantly affects the construction sector, such as rainfall fluctuations, due to the outdoor nature of most construction activities (Hidayat, A. 2023; Charan, D., et all, 2018). Rainfall fluctuations can extend project durations by up to 21% (Dolamore, P., 2023). Field observations indicate that not all construction projects proceed as scheduled according to their contractual timelines (Witjaksana, B., et all, 2024; Morioka, K., et all, 2019). Risk management concerning climate change has emerged in recent years as one of the critical challenges in the construction sector, necessitating comprehensive problem-solving strategies for mitigating infrastructure project risks (Deubelli, TM, & Merchler, R., 2021; Yudhaningsih, K., et all, 2022). Risk perception plays a critical role in risk management (Yu, T.K., 2020), and therefore significantly impacts decision-making in implementing adaptive measures in construction projects (Muflihah, S., & Pudjihardjo, 2019). In certain situations, risks can lead to the termination of a project, underscoring the importance of effective risk management. The objective of risk management is to ensure project sustainability through the proper handling of risks (Herawati, N., & Kartikasari, D., 2021). Thus, this study aims to assess the performance of road infrastructure projects in relation to climate change risks and to identify appropriate risk response strategies for the dominant medium-high risks that significantly affect cost and time.

METHOD

Primary data for this research was obtained directly from the distribution of questionnaires. The questionnaires were distributed to respondents, including contractor and consultant companies operating in Bireuen Regency. A closed-ended questionnaire format was used. Data collection was conducted in two stages: the first stage involved a preliminary survey to identify risks, and the second stage tested the application of risk variables gathered from the literature for ongoing projects. Secondary data used in this study included administrative maps of Bireuen Regency, rainfall data, and a list of consultants and contractors registered as members of the Indonesian National Construction Executing Agency (GAPENSI). The targeted contractor companies ranged from small, medium, to large qualifications (K, M, and B), both those currently working on and those who have completed road infrastructure projects in Bireuen Regency.

The research stages include risk identification, risk analysis, risk evaluation, and determining responses to the risks. Data analysis utilized the Severity Index method, which aims to categorize probability (P) and impact (I). The Severity Index is calculated based on responses from all participants. Each risk is assessed based on its probability and its impact on project objectives. The Severity Index values are then converted into a probability and impact rating scale to determine the risk category based on the Severity Index (SI) percentage

a. Very Rare/Low (SJ/SR) = $0.00 \leq SI < 12.5$
b. Rare/Low (J/R) = $12.5 \leq SI < 37.5$
c. Moderate (C/S) = $37.5 \leq SI < 62.5$
d. Frequent/High (S/T) = $62.5 \leq SI < 87.5$

RESULTS

The risk identification process was carried out through a questionnaire to verify and determine the relevance of risk variables taken from literature studies. The research data involved 32 respondents and were analyzed based on variables that affect the performance of road infrastructure projects in Bireuen Regency, Aceh Province. The results of the survey and field observations were categorized according to the severity and frequency of occurrence to produce a Severity Index for each risk factor.

Table 1: Analysis *Severity Index* Climate Change Risks on Road Infrastructure in Bireuen Regency

Risk Category	Risk Description	Location	Severity Index (%)	Main Impact
Physical Damage Due to Floods and Extreme Rain	Road damage due to flooding and waterlogging for more than 24 hours after heavy rain.	From Gandapura to Samalanga	88	Damage to the road surface layer; standing water damages the structure
Material Degradation Due to Extreme Temperatures	Degradation of asphalt material due to extreme temperatures, especially in April to July.	Bireuen-Takengon Road	72	Micro cracks in road layers, reducing the life of the material due to extreme temperature fluctuations
Functionality and Security Issues	Significant road deformation, especially on roads frequently used by heavy vehicles, increases the risk of accidents.	Road sections in Juli, Kutablang and Peudada Districts	77	Increased accidents; decreased road surface quality.
Increased Maintenance Costs	Increased annual costs of up to 20% due to more frequent repairs caused by flooding and extreme temperatures.	The Road to Peusangan	82	The budget burden increases significantly for periodic maintenance by up to 20% because the frequency of breakdowns occurs more frequently.

Based on Table 1 regarding risk categories with analysis severity index on road infrastructure projects in Bireuen Regency, is described as follows:

1. Physical Damage Due to Floods and Extreme Rain
   The results of the analysis show that the main roads, especially in Gandapura District to Samalanga District, Bireuen Regency experienced severe damage due to flooding that occurred during the rainy season. Based on the survey conducted, it was found that 60% of the roads in the area experienced more than 10 cm of water inundation for more than 24 hours after heavy rain, causing damage to the road surface layer. The Severity Index for physical damage in Bireuen Regency reached 88%, with the most significant damage occurring on the national road sections in Peudada District and Samalanga District.
2. Material Degradation Due to Extreme Temperatures
   Based on data from the road rehabilitation project in Bireuen Regency in 2022-2023, the degradation of the materials used, especially asphalt, occurs faster due to extreme temperatures. In the months with high temperatures (April to July), micro cracks begin to appear on several road sections, especially on the Bireuen-Takengon Road, with an average temperature reaching 35°C during the day, the Severity Index for material degradation is 72% indicating that conventional asphalt is not resistant enough to extreme temperature changes, requiring more frequent repairs.
3. Functionality and Security Disruptions
   Based on a survey on the route connecting the city center with sub-districts in Bireuen Regency, there has been a significant increase in disruption of road functionality. Based on data from the Transportation Agency in 2023, it showed an increase in accident reports due to road deformation by 12%. The Severity Index for disruption of functionality reached 77%, with the worst conditions found on road sections that are often passed by heavy trucks and experience a decrease in surface quality due to high rainfall, such as in Juli, Kutablang and Peudada Districts.

Discussion

Based on the analysis of road infrastructure project performance against climate change risks using the severity index method , it focuses on several critical aspects, such as physical damage, material degradation, disruption of functionality and safety, and increased maintenance costs caused by climate risks.

Table 2: High-Level Risk Management of Cost and Time

Risk Category	Mitigation Strategy	Implementation
Physical Damage Effects of Floods and Extreme Rain	Repair and improvement of drainage systems.	Check and clean the drainage regularly.
		Adjust road elevation in flood-prone areas.
	Use waterproof road materials (polymer asphalt, permeable concrete).	Implement the use of waterproof materials on new projects or road rehabilitation.
Material Degradation Due to Extreme Temperatures	Use modified asphalt such as polymer asphalt.	Conduct material trials before large-scale implementation.
		Educate contractors about adaptive materials.
	Apply Cold Mix Asphalt technology.	Evaluation of the use of Cold Mix Asphalt on road sections with fluctuating temperatures.
Functionality and Security Issues	Perform preventive maintenance regularly.	Routine inspections on roads frequently used by heavy vehicles.
		Quick fix for minor deformations.
	Use automatic monitoring technology (road quality sensors).	Install deformation monitoring sensors on strategic road sections.
Increased Maintenance Costs	Create a risk-based budget.	Allocate reserve funds for climate risks in project budget planning.
	Focus on initial investments in durable materials and technologies.	Collaboration with academics for maintenance cost efficiency.

1. Physical Damage Due to Floods and Extreme Rain
   The high Severity Index of 88% for physical damage in Bireuen Regency, especially on the Gandapura to Samalanga road section, indicates that the design and materials used in current road infrastructure are inadequate in dealing with extreme climate conditions. This condition is in line with a study by Herawati and Kartikasari (2021), which states that coastal areas in Aceh, including Bireuen, are vulnerable to flash floods and waterlogging due to extreme rainfall. Solutions that need to be implemented include improving the drainage system and using road materials that are more resistant to water and moisture. Materials such as polymer asphalt or permeable concrete can reduce damage due to waterlogging. This is also supported by a study by Lendawati (2022), which shows that improving the drainage system can reduce the risk of damage by up to 40%.
2. Material Degradation Due to Extreme Temperatures
   With a Severity Index of 72% for material degradation due to extreme temperatures, it is clear that conventional asphalt used on roads in Bireuen is less able to withstand extreme temperature fluctuations. Research by Santoso (2020) shows that the use of modified asphalt such as polymer asphalt can increase resistance to high temperatures by up to 30%. In areas such as Bireuen, where temperatures can reach 35°C, the use of this material can extend the life of the road and reduce the frequency of repairs. In addition, the more environmentally friendly Cold Mix Asphalt technology can also be considered to reduce the negative impacts of extreme temperatures.
3. Functionality and Security Issues
   The Severity Index of 77% for functional and safety impairment in Bireuen Regency reflects that road deformation due to heavy vehicle loads and extreme weather significantly contributes to the decline in road quality. A study by Arifin (2021) highlighted that roads in areas passed by heavy vehicles without regular maintenance experience faster surface quality decline, increasing the risk of accidents. In the case of Bireuen, mitigation steps that can be taken include increasing routine preventive repairs and introducing road quality monitoring sensors that can detect deformation before significant damage occurs. This has proven effective in several countries such as Japan and South

Korea, which have used road monitoring sensors to reduce repair costs by up to 20% (Yamada et al., 2020).

4. Increased Maintenance Costs
   The Severity Index of 82% for maintenance costs in Bireuen Regency reflects the major challenges in managing the budget for road infrastructure maintenance. As stated by Abidin (2021), the increased frequency of road repairs due to climate change can significantly increase maintenance costs. In the context of Bireuen, the 20% increase in maintenance costs between 2020 and 2023 suggests that local governments should start considering the use of more durable and climate-friendly materials and technologies. A study by Nugroho (2022) shows that initial investment in the use of temperature-resistant asphalt materials and better drainage systems can reduce maintenance costs by up to 30% in the long term.

Risk management is a strategic step to minimize the impact of climate change on road infrastructure projects, especially those that impact costs and time. Risks with high severity (medium-high) require a planned and effective approach to ensure project sustainability.

CONCLUSION

Based on the analysis using the Severity Index , the performance of road infrastructure projects in Bireuen Regency against climate change risks shows that physical damage due to floods and extreme rain, material degradation due to extreme temperatures, disruption of functionality and safety, and increased maintenance costs are significant issues that need to be addressed immediately. The high Severity Index values for several indicators indicate that climate change, such as floods and extreme temperatures, contribute greatly to the decline in the quality of road infrastructure. Specific data in Bireuen Regency, especially on the Gandapura-Samalanga and Bireuen-Takengon roads, reinforce the fact that the condition of road infrastructure is greatly affected by increasingly extreme climate change. Physical damage due to flooding and extreme rainfall is the most crucial, with the highest Severity Index reaching 88%. Material degradation due to extreme temperatures and disruption of functionality and safety also have a major impact on road quality, with increased risk of accidents and more frequent maintenance needs. Ultimately, all these factors contribute to increasing road maintenance costs in Bireuen Regency, which will increase by 20% between 2020-2023. Vulnerability to climate change can be minimized through technological innovation, the use of materials that are more resistant to extreme weather conditions, and improvements to adequate drainage systems. Investment in proactive maintenance and the introduction of automated monitoring technologies will provide long-term benefits to reduce maintenance costs and increase road life

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