

Assessment of Scour-Induced Damage and Service Life Prediction of a River Bridge Based on Bridge Management System

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This study assesses the condition of the Sungai Salak Bridge (Sungai Taib Village, Kotabaru Regency) using a visual inspection approach based on the Indonesian Bridge Management System (BMS) procedure. The objective is to identify damage levels at the element and system levels and to provide maintenance-oriented recommendations for a riverine bridge affected by erosion, landslide, and settlement processes. Field observations and BMS scoring indicate that several critical elements have reached severe deterioration, particularly the protective works (retaining structures), arch-related components, railings, and bridge accessories, while the deck system and several crossing elements remain visually intact. The BMS evaluation yields an average condition value of $NK = 3$, classifying the bridge as damaged, with an equivalent service age estimate of approximately 41 years. Visual evidence suggests that scour-induced erosion and embankment instability have contributed to progressive loss of protection and displacement of structural components, including lateral movement of box culvert units. Based on technical screening, the bridge requires corrective maintenance focused on rehabilitation rather than routine maintenance alone. Priority actions include restoring retaining/protective structures, replacing damaged railings, and reinstating traffic safety facilities (lighting, signs, and markings). The findings demonstrate that combining BMS-based condition ratings with riverine hazard interpretation supports more reliable rehabilitation planning and improved operational safety for flood- and scour-prone bridges.

Keywords: Bridge Management System (BMS), Bridge Condition Assessment, Scour-Induced Damage, Service Life Prediction

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Introduction

Bridges located in riverine environments are continuously exposed to hydraulic loading, sediment transport, and geomorphological changes that may compromise their structural integrity over time. Among various deterioration mechanisms, local scour around abutments and piers has been consistently identified as one of the leading causes of bridge instability and failure during flood events (Deng & Cai, 2010; Holemba & Matsumoto, 2019; Prendergast et al., 2016). Scour processes can reduce foundation embedment depth, diminish bearing capacity, and induce horizontal displacement or rotation of abutments, particularly when combined with debris accumulation and high-velocity flows (Argyroudis et al., 2019; Ettema & Nakato, 2010). Consequently, accurate assessment of

scour-induced damage is essential for ensuring bridge safety and resilience.

Local scour depth estimation is widely recognized as a prerequisite for evaluating abutment stability. Empirical and semi-empirical formulations commonly incorporate hydraulic parameters, flow depth, abutment geometry, and correction factors for embankment configuration (Arias-Román & Suazo-Dávila, 2019; Cardoso & Fael, 2009). However, scour depth alone does not fully determine structural vulnerability. The interaction between hydraulic erosion and geotechnical stability of the abutment-backfill system plays a critical role in defining the ultimate damage state (Ettema & Nakato, 2010). In dynamic fluvial systems, riverbank erosion and settlement further exacerbate instability by altering channel geometry, intensifying local flow concentration, and exposing foundation elements

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(Arora et al., 2023; Yang et al., 2024). These coupled processes highlight the need for integrated structural and geomorphological assessment.

In practice, many bridge condition assessments rely on visual inspection-based approaches embedded within Bridge Management Systems (BMS). While BMS provides a structured framework for condition rating and maintenance prioritization, the reliability of visual inspection has been questioned due to subjectivity, surface-only detection capability, and limited subsurface diagnosis (Abdelkhalek & Zayed, 2020; Alsharqawi et al., 2017; Stochino et al., 2018). The inherent uncertainty in condition ratings may propagate into deterioration modelling and service life prediction, affecting rehabilitation decisions (Santamaría et al., 2020; Bu et al., 2015). Despite these limitations, BMS remains widely implemented in developing countries due to its practicality and resource efficiency.

Recent advances in reliability-based assessment, probabilistic deterioration modelling, and digital twin frameworks demonstrate that condition indices can be systematically linked to remaining service life (RSL) estimation (Chen et al., 2021; Heng et al., 2019; Wimmer & Braml, 2024). These approaches emphasize the importance of integrating condition ratings with deterioration models to quantify structural performance over time under uncertainty. However, in many regional bridge networks, especially in developing contexts, assessment still depends primarily on visual-based BMS procedures without deeper analytical interpretation of scour-induced mechanisms or service life implications.

The Sungai Salak Bridge, located on a national road corridor, experienced scour-related damage and structural modification following riverbank erosion and settlement. Changes in structural configuration, deterioration of abutment components, and deformation of box culvert elements indicate potential hydraulic–geotechnical interaction effects that require systematic evaluation. Given the strategic function of the bridge and its exposure to hydraulic hazards, a comprehensive condition assessment that interprets BMS results in the context of scour-induced instability and service life prediction is warranted.

Therefore, this study aims to (1) assess the structural condition of the Sungai Salak Bridge using the Bridge Management System framework, (2) interpret observed damage in relation to scour and settlement mechanisms based on established literature, and (3) estimate the remaining service life of the bridge using condition-based evaluation.

By integrating visual-based BMS assessment with theoretical insights on scour-induced damage and reliability-oriented service life concepts, this study contributes to improving practical bridge evaluation approaches in riverine environments.

Methodology

This study was conducted at the Sungai Salak Bridge located in Sungai Taib Village, Kotabaru Regency, Indonesia. The bridge forms part of a national road corridor and serves as a strategic transportation link supporting inter-regional mobility and economic activities. Geographically, the bridge is located at approximately 3°15'38.36" S and 116°12'15.92" E. The site is situated within a riverine environment characterized by active channel processes and periodic high-flow conditions, which increase its exposure to hydraulic hazards.

The spatial location of the bridge and its surrounding fluvial context are illustrated in Figure 1, which presents the satellite-based mapping of the study area. The figure provides an overview of the river alignment, bridge crossing position, and adjacent embankment configuration, which are relevant to understanding potential scour concentration zones and riverbank instability patterns.



Figure 1 Location of the Sungai Salak Bridge assessment (Source: Google Earth, 2024)

The bridge consists of two traffic lanes, with an overall length of about 13.70 m and a span width of approximately 9.00 m. Based on field observations and historical information from local agencies, the structure has undergone major configuration changes following flood-related damage. The original bridge configuration was identified as an arch-type structure, while the current condition reflects a modified configuration that includes multiple box culvert units and temporary embankment treatments to restore traffic continuity and accommodate river flow.

The research design employed a condition-based assessment framework comprising three sequential stages: (1) bridge condition evaluation through visual inspection using the Bridge Management System (BMS) procedure, (2) technical screening and interpretation of observed damage patterns in relation to scour and settlement mechanisms, and (3) prediction of remaining service life based on condition indices. This structure was selected to ensure that the BMS outputs do not remain purely descriptive, but are analytically interpreted using evidence-based understanding of

scour-induced instability and infrastructure performance deterioration.

Visual documentation was used to support interpretation and to provide context for field conditions. Figure 2 presents the temporary condition of the Sungai Salak Bridge following slope instability and post-event emergency handling. The warning signage and the visible road deformation indicate the presence of landslide-related disruption and likely settlement processes along the approach, which are consistent with riverbank erosion and settlement phenomena reported in the literature for riverine infrastructures (Arora et al., 2023; Yang et al., 2024).



Figure 2 Temporary condition of the Sungai Salak Bridge

Bridge condition assessment was performed using the Bridge Management System (BMS) procedure developed by the Directorate General of Highways. The BMS framework provides a structured approach for evaluating bridge condition using visual inspection, with element-level ratings and systematic aggregation to produce an overall condition value. In this study, each relevant bridge element was assessed using five BMS parameters: structural condition (S), degree of damage (R), damage progression (K), functional performance (F), and influence on safety and serviceability (P). The assessment results are expressed as a Condition Value (Nilai Kondisi, NK), representing the overall condition of the bridge and supporting maintenance decision-making. While BMS is practical and widely used for bridge network management, its dependence on visual judgment introduces uncertainty and may not capture subsurface deterioration or hidden defects, as highlighted by inspection reliability studies (Abdelkhalek & Zayed, 2020; Alsharqawi et al., 2017). Therefore, the BMS rating outcomes in this work were interpreted alongside established hydraulic–geotechnical principles to strengthen analytical depth.

To support interpretation of the observed damage, the study incorporated an evidence-based mechanism analysis focused on scour-induced instability and riverbank-related settlement. Local scour around abutments is recognized as a dominant contributor to bridge instability in flood-prone environments, with potential to reduce foundation embedment, weaken

bearing resistance, and initiate displacement or rotation of abutment systems (Deng & Cai, 2010; Ettema & Nakato, 2010). In addition, scour impacts may be amplified in dynamic fluvial settings where riverbank erosion and channel adjustments concentrate flow energy near bridge approaches and supports (Arora et al., 2023; Rafiqii et al., 2023). This study used these theoretical insights to interpret field indicators such as loss of protective elements, deformation of approach embankment, and lateral movement of the box culvert units, emphasizing that these symptoms can reflect coupled hydraulic and geotechnical processes rather than isolated surface damage.

After the element-level evaluation, technical screening was applied to classify the bridge into appropriate maintenance action categories. Following common asset management practice, the bridge condition was screened into one of three intervention classes: routine maintenance, rehabilitation (including strengthening or functional restoration), or replacement. This classification was used to translate the condition ratings into actionable recommendations, consistent with risk-informed bridge management perspectives that connect observed condition states with network-level resilience considerations (Argyroudis et al., 2019).

Remaining service life was estimated using a condition-based predictive model that links the BMS condition value to an empirical service-life relationship. The estimation uses the bridge condition value (NK) as the primary indicator to infer structural age equivalence and remaining service capacity. The conceptual basis of using condition indices for service-life estimation aligns with life-cycle modelling literature, which recognizes that condition indicators can serve as proxies for deterioration states when detailed monitoring data are unavailable (Chen et al., 2021; Verma et al., 2014). Because the present study relies primarily on visual inspection data, the service-life prediction is intended as a practical decision-support metric for maintenance planning rather than a full probabilistic reliability assessment.

This methodology has limitations. The assessment is predominantly based on visual inspection, without direct measurement of scour depth, subsurface geotechnical investigation, or structural health monitoring instrumentation. As noted in prior research, visual inspection alone can miss hidden deterioration and may introduce subjectivity into condition ratings (Abdelkhalek & Zayed, 2020; Stochino et al., 2018). Accordingly, the results should be interpreted as a condition-based and mechanism-informed evaluation, suitable for prioritizing rehabilitation actions under resource constraints, while acknowledging the potential need for targeted detailed investigation for high-risk elements.

Results and Discussion

Traffic Function and Network Redundancy

Field observations indicate that the Sungai Salak Bridge remains functionally passable for daily traffic. Based on the BMS traffic-width classification, the bridge was categorized as “wide” (Category 1), meaning vehicles can pass freely without frequent stopping or queuing (Table 1). This finding suggests that, from an operational standpoint, the existing carriageway width still supports current traffic movement; however, functional serviceability should not be interpreted as structural adequacy, particularly for riverine bridges exposed to hydraulic and geotechnical hazards.

Network redundancy was assessed to understand the consequence of potential closure. The inspection form confirms that an alternative route is available, requiring an additional detour distance of approximately 2.4 km (Table 2). While this reduces complete isolation risk, the bridge remains strategically important due to its role within a national road corridor and its function as a primary crossing for local and inter-regional mobility.

Table 1 Traffic Flow Condition

Existing bridge width and its effect on traffic	Choice (1–3)
1. Wide – vehicles can pass freely on the bridge	1
2. Moderately wide – vehicles slow down when crossing	
3. Narrow – vehicles frequently stop and queue	

Table 2 Alternative Route and Detour

Item	Response
Alternative route available if bridge is closed	Yes
Additional travel distance	2.4 km

Special Inspection and Emergency Actions

The inspection results indicate that special inspection is recommended for specific safety-related components. The left bridge railing (Element Code 4.622) requires additional inspection due to visible erosion at several points (Table 3). This aligns with the role of railings as critical safety elements whose degradation can increase user risk, even when the structural system remains partially functional.

Emergency actions were also identified as necessary. The right bridge railing (Element Code 4.622) was reported to have collapsed and not been replaced, directly endangering road users. In addition, the retaining structure (Element Code 4.277, DPT) shows missing elements in the arch-related zone, indicating loss of protective and supporting function (Table 4). The need for emergency intervention at these components suggests that safety and stability concerns extend

beyond routine maintenance and require prioritized corrective action.

Table 3 Special Inspection Requirement

Element code	Location	Reason
4.622	Left bridge railing	Erosion observed at several points

Table 4 Emergency Action Requirement

Element code	Location	Reason
4.622	Right bridge railing	Collapsed and not replaced, creating safety hazard
4.277	Retaining wall (DPT)	Missing elements in the arch-related section

Routine Maintenance Checklist and Documentation Gap

Routine maintenance items were listed in the inspection form, including river debris, dirt accumulation, vegetation growth, blocked drainage spouts, insufficient embankment drainage, surface defects, and missing plates (Table 5). However, the available dataset does not record the yes/no responses for these checklist items. This gap is important from a bridge management perspective because incomplete routine-maintenance documentation reduces the reliability of downstream decisions and condition trend interpretation, particularly when the primary assessment method is visual inspection-based.

Table 5 Routine Maintenance Checklist

Routine maintenance item	Yes	No
Debris accumulation/obstacles in the river		
Dirt accumulation on bridge elements		
Wild vegetation growth		
Blocked deck drainage spouts		
Insufficient drainage at embankment area		
Potholes/uneven road surface		
Railings require repainting		
Identification plate incorrect/missing		
Name plate incorrect/missing		

Spatial Context and Adjacent Bridges

To understand network positioning, the distance to adjacent bridges was evaluated. As listed in Table 6, the Sungai Salak Bridge is located approximately 886 m from Jembatan Mandin and about 700 m from Jembatan Sungai Taib. This spatial proximity suggests that hydraulic flow redistribution during flood events may influence multiple bridge crossings within the same river corridor. Channel adjustment and localized scour at one crossing could potentially affect hydraulic

behavior near adjacent bridges, particularly in confined river reaches.

Table 6 Bridges located near Sungai Salak Bridge

Bridge Name	Length	Width	Distance Between Bridges
Mandin Bridge	±10 m	±7 m	886 m
Sungai Salak Bridge	14.50 m	9 m	—
Sungai Taib Bridge	±30 m	±8 m	700 m

BMS Element-Level Condition Results

The core findings of this study are captured by the Bridge Management System (BMS) element-level evaluation (Table 7). At Level 3, critical condition values (NK = 5) were identified for the protective structure, arch element, railings, and bridge equipment/accessories. In contrast, the deck system and the culvert components received NK values of 0, indicating visually sound condition at the surface level. The river-flow element scored NK = 2, suggesting minor issues but not immediate failure classification.

Table 7 Element-Level Condition Evaluation (BMS)
Level 3 – Condition Values

Code	Element	S	R	K	F	P	NK
3.21	River flow	1	0	0	0	1	2
3.22	Protective structure	1	1	1	1	1	5
3.43	Arch	1	1	1	1	1	5
3.5	Deck system	0	0	0	0	0	0
3.62	Railing	1	1	1	1	1	5
3.7	Accessories/equipment	1	1	1	1	1	5
3.8	Box culvert	0	0	0	0	0	0
3.9	Wet crossing surface	0	0	0	0	0	0

Level 3 – Condition Values

Code	Element	S	R	K	F	P	NK
2.2	River flow/embankment	1	0	0	0	1	2
2.3	Substructure	1	1	1	1	1	5
2.4	Superstructure	0	1	0	0	1	2
2.7	Accessories/equipment	1	1	1	1	1	5
2.8	Box culvert	0	0	0	0	0	0
2.9	Wet crossing	0	0	0	0	0	0

At Level 2, the substructure scored NK = 5, indicating severe deterioration or failure-level condition, while the superstructure scored NK = 2. Equipment/accessories

again scored NK = 5. These findings demonstrate a clear pattern: the most severe deterioration is concentrated in river-interacting and support-related components (protective structures, arch/substructure, safety elements), while the traffic-bearing surface appears comparatively intact. This distribution is consistent with riverine bridge damage pathways where local scour and embankment instability undermine supports and protective systems before obvious failure of the deck surface becomes apparent (Deng & Cai, 2010; Ettema & Nakato, 2010).

Scour-Induced Damage Mechanism

The structural symptoms observed in the field support a scour-induced deterioration mechanism. Figure 3 shows erosion at the A1 arch element (Code 3.430), where foundation stones have been undermined due to river flow velocity. This condition is consistent with local scour processes that reduce foundation embedment depth and compromise bearing resistance (Deng & Cai, 2010).



Figure 3 Scour-induced erosion at arch element (A1)

Figure 4 illustrates partial collapse at the A2 arch segment, indicating progressive instability likely initiated by foundation undermining and embankment settlement.



Figure 4 Arch failure due to settlement and slope instability

Additionally, Figure 5 shows lateral displacement of box culvert units. The culverts, each measuring approximately 1 m × 1 m × 1 m and installed in a series of 16 units, exhibit lateral movement. Such displacement suggests differential settlement and soil–structure interaction effects, potentially triggered by

toe erosion and embankment instability (Ettema & Nakato, 2010; Arora et al., 2023).

Figure 5. Lateral displacement of box culvert units

The combination of arch failure, retaining wall loss, and box culvert displacement indicates coupled hydraulic–geotechnical instability rather than isolated surface deterioration.

Technical Screening and Intervention Implications

The technical screening results (Table 8) consolidate the BMS indicators into intervention-relevant categories. The protective structure (DPT), arch section, and railings were categorized as “failed/collapsed” (NK = 5), while the box culvert was categorized as minor damage (NK = 2). The deck surface and wet crossing elements were classified as excellent (NK = 0). In addition, lighting, traffic signs, and road markings were reported as not available, indicating loss of functional safety infrastructure even if traffic still passes.

Table 8 Condition Screening Results

Structural type	S	R	K	F	P	NK	Condition description
River channel zone	0	0	0	0	0	0	Excellent
Protective structure (DPT)	1	1	1	1	1	5	Failed/Collapsed
Arch section	1	1	1	1	1	5	Failed/Collapsed
Bridge deck surface	0	0	0	0	0	0	Excellent
Bridge railing	1	1	1	1	1	5	Failed/Collapsed
Box culvert	1	0	0	0	1	2	Minor damage
Wet crossing	0	0	0	0	0	0	Excellent
Street lighting	1	1	1	1	1	5	Not available
Traffic signs	1	1	1	1	1	5	Not available
Road markings	1	1	1	1	1	5	Not available
Average condition rating							Damaged

This pattern supports a rehabilitation-oriented intervention. The bridge is not simply experiencing superficial wear; rather, critical river-interacting components have reached failure-level condition, implying that corrective maintenance and structural rehabilitation are necessary to restore safety and resilience. In resilience-focused infrastructure management, prioritizing rehabilitation for scour-vulnerable components (protection works, substructure) is essential because these elements often

govern the threshold between serviceable and catastrophic failure (Argyroudis et al., 2019; Deng & Cai, 2010).

3.7 Remaining Service Life Estimation

Remaining service life was estimated using a condition-based empirical relationship incorporating:

- NK = Condition Value
- Y = Estimated structural age
- N = Design life
- $\alpha = 4.66$
- $b = 1.9051$

Based on the computed NK and empirical constants, the estimated equivalent service age of the bridge is approximately 41 years. This suggests that the structure has entered an advanced deterioration stage relative to its intended design life.

Condition-based life prediction aligns with probabilistic deterioration concepts in the literature, where condition indices serve as proxies for structural aging and performance reduction (Chen et al., 2021; Verma et al., 2014). However, because the current evaluation is based on visual BMS assessment, the service life estimate should be interpreted as an indicative management metric rather than a fully reliability-calibrated prediction.

Implications for Riverine Bridge Asset Management

The findings of this study highlight important implications for riverine bridge asset management, particularly when bridge condition assessment relies primarily on visual inspection through the Bridge Management System (BMS). While the BMS framework provides a structured approach for identifying surface-level deterioration and prioritizing maintenance actions, the observed damage patterns at the Sungai Salak Bridge indicate that hydraulic and geotechnical processes, especially local scour and embankment instability, may develop beyond what is immediately visible during routine inspection. Previous studies have emphasized that local scour around abutments and foundations is among the leading causes of bridge instability and failure in river environments, as it can progressively reduce foundation embedment and trigger structural displacement (Deng & Cai, 2010; Prendergast et al., 2016). Therefore, visual inspection results should be interpreted alongside hydraulic and geomorphological indicators to avoid underestimating potential structural risk.

Based on the observed deterioration mechanisms, several minimum follow-up inspection actions are recommended to support more reliable bridge asset management. First, field measurements of potential scour depth around abutments and protective structures should be conducted to verify whether foundation embedment has been compromised. Second, stability assessment of the approach embankment and retaining structures is necessary to

evaluate settlement and lateral soil movement that may influence structural alignment. Third, periodic monitoring of structural displacement—particularly at the arch and box culvert elements—can provide early indicators of progressive instability. Even relatively simple monitoring techniques, such as repeated visual documentation, level measurements, or installation of basic reference markers, can significantly improve deterioration tracking when advanced structural health monitoring systems are not available.

Integrating these additional inspection steps with the existing BMS framework can strengthen decision-making in riverine bridge management. As highlighted in resilience-oriented infrastructure studies, effective bridge asset management requires combining condition-based inspection with hazard-aware evaluation, especially in environments exposed to flooding and river morphodynamics (Argyroudis et al., 2019). By incorporating targeted scour assessment, embankment stability checks, and basic monitoring practices, bridge authorities can improve the reliability of maintenance prioritization and reduce the risk of sudden failure in river-crossing structures.

Conclusion

The Bridge Management System (BMS) evaluation indicates that the Sungai Salak Bridge is in a damaged condition with an average condition value of $NK = 3$. The deterioration is mainly associated with failure of protective structures, arch elements, and bridge safety components, while the deck surface and culvert units remain visually intact. The observed damage patterns are consistent with scour-induced erosion and embankment instability commonly found in riverine bridge environments.

Based on the condition assessment, the bridge is estimated to have an equivalent service age of approximately 41 years, indicating that the structure has entered an advanced deterioration stage relative to its intended service life. Therefore, rehabilitation measures are recommended rather than routine maintenance or full replacement.

Priority rehabilitation actions should focus on restoring the retaining structures (DPT), bridge railings, lighting systems, and traffic safety devices, as these elements directly influence structural protection and road-user safety. Implementing these measures together with improved inspection of scour and embankment stability can enhance the resilience and operational safety of the bridge.

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