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Bridging the Gap: Lessons Learned from the Jenelata Bridge Collapse and Future Restoration Plans

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ABSTRACT

The collapse of the Jenelata Bridge underscores the vulnerability of bridge infrastructure in areas with significant hydraulic forces. This study investigates the primary causes of the bridge's collapse and proposes a restoration approach to prevent similar incidents in the future. The findings reveal that intense scouring around the foundation, exacerbated by the bridge's proximity to a river meander, weakened the abutment structure. The foundation's design, which used shallow footings instead of more suitable deep foundations, was found inadequate to withstand the hydraulic pressures, resulting in instability and eventual structural failure. Notably, simulation analysis confirmed that the bridge itself was structurally sound to support traffic loads, ruling out overloading as a collapse factor.

For restoration, a comprehensive approach has been proposed, beginning with replacing the existing 30-meter span with a 50-meter steel truss bridge to enhance load-bearing capacity and structural flexibility. Additionally, the abutment will be relocated more than 20 meters from the scour zone to mitigate erosion risks and increase stability. Reinforcement of the existing pier is also planned to ensure it can support the weight of the new steel bridge span and a 30-meter composite bridge. Furthermore, a riverbank protection structure will be constructed to safeguard the abutment from landslides, thus enhancing the bridge's resilience to extreme environmental conditions.

This study emphasizes the importance of adapting bridge foundation designs to hydrodynamic forces in erosion-prone areas. These findings provide valuable insights into bridge design and restoration practices that can enhance structural safety and stability, particularly in challenging riverine environments.

Keywords: Jenelata Bridge, bridge collapse, scouring, structural restoration, deep foundations, riverbank protection, hydraulic forces

INTRODUCTION

Bridge infrastructure plays a critical role in connecting regions, enabling the efficient movement of people and goods. However, bridge structures are subject to various natural forces that can undermine their stability, especially in riverine environments with dynamic hydraulic conditions. Scouring, or the erosion of soil around bridge foundations due to water flow, is a primary risk factor for bridge instability and collapse, especially in areas rivers meander or experience high flow velocities. Studies have shown that bridges located near river bends, like the Jenelata Bridge, are particularly vulnerable to scouring, which weakens foundations over time, compromising structural integrity and leading to potential collapse.

Despite these insights, there remain significant gaps in bridge design and restoration approaches, particularly concerning adaptation to high-scour environments. Existing literature often focuses on standard structural load management but lacks emphasis on the need for foundation designs that can withstand intense hydraulic pressures. In cases like the Jenelata

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Bridge, shallow foundations are insufficient, yet they continue to be implemented due to cost or site constraints. This shortfall points to a need for more specialized, location-sensitive engineering strategies that address both the structural and environmental challenges posed by such sites.

Picture 1. Jenelata Bridge Location

This study investigates the failure factors leading to the collapse of the Jenelata Bridge, highlighting the limitations of shallow foundations in scour-prone areas. By analyzing these factors, we propose restoration strategies that prioritize enhanced stability and adaptability to hydraulic forces, including deep foundations, foundation relocation, and protective structures against riverbank erosion. Our findings aim to bridge the gap in current restoration practices and provide a model for similar structures in high-risk areas. In doing so, this research underscores the significance of integrating hydrodynamic considerations into bridge design and restoration, ensuring safer, more resilient infrastructure in challenging environments.

LITERATURE REVIEW

Erosion is a critical factor that significantly impacts the stability of bridge structures, particularly those situated near waterways. Banuwa (2013) in Arsyad (2010) defines erosion as the natural process through which soil or land material is transported from one location to another. This study categorizes erosion into three main types: rainfall-induced erosion, wind-induced erosion, and glacial erosion, with a particular focus on how these processes lead to soil loss through surface runoff. Such foundational knowledge of erosion mechanisms is essential for evaluating their effects on structural integrity. Further research by Junaidi and Zulfan (2017) emphasizes the importance of geological, geographical, and hydrological conditions, highlighting that these factors significantly influence the stability of structures, especially in areas prone to landslides or erosion. Their findings suggest that incorporating soil properties and environmental conditions into bridge design and maintenance is crucial for enhancing safety and longevity.

The mechanisms of scouring, particularly around bridge piers and abutments, have also garnered considerable attention in the literature. Breuser and Raudkivi (1991) identify three types of scour: general scour, local scour, and localized or constriction scour. General scour occurs naturally across the riverbed, while local scour is concentrated around structural elements, resulting from flow disruptions caused by the presence of the bridge. Their study emphasizes the need for a thorough understanding of hydraulic interactions and vortex formations around structures, as these can lead to significant material loss and potential structural failures. Additionally, Ratay (2010) explores the importance of assessing scour risk during the design phase of bridges, advocating for multi-level analytical approaches that integrate hydraulic modeling to predict scouring behavior. This evolution in scour analysis underscores the necessity for ongoing research to develop effective design strategies that mitigate scouring risks, highlighting the increasing relevance of hydraulic considerations in bridge engineering.

Forensic engineering is another crucial aspect that contributes to our understanding of bridge failures and informs future design improvements. Noon (2000) defines forensic engineering as the application of engineering principles to investigate structural failures, with the primary objectives of determining the extent of damage, the timing of failures, and the underlying causes. Rao (2016) emphasizes the importance of systematic analysis in identifying the causes of failure and recommending design enhancements. His study outlines the need for a structured approach to forensic investigations, which involves initial stabilization efforts followed by a detailed analysis of failure mechanisms. This chronological understanding of failures is vital for deriving critical insights that can prevent similar occurrences in future designs. The literature on forensic engineering highlights the increasing necessity for integrating forensic principles into the broader field of civil engineering, as Gupta (2010) notes that the lifespan of reinforced concrete structures, typically expected to be around 100 years, is often compromised by unexpected failures. This underscores the urgent need for enhanced design protocols that prioritize safety and durability.

Current trends in bridge engineering emphasize the integration of advanced technologies and methodologies to enhance structural performance and resilience. The Bridge Management System (1992) and its subsequent revisions have established benchmarks for bridge design codes, focusing on load-bearing and structural planning. Recent advancements in hydraulic modeling and erosion prediction are becoming increasingly relevant in bridge design practices, as the combination of empirical data, hydraulic simulations, and forensic analysis is expected to yield more robust and resilient bridge structures. Future research should concentrate on developing adaptive design principles that incorporate real-time data and account for environmental changes, particularly in light of climate variability. Additionally, the ongoing challenges associated with urban development and land use highlight the importance of sustainable practices in bridge design and construction. The current literature points to a growing recognition of the need for interdisciplinary approaches that encompass hydrology, geology, and civil engineering to address these challenges effectively.

MATERIALS AND METHODS

Problem Identification

This stage involves identifying the specific issues contributing to the bridge collapse, including potential structural, hydrological, and environmental factors. These findings guide the focus of data collection and inspection.

Picture 2. Jenelata Bridge after fall during flood season

Literature Review

The literature review contextualizes the study within existing research on structural failure mechanisms, hydrological effects, soil-structure interactions, and bridge restoration approaches, establishing a foundation for hypothesis development.

Primary and Secondary Data Collection

Data collection consists of primary and secondary data to capture a comprehensive picture of the structure and surrounding environment.

Primary Data Collection:

a. Field Observations and Visual Inspection: Preliminary site visits provide an overview of visible damage, erosion, sediment deposits, and structural abnormalities, aiding in identifying suspect areas for further investigation.
b. Detailed Inspection of Suspected Failure Areas: Based on problem identification, this phase concentrates on parts of the structure identified as potential failure sources. Specific inspection techniques include:
    - Hammer Test: Conducted on the suspected areas, this non-destructive test assesses concrete strength and potential degradation. By measuring surface hardness, this test provides early indications of weakened or deteriorated concrete sections.
    - Rebar Scanning: Rebar scanning uses ground-penetrating radar (GPR) or electromagnetic devices to examine rebar positioning and condition in areas of suspected failure. This scan identifies structural integrity issues stemming from corrosion, insufficient coverage, or rebar displacement.
    - Geotechnical Survey: Focused on the soil and foundation around failure-suspect areas, the geotechnical survey involves soil sampling and testing, such as Cone Penetration Testing (CPT) and Standard Penetration Testing (SPT). This data reveals soil composition, load-bearing capacity, and susceptibility to erosion, providing insights into soil-structure interactions.
    - Drone-Based Photogrammetry and High-Resolution Imagery: Drone surveys capture detailed aerial images of the bridge, focusing on suspect zones. This visual data supports the analysis of degradation patterns, erosion proximity, and any observable shifts in the structural layout.

Secondary Data Collection:

Structural Design and Maintenance Records: Historical records, including original design specifications, inspection reports, and repair logs, are reviewed to verify prior interventions and track any areas previously marked for concern.

- Environmental Data: Climate records, river flow data, and topographic maps are collected to examine the environmental context, especially historical flood levels, rainfall data, and river dynamics around the structure.
- Geotechnical Reports: Previously conducted geotechnical studies provide a historical record of soil conditions, useful for understanding long-term structural interactions with the environment.

Data Analysis and Hypothesis Formulation

This phase integrates the collected data to form initial hypotheses regarding the causes of bridge failure, informed by visual and technical findings from field inspections, environmental conditions, and historical data.

Hypothesis Testing through Analysis and Modeling

The hypotheses undergo testing through advanced modeling and analysis techniques.

a. Hydrological Modeling: HEC-RAS (Hydrologic Engineering Centers River Analysis

System) is used to model river dynamics and scouring effects under different flood scenarios. Key modeling steps include:

- Defining cross-sectional profiles at strategic river points near the bridge.
- Running flow data simulations to evaluate potential scour depths and lateral erosion impacts, especially near foundation elements.

b. Structural Assessment: Finite Element Modeling (FEM) with CSI Bridge software allows detailed assessment of load distribution in suspect areas, focusing on critical components such as piers, abutments, and deck slabs. This analysis helps evaluate load-bearing adequacy and identify any potential structural weaknesses that could have contributed to the failure.

Testing results either validate hypotheses—confirming contributing failure factors—or reject them, narrowing down the true cause.

Conclusion of Failure Cause

Validated hypotheses identify the most probable causes of the bridge failure, allowing for an in-depth understanding of the contributing structural or environmental factors.

Development of Restoration Solution

Upon identifying the causes of failure, a targeted restoration solution is developed. This solution addresses identified vulnerabilities and incorporates reinforcement and preventative measures, including modifications to mitigate erosion and strengthen critical structural elements.

Final Summary and Recommendations

The methodology concludes with a synthesis of findings, offering recommendations for future maintenance, enhanced design practices, and ongoing monitoring to prevent recurrence.

RESULTS AND DISCUSSION

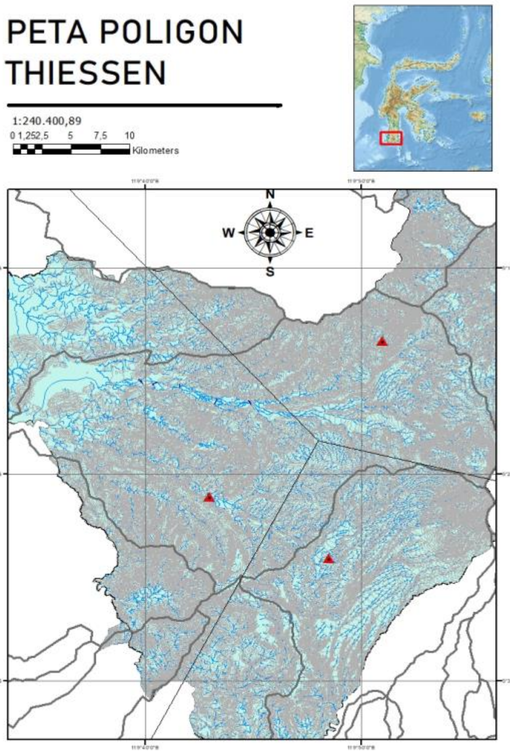
Analysis of Bridge Failure Causes

The investigation into the collapse of the Jenelata Bridge involved a systematic approach to identify and validate potential failure causes, utilizing hypothesis testing through analysis and modeling. Each hypothesis was tested against the data collected and analyzed through hydrological and structural modeling tools, providing a comprehensive understanding of the failure mechanisms involved.

1. ***River Flow Dynamics and Bridge Position***

Prior to conducting modeling with HEC-RAS, a thorough analysis of rainfall patterns in the area was performed. This analysis included several methodologies: the distribution of rainfall was assessed using the Thiessen polygon method, while frequency distribution was analyzed through various probability distributions, including normal, log-normal, Gumbel, and Log Pearson III. The suitability of these distributions was evaluated using Chi-squared and Kolmogorov-Smirnov tests.

The intensity of rainfall was determined using the Monobe method, and net rainfall was calculated to gauge effective precipitation levels. Additionally, Intensity-Duration-Frequency (IDF) analyses were conducted using the Talbot, Sherman, and Ishiguro methods. Flood design discharge was estimated through synthetic unit hydrographs (HSS) using Gamma-I and Nakayasu methods, as well as rational methods proposed by Melchior, Weduwen, and Hasper.



Picture 3. Thiessen polygon method

Table 1. Result of flood design discharge with 6 methods

Gamma-I	217,5432	m^3/s
Nakayasu	229,4086	m^3/s
Rasional	643,64	m^3/s
Weduwen	39,085	m^3/s
Haspers	31,278	m^3/s
Melchior	8,086	m^3/s

The Creager graph was utilized to choose which result that will be use on next analysis.

For assessing scouring around the abutments, methodologies including Laursen, Lacey, and Touch were employed to evaluate the erosive potential of the flow dynamics. These analyses provided a foundation for HEC-RAS modeling, which confirmed that the bridge's proximity to a meander subjected it to intense hydraulic forces, significantly increasing the risk of scouring at the foundation. The modeling confirmed that water flow intensified around the river bend, impacting the bridge abutments directly. The results showed scouring depths reaching approximately 3.47 meters, well beyond what the foundation was designed to handle, indicating a major failure factor due to river-induced erosion. This finding supported the hypothesis that the bridge's location near the bend significantly contributed to its collapse.

2. Local Scouring and Abutment Deterioration

Observational data from the site, including geotechnical surveys, provided direct evidence of structural degradation at the abutments due to severe scouring. Hypothesis testing at this stage confirmed that the local scouring depths exceeded foundation tolerance, weakening the abutments over time. This scouring-induced deterioration led to tilting of the abutments, further compromising the foundation's stability and supporting the hypothesis that the abutments failed due to progressive, localized erosion forces. This degradation was visible from field data and photographic documentation, linking it to the bridge's structural vulnerability in the face of natural erosion dynamics.

Picture 4. Abutment of Jenelata Bridge

3. ***Foundation Design and Suitability***

The hypothesis that the bridge's shallow footing foundation was inadequate for the high-scour environment was also tested through geotechnical analysis and data comparisons with typical foundation requirements for high-flow areas. The investigation showed that the original design, which employed a shallow footing foundation, was insufficient for the conditions identified at the bridge site. Alternative foundation types, such as caissons or piles, would have better suited the structure, as these designs provide greater resistance to deep scouring. Testing validated that the shallow foundation design, without reinforcement to counteract scouring effects, contributed to structural failure, supporting the hypothesis that foundation inadequacy was a primary failure cause.

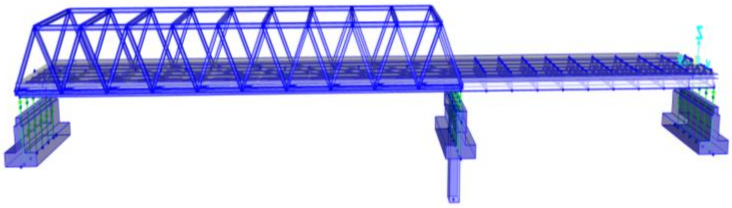
4. ***Load-Bearing Capacity of the Bridge Structure***

Structural modeling and analysis via finite element modeling (FEM) with CSI Bridge software addressed the hypothesis that excessive loads might have contributed to the collapse. Simulation under the Indonesian Standard for Bridge Loading (SNI 1726:2016) confirmed that the bridge's materials and structural components were capable of withstanding the designated traffic loads without additional failure. This supported the hypothesis that load-bearing capacity was sufficient and that structural overloading was not a contributing factor in the bridge collapse. Therefore, the collapse was determined to be primarily environmental and foundation-related, rather than due to load-induced structural failure.

Restoration Solutions Based on Findings

Based on the analysis of the failure causes, the following restoration solutions have been proposed to address the identified issues and enhance the bridge's stability and resilience:

1. Replacement of Bridge Span and Type: One of the proposed solutions is to replace the existing span of 30 meters with a steel frame span of 50 meters. The steel frame will provide greater strength and flexibility, allowing it to withstand heavier loads and improve overall structural resilience.



Picture 5. Modeling of new design of Jenelata Bridge

2. Abutment Relocation: The second recommendation involves relocating one of the damaged abutments to a safer position, at least 20 meters away from the scoured area. This will mitigate the risk of further damage from erosion and enhance the stability of the abutment by moving it away from high-risk areas.

3. Pier Inspection and Strengthening: A thorough evaluation and reinforcement of the existing bridge pier will be conducted to ensure it can support the loads from the new 50-meter steel span and the existing 30-meter composite span. The analysis indicated that the existing pier is capable of bearing a reaction of approximately 1975.382 kN (201.90 tons) after the addition of the new steel span, ensuring it remains functional and stable.

CONCLUSION

The investigation into the collapse of the Jenelata Bridge revealed several critical factors contributing to its failure.

Firstly, the bridge's proximity to a river bend subjected its foundations to intense scouring, significantly weakening the surrounding soil and compromising the stability of the abutments. Analysis indicated scouring depths reaching approximately 3.47 meters, which exceeded the foundation's capacity to withstand such erosion.

Secondly, localized scouring resulted in substantial physical damage to the abutments, leading to tilting and further loss of structural integrity. Detailed inspections and geotechnical surveys confirmed that the extent of the damage significantly contributed to the overall collapse.

Additionally, the existing shallow footing foundation was found to be inadequate for the environmental conditions, where a deep foundation system would have provided better support and stability against high-flow scenarios, indicating a crucial misalignment between design and environmental needs. Importantly, structural analysis indicated that the bridge was capable of supporting traffic loads, as evidenced by simulations conducted in compliance with Indonesian standards, ruling out load-related failure as a contributing factor to the collapse.

In light of these findings, several restoration strategies have been proposed to enhance the structural integrity and resilience of the bridge. These include replacing the existing span with a steel frame of greater capacity, relocating the damaged abutment to a safer position, strengthening the existing pier, and constructing protective measures along the riverbanks to mitigate future erosion risks.

Overall, this study highlights the necessity for comprehensive hydrological analysis, careful foundation design, and proactive maintenance strategies in bridge engineering. Implementing these solutions will not only restore the Jenelata Bridge but also ensure its safety and functionality for years to come.

CONFLICT OF INTEREST

The authors declare no conflict of interest

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