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Alternative Design of Steel-Based Approach Structure for Pedestrian Suspension Bridge: A Case Study in Lobang Baru Village, Indonesia

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Abstract: This research investigates an alternative structural design for the approach bridge of a pedestrian suspension bridge by replacing reinforced concrete with structural steel to address construction challenges in remote areas. The study focuses on the Lobang Baru Pedestrian Suspension Bridge in Banjar Regency, South Kalimantan, where the Kulur Tengah side faces significant logistical constraints including limited accessibility, frequent river flooding, and inadequate transportation infrastructure for concrete materials. Using finite element modeling analysis, two structural systems were comprehensively evaluated: the existing reinforced concrete design and a proposed steel-based alternative. The steel alternative design employs H-shaped steel sections for main girders (H350x350-12/19), diaphragms (H200x200-8/12), and cross girders (H300x300-10/15), with hollow structural sections (HSS 508x9.5) for columns and 8mm steel deck plates. Results demonstrate substantial improvements: total structural weight decreased by 72.2% from 55.92 tons to 15.55 tons, with the weight per unit length reduced from 3.43 ton/m to 0.65 ton/m. The steel design eliminated 23.79 m^3 of concrete from the superstructure while requiring only a single support at the pillar block instead of dual supports at both pillar and anchor blocks, thereby reducing structural complexity and foundation loads. Although substructure concrete volume increased by 27.12 m^3 due to the separate abutment construction, the overall design significantly improves constructability through prefabrication, modular assembly, and reduced vulnerability to environmental conditions. These findings validate the technical and practical feasibility of steel-based approach structures for pedestrian suspension bridges in challenging rural environments, offering a replicable solution for similar infrastructure projects across Indonesia and other developing regions facing comparable geographic and climatic constraints.

Keywords: Pedestrian Suspension Bridge, Approach Bridge Design, Steel Structure, Rural Infrastructure

Introduction

Rural accessibility in Indonesia remains critically limited, particularly in regions divided by natural barriers such as rivers, valleys, steep slopes, and mountainous terrain. These geographical obstacles severely restrict daily activities, limiting access to essential services including education, healthcare, agricultural markets, and economic opportunities (Gatot Sukmara & Widi Nugraha, 2015). Pedestrian suspension bridges have emerged as an effective solution to overcome these accessibility challenges, providing vital connections for rural communities while requiring relatively modest investment compared to vehicular bridges.

The Lobang Baru Pedestrian Suspension Bridge project, located in Lok Tunggul Village, Pengaron Subdistrict, Banjar Regency, South Kalimantan, exemplifies both the necessity and challenges of rural bridge construction. Initiated by the Directorate General of Highways, Ministry of Public Works and Housing in 2019, this bridge consists of a 60-meter main suspension span, a 15.89-meter approach bridge on the Kulur Tengah side, and approach ramps of 23.19 meters (Lok Tunggul side) and 20.75 meters (Kulur Tengah side) (Balai Besar Pelaksanaan Jalan Nasional XI, 2018).

The construction site on the Kulur Tengah side presents substantial technical and logistical challenges. The area lacks adequate road access, making conventional construction methods problematic. Material transportation relies solely on river crossing using only small traditional wooden boats (jukung) and motorized wooden boats (kelotok), as larger barges cannot navigate the mountainous river conditions from the nearest city, Banjarmasin. Furthermore, the site experiences highly fluctuating river water levels dependent on upstream rainfall, with frequent flooding that inundates the construction area on the Kulur Tengah side, which sits at a lower elevation than the Lok Tunggul side. These conditions significantly impede concrete work, particularly for the pillar and anchor blocks requiring stable environmental conditions for proper curing.

Difficult site accessibility contributes substantially to construction delays (Ghozali et al, 2017) (Isramaulanan et al, 2017), as it causes material transportation delays (Khoirunnizam, 2022) (Messah et al, 2013). Natural factors such as fluctuating water levels further extend concrete work duration and overall project timelines (Al-Hazim & Abusalem, 2015) (Wahyuningtyas & Waskito, 2021), while concrete casting under flooded conditions compromises concrete quality (Aminullah, 2018). These challenges necessitate alternative construction approaches that can mitigate environmental vulnerabilities while maintaining structural integrity.

Steel structures offer distinct advantages for remote construction projects: lighter weight facilitating transportation, faster assembly reducing weather exposure, factory prefabrication ensuring quality control, and modular installation minimizing on-site work (Chen & Duan, 2014). This research proposes substituting the concrete approach bridge structure with a steel-based system, specifically addressing the efficiency of construction execution for the overall Lok Tunggul Pedestrian Suspension Bridge project given the significant impact of fluctuating river water levels and difficult site accessibility.

Previous research on pedestrian suspension bridges has primarily focused on main bridge structures rather than approach bridges. Studies have examined structural parameters (Anggraeni & Herbudiman, 2008), dynamic response to pedestrian loading (Kearney & Jeffrey A. Laman, 2013), load capacity optimization (Widyaningsih, 2020), connection details (Sirait et al, 2021), failure analysis (Dewobroto, 2022), and anchorage block design (Fischer IJ et al, 2022). However, approach bridge design alternatives remain largely unexplored, despite their critical role in projects where embankment construction proves unfeasible.

This study aims to: (1) develop an alternative structural design for the approach bridge replacing reinforced concrete structural elements with steel, and (2) quantify the reduction in concrete material usage resulting from steel substitution. The research employs finite element modeling to analyze both existing and proposed designs under comprehensive loading conditions including dead loads, live loads, wind loads, current forces, and seismic forces, following Indonesian bridge design standards (SNI 1725:2016, SNI 2833:2016, SNI 8460:2017) and AASHTO LRFD Bridge Design Specifications.

Methodology

Research Approach

This research employs an experimental approach through numerical simulation, manipulating independent variables (concrete and steel materials) and dependent variables (weight, deformation, and strength) to examine cause-and-effect relationships. The analytical instrument utilized is finite element method-based structural analysis software, enabling comprehensive modeling and evaluation of both structural systems.

Data Collection

1. Primary Data

Geometric data of the existing approach bridge was collected through direct field measurements conducted by a survey team (Figure 1). Measurements documented all structural dimensions including spans, member sizes, support locations, and elevation differences. Field verification ensured accuracy of as-built conditions compared to design documents.

2. Secondary Data

Material specifications were obtained from the detailed engineering design (DED) documents of the Lobang Baru Bridge project, including:

a. Mini pile concrete: 25x25 cm, K500 grade (f'c = 40 MPa).
b. Structural concrete: f'c = 20 MPa for pillar blocks, anchor blocks, and approach bridge
c. Reinforcement: BJTP 280 for diameter < 13 mm; BJTS 420A for diameter ≥ 13 mm..
d. Steel sections: A36 grade for the proposed alternative design.

Structural Modeling

1. Existing Concrete Approach Bridge

The existing structure was modeled as a three-dimensional rigid frame system with reinforced concrete elements (f'c = 20 MPa). The model includes:

a. Main girders: 30 cm × 65 cm
b. Diaphragms: 30 cm × 40 cm
c. Columns: 50 cm × 50 cm
d. Deck slab: 25 cm thick
e. Total span: 16.28 m with four pairs of supports (one pair at pillar block, one pair at anchor block, and two pairs on separate foundations)

Support conditions were modeled as rollers at pillar and anchor blocks, and fixed supports at intermediate foundations. This configuration ensures only vertical reactions at the suspension bridge structural components.

2. Proposed Steel Approach Bridge

The alternative design employs a single-span steel plate girder system with the following specifications:

a. Main girders: H350×350-12/19 steel sections
b. Cross girders: H300×300-10/15
c. Diaphragms: H200×200-8/12
d. Columns: HSS 508×9.5 (hollow structural section)
e. Deck: 8 mm steel plate supported on H125×125-6.5/9 floor beams at 333 mm spacing
f. Railings: T100×200-8/12 posts with 101.6 mm diameter, 5 mm thick pipe rails
g. Total span: 23.93 m with three pairs of supports (one pair at pillar block, one pair at separate abutment, and one pair on intermediate foundation)

The proposed design intentionally avoids loading the anchor block by terminating at a separate abutment structure, thereby eliminating the approach bridge's influence on the anchor block system.

3. Loading Analysis

Comprehensive loading conditions were applied following Indonesian standards (SNI 1725:2016, SNI 2833:2016) and AASHTO LRFD specifications:

a. Dead Loads

1) Self-weight calculated automatically based on member geometry and material density
2) Superimposed dead loads: railings and posts (0.669 kN/m)

b. Live Loads

1) Uniformly distributed pedestrian load: 5 kPa
2) Concentrated vehicle load: 20 kN (representing light farm vehicles)

c. Braking Force

1) 25% of axle load = 2.5 kN, distributed over girder length
2) Equivalent uniform load: 0.052 kN/m

d. Current Force

1) Applied to cylindrical column during flood conditions
2) Water depth: 2.62 m
3) Flow velocity: 1 m/s (assumed)
4) Drag coefficient: 0.7 (circular section)
5) Drag force: 0.1778 kN/m

e. Wind Load

1) Wind pressure: 130 kg/m^2 = 1.27 kN/m^2
2) Applied to exposed structural surfaces (girders, posts, railings)

f. Seismic Load

1) Site location: Latitude -3.313363°, Longitude 115.082348°
2) Peak ground acceleration (PGA): 0.059g
3) Spectral acceleration at T=0.2s: Ss = 0.12
4) Spectral acceleration at T=1.0s: S1 = 0.035
5) Site class: Soft soil (average SPT N-value: 10.55)
6) Response spectrum developed per SNI 2833:2016

g. Load Combinations

Analysis employed strength limit state, service limit state, and extreme event combinations per SNI 1725:2016, incorporating appropriate load factors for each combination.

Foundation Design

1. Pillar Foundation

A 3×4 pile group configuration using 25×25 cm prestressed concrete piles (K500) at 1.0 m center-to-center spacing supports a 300 cm × 400 cm × 80 cm pile cap (f'c = 25 MPa). Design criteria:

a. Allowable vertical deflection: ≤ 10 mm
b. Allowable horizontal deflection: ≤ 12 mm
c. Safety factor: 3.0

2. Abutment Foundation

A 4×9 pile group with similar pile specifications and spacing supports a larger pile cap to resist both vertical loads and lateral earth pressure from the approach embankment. Design follows Working Stress Design methodology with identical deflection and safety criteria.

3. Bearing Design

Steel bearing assemblies consisting of base plates and anchor bolts connect steel members to concrete pile caps, designed per AASHTO LRFD specifications to transfer all force components (axial, shear, moment) from superstructure to foundations.

4. Analysis Procedure

The research methodology follows the flowchart sequence:

a. Literature review and problem identification
b. Primary data collection (field measurements)
c. Secondary data collection (DED documents)
d. Structural modeling (existing and proposed systems)
e. Load application and combination
f. Finite element analysis
g. Design verification (members, connections, foundations)
h. Results comparison and discussion
i. Conclusions and recommendations

Result and Discussion

Existing Concrete Approach Bridge Performance

The existing reinforced concrete approach bridge operates as a continuous rigid frame structure spanning 16.28 meters with eight support points. Finite element analysis reveals the structural responses under service loading conditions. Table 1 presents the vertical reactions at supports located at the pillar block and anchor block.

Table 1. Support reactions of existing concrete approach bridge at pillar block

No	Load Case	Reaction (kN)
1	Dead Load	114.73
2	Superimposed Dead Load	2.28
3	Pedestrian Live Load	17.98
4	Vehicle Live Load	3.75

Table 2. Support reactions of existing concrete approach bridge at anchor block

No	Load Case	Reaction (kN)
1	Dead Load	114.73
2	Superimposed Dead Load	2.28
3	Pedestrian Live Load	17.98
4	Vehicle Live Load	3.75

The existing design imposes substantial loads on both the pillar block and anchor block of the suspension bridge system. Each support pair transfers approximately 115 kN dead load plus additional live load effects, which must be considered in the design of these critical suspension bridge components.

Proposed Steel Approach Bridge Performance

The alternative steel structure employs a simplified support configuration with only three support pairs, eliminating direct loading on the anchor block. Figure 2 illustrates the three-dimensional structural model with its geometric configuration and member arrangement.

Figure 2. Three-dimensional finite element model of proposed steel approach bridge

The steel design utilizes A36 grade structural steel (fy = 250 MPa) for all members. Table 3 summarizes the section properties of the primary structural elements.

Table 3. Steel section properties for main structural members

No	Element	Section	Area (cm^2)	Ix (cm^4)	Iy (cm^4)	Weight (kg/m)
1	Main Girder	H350×350-12/19	243.15	98,614	32,641	190.87
2	Cross Girder	H300×300-10/15	158.70	46,512	15,371	124.58
3	Diaphragm	H200×200-8/12	84.12	11,170	3,688	66.03
4	Column	HSS 508×9.5	147.48	46,046	46,046	115.77

Under comprehensive loading including dead load, live load, wind, current force, and seismic effects, the structural analysis demonstrates adequate performance with all members satisfying strength requirements. The demand-capacity ratios for critical members remain below 1.0, with maximum ratios of 0.87 for main girders and 0.76 for columns under the most severe load combinations.

Comparative Analysis of Support Reactions

Table 4 compares the vertical reactions at the pillar block between the existing concrete and proposed steel designs under equivalent loading conditions.

Table 4. Comparison of approach bridge reactions at pillar block

No	Load Case	Existing Concrete (kN)	Proposed Steel (kN)	Difference (%)
1	Dead Load	114.73	89.21	-22.2
2	Superimposed Dead Load	2.28	1.95	-14.5
3	Pedestrian Live Load	17.98	16.34	-9.1
4	Vehicle Live Load	3.75	3.82	+1.9

The proposed steel design generally reduces reactions at the pillar block across most loading conditions. While the vehicle live load reaction shows a slight increase of 1.9%, this difference is negligible in practical terms. More significantly, the steel alternative completely eliminates loading on the anchor block by terminating at a separate abutment structure, representing a substantial qualitative improvement in the overall system behavior.

Concrete Material Reduction

Superstructure Concrete

The existing concrete approach bridge superstructure requires:

1. Main girders (2 members, 16.28 m each): 19.54 m^3
2. Diaphragms (8 members): 0.96 m^3
3. Columns (4 members): 2.00 m^3
4. Deck slab: 1.29 m^3
5. Total superstructure concrete: 23.79 m^3

The proposed steel design eliminates all superstructure concrete, replacing it with structural steel sections and steel deck plates. This represents a 100% reduction in superstructure concrete volume.

Substructure Concrete

Existing substructure components:

1. Pile caps and foundations: 8.70 m^3
2. Proposed substructure components:
3. Pillar foundation pile cap: 9.60 m^3
4. Abutment foundation pile cap: 34.56 m^3
5. Abutment wall: 15.45 m^3
6. Total proposed substructure concrete: 59.61 m^3

The substructure concrete increases by 50.91 m^3 due to two factors: (1) construction of a separate abutment structure independent from the anchor block, and (2) increased approach elevation to maintain minimum 0.5 m clearance above flood levels, requiring a larger abutment to resist higher lateral earth pressures.

Net Concrete Change

1. Superstructure reduction: -23.79 m^3
2. Substructure increase: +50.91 m^3
3. Net increase: +27.12 m^3 (83.6% of original total volume)

While total concrete volume increases, this change serves a critical functional purpose: eliminating approach bridge loads from the anchor block system. The anchor block no longer experiences lateral earth pressure from the approach embankment, as these forces transfer to the independent abutment structure. This redistribution improves the overall structural performance and safety of the suspension bridge system.

Structural Weight Comparison

Table 5 presents the detailed weight breakdown for both bridge designs.

Table 5. Weight comparison between existing and proposed approach bridges

No	Component	Existing Concrete (kg)	Proposed Steel (kg)
1	Main structural elements	30,893.78	4,839.89
2	Deck system	—	1,830.51
3	Railings and posts	—	605.00
4	Total superstructure	30,893.78	7,275.40

The steel alternative achieves a 76.4% weight reduction in the superstructure, decreasing total weight from 30,893.78 kg to 7,275.40 kg. This dramatic reduction translates to significantly lower foundation demands.

Weight per unit length provides a normalized comparison:

a. Existing concrete: 30,893.78 kg / 16.28 m = 1,897.4 kg/m

b. Proposed steel: 7,275.40 kg / 23.93 m = 304.1 kg/m

The steel design achieves an 84.0% reduction in weight per unit length, demonstrating exceptional structural efficiency. This weight advantage directly benefits foundation design, reduces transportation requirements, and simplifies construction logistics in the remote site conditions.

Foundation Load Reduction

The substantial weight reduction produces corresponding benefits in foundation design. Table 6 summarizes the total vertical loads acting on the pillar foundation.

Table 6. Total vertical loads on pillar foundation

No	Load Combination	Existing (kN)	Proposed (kN)	Reduction (%)
1	Service I	469.18	342.67	27.0
2	Strength I	587.97	428.34	27.1

The reduced superstructure weight enables more efficient foundation solutions. The proposed design employs a 3×4 pile group (12 piles) compared to potentially larger configurations required for the heavier concrete structure. Foundation design verification confirms:

a. Total allowable capacity: 2,610.41 kN > 469.69 kN applied load (SF = 5.55)

b. Vertical deflection: 0.34 mm < 10 mm allowable

c. Horizontal deflection: 0.32 mm < 12 mm allowable

All criteria satisfy design requirements with comfortable margins, validating the foundation adequacy.

Constructability Advantages

Beyond quantitative performance metrics, the steel alternative offers substantial constructability improvements particularly relevant to the challenging site conditions:

Prefabrication and Quality Control

Steel members fabricate in controlled factory environments, ensuring:

a. Precise dimensional accuracy
b. Consistent material properties
c. Quality welding and connection details
d. Protective coating application before site delivery

This approach contrasts sharply with in-situ concrete construction, where quality depends heavily on site conditions, material handling, and weather during placement and curing.

Transportation and Logistics

Individual steel members (maximum weight approximately 450 kg for a 3-meter main girder segment) can transport using available small boats (jukung and kelotok), whereas concrete construction requires transporting cement, aggregates, water, reinforcement, formwork, and mixing equipment—all substantially more voluminous and challenging in the remote location.

Assembly Speed

Steel erection proceeds rapidly through bolted connections, potentially completing superstructure assembly in days rather than the weeks required for concrete formwork, reinforcement placement, casting, and curing. This speed reduces weather exposure risk and shortens the critical path for accessing the site during dry season construction windows.

Flood Resilience

The steel structure tolerates temporary flooding better than concrete construction. Rising water levels that would halt concrete operations merely delay steel erection activities without compromising material quality or requiring rework.

Design Considerations and Limitations

Corrosion Protection

The flood-prone environment necessitates robust corrosion protection for steel elements. The design specifies:

a. Hot-dip galvanizing for all structural steel members
b. Additional protective coating systems for submerged or splash zone components
c. Regular inspection and maintenance protocols

Properly protected steel structures demonstrate excellent long-term durability even in aggressive environments. The 50-year design life specified for the pedestrian suspension bridge standard is achievable with appropriate coating systems and maintenance.

Abutment Construction Requirements

The independent abutment structure requires substantial concrete volume (59.61 m^3) and must resist significant lateral earth pressures from the approach embankment. However, this component:

a. Constructs using conventional methods on stable ground above typical flood elevations
b. Provides clear separation between approach bridge and anchor block functions
c. Enables independent construction sequencing that can proceed during periods when the flood-prone anchor block area is inaccessible.

Economic Considerations

While detailed cost analysis exceeds this study's scope, several economic factors merit consideration:

Initial material costs for structural steel typically exceed concrete on a per-kilogram basis. However, comprehensive economic evaluation must account for:

a. Reduced foundation costs from lighter superstructure
b. Eliminated formwork expenses
c. Reduced site labor requirements
d. Shorter construction duration reducing overhead and financing costs
e. Lower transportation costs for prefabricated components
f. Reduced risk of construction delays and associated costs

For remote, logistically constrained projects, these factors often favor steel construction despite higher base material costs.

Implications for Rural Infrastructure Development

This research demonstrates a viable alternative approach for pedestrian bridge construction in challenging rural environments. The methodology proves adaptable to similar projects facing:

a. Limited accessibility restricting heavy equipment and material transport
b. Flood-prone sites where stable conditions for concrete work are uncertain
c. Compressed construction schedules requiring rapid assembly
d. Remote locations where quality control of in-situ concrete is problematic

The approach bridges represents only one component of the complete suspension bridge system, yet its successful alternative design validates the principle of material substitution as a strategy for overcoming site-specific constraints. Future research could extend this methodology to other bridge components or alternative structural systems.

Conclusion

This research successfully developed and validated an alternative steel-based design for the approach structure of the Lobang Baru Pedestrian Suspension Bridge, demonstrating significant technical and constructability advantages over the original reinforced concrete design.

Key Findings:

1. Structural Efficiency: The proposed steel design achieved 76.4% total weight reduction (from 30,893.78 kg to 7,275.40 kg) and 84.0% reduction in weight per unit length (from 1,897.4 kg/m to 304.1 kg/m), substantially decreasing foundation demands and transportation requirements.
2. Load Path Optimization: The alternative design employs three support pairs instead of four, eliminating direct loading on the anchor block by terminating at an independent abutment structure. This simplification reduces the approach bridge's influence on critical suspension bridge components.
3. Material Usage: While superstructure concrete was completely eliminated (23.79 m^3 reduction), substructure concrete increased by 50.91 m^3 for the separate abutment, resulting in a net increase of 27.12 m^3. This trade-off provides functional benefits by isolating anchor block loads and accommodating increased approach elevation requirements.
4. Constructability: The steel system enables prefabrication, quality-controlled manufacturing, simplified transportation using available small boats, rapid bolted assembly, and improved resilience to flood disruptions—all critical advantages for the remote, flood-prone site conditions.
5. Structural Performance: Finite element analysis confirms that all steel members satisfy strength requirements under comprehensive loading including dead, live, wind, current, and seismic forces, with demand-capacity ratios remaining below unity.

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