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Limit state design of a single-span PSC box Girder Bridge for a seismically active Hilly River crossing: Case study of the Mardi River, Nepal

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Abstract

This study presents the complete analysis and limit state design of a 40-meter single-span box girder bridge made of prestressed concrete (PSC) that spans the Mardi River in Kaski, Nepal. In addition to regional-specific issues like seismicity and mixed traffic loading, the design takes into account a thorough site evaluation that includes in-depth topographic, hydrological, and geotechnical surveys. The effective width approach is used to analyze the deck slab, design the superstructure, a PSC box girder, for dead, live (Indian Road Congress (IRC) Class A and Class 70R traffic loads), and seismic loads. Pot Polytetrafluoroethylene (PTFE) bearings are used to transfer load from the superstructure to the substructure. Cantilever abutments and footings are substructure elements developed for stability and load transfer efficiency, with a focus on scour and seismic resistance. A strong, affordable, and long-lasting infrastructure solution appropriate for challenging topography is demonstrated by the provided design, which closely complies with IRC norms.

1. Introduction

Bridges play a vital role in connecting communities and supporting economic growth, especially in geographically demanding areas like the Himalayan foothills of Nepal. Choosing the right type of bridge and following a careful, well-informed design process are essential to ensure safety, durability, and cost-effectiveness. Among the various options, PSC box girder bridges are widely favored for their structural efficiency and adaptability—particularly for medium spans where their torsional stiffness and strength-to-weight ratio offer clear advantages. Recent studies by Kumar and Rao [1] on PSC bridge optimization and research by Kawashima et al. [2] on seismic design of bridges in mountainous terrain provide valuable frameworks applicable to Nepal's context.

Studies by Gupta and Rao [3] on PSC bridges in Himalayan regions document the enhanced durability and reduced maintenance costs of PSC compared to conventional reinforced concrete girders over 50-year service periods. This paper presents the detailed design and analysis of a 40-meter single-span PSC box girder bridge across the Mardi River in Kaski, Nepal. The main goal is to create a strong, cost-effective structure that fully complies with IRC standards, ensuring long-term performance under expected traffic and environmental loads.

The proposed bridge site is in Lumre, Machhapuchchhre Rural Municipality, Kaski, Gandaki Province, Nepal, spanning the Mardi River. The bridge site is located at Latitude 28° 20' 24.42" N and Longitude 83°53'12.5" E. The local topography is characterized by hilly terrain.

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2. Methodologies and design philosophy

2.1. Structural planning

The preliminary design is guided by an analysis of existing reports, design manuals, literature, and codes. The following standards and codes are used:

- **IRC 5:** 2015 [4] - General Features of Design
- **IRC 6:** 2017 [5] - Loads and Load Combinations
- **IRC 112:** 2020 [6] - Code of Practice for Concrete Road Bridges.
- **Nepal Bridge Standards:** 2067 [7]
- Standard Specification of Roads and Bridges, [8] Government of Nepal
- **IRC 83:** 1987 [9] (Part III) - Pot, pin, metallic guide, and plane sliding bearings
- **IRC 78:** 2000 [10] - Foundation and Substructures

2.2. Topographic and Geological surveys

Detailed topographic surveys conducted to establish precise ground profiles, river cross-sections, and approach alignments are crucial for determining the optimal bridge length (40 m single span) and vertical clearances. Geological investigations revealed a net allowable bearing capacity of 450 kN/m², informing the foundation design. Figure 1 demonstrates the land use land coverage map obtained using ArcGIS.

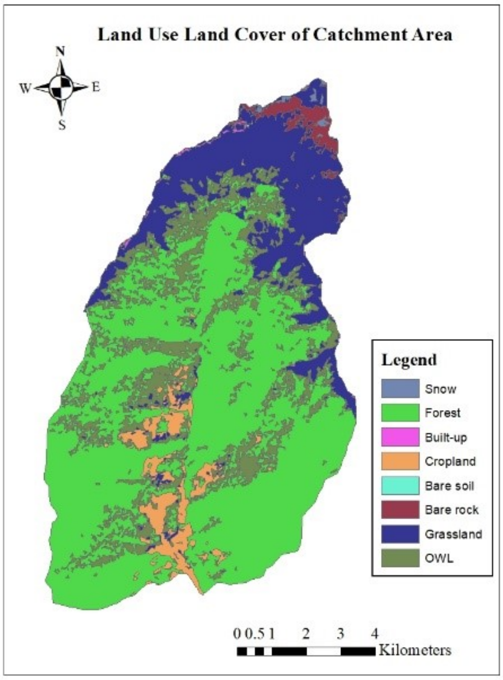

Figure 1: Land Use Land Coverage of Catchment

2.3. Hydrological and Hydraulic analysis

The delineated catchment area of the Mardi River at the bridge site is approximately 94.7 km². Based on historical rainfall data and hydrological modeling (e.g., using the Rational Method [11]), the estimated design discharge for a 100-year return period is calculated as 751 m³/s. The corresponding scour depth, a critical parameter for foundation design, is determined to be 7.5 m below the High Flood Level (HFL), which is established at an elevation of 1130.97 m. River scour assessment in mountainous regions requires particular attention to sediment transport dynamics and seasonal variations [12].

2.4. Traffic and load data

Traffic data collection involves projections for design traffic classes, specifically IRC Class A and Class 70R vehicles. Class A loads represent standard vehicular traffic, while Class 70R covers heavy-duty wheeled, bogie, and tracked vehicles, which impose significant concentrated loads. These load specifications are fundamental for determining critical bending moments and shear forces in the superstructure.

2.5. Analysis and design philosophy

The bridge design adopted the Limit State Design (LSD) approach, as prescribed by IRC:112-2020 [6] for concrete bridges, which considers both Ultimate Limit States (ULS) and Serviceability Limit States (SLS). This approach ensures structural integrity against collapse and satisfactory performance under service conditions.

2.5.1. Structural system and configuration

A single-span PSC box girder bridge is selected. The bridge features a total width of 8.4 m, comprising a 6 m wide carriageway and 1.2 m wide footpaths on either side. The box girder section is chosen for its torsional rigidity and efficient load distribution across its cross-section.

2.5.2. Load analysis

All relevant loads are considered in accordance with IRC:6-2017[5] and IRC:78-2014[10]:

- **Dead Loads (DL):** This includes the self-weight of the structural elements (box girder, deck slab, diaphragms, parapets) and superimposed dead

Table 1: Hydraulic design parameters

S.N.	Parameters	Value
1	Slope of the river bed	0.02709
2	HFL	1130.97 m
3	Linear waterway	40 m
4	Afflux	0.15 m
5	Freeboard	1.5 m
6	Maximum scour depth for abutment	7.5 m
7	Maximum scour depth for the pier	No pier provided
8	RL of bottom of superstructure (= HFL + Freeboard)	1132.47 m

Table 2: Maximum BM and SF for Various IRC Loading

IRC Loading	Maximum Bending Moment (kNm)	Maximum Shear Force (kN)
Class A	69.257	68.256
Class 70R Wheeled	61.711	67.347
Class 70R Tracked	69.219	77.476
Class 70R Bogie	69.753	82.82

loads such as wearing course and utilities. The dead load is calculated to be approximately 24 kN/m per girder line.

- **Live Loads (LL):** IRC Class A and Class 70R vehicular loads are positioned to generate maximum bending moments and shear forces using influence line diagrams. These include distributed and concentrated loads representing typical and heavy traffic.
- **Seismic Loads (EQ):** Nepal is an earthquake-prone region. Seismic forces are determined based on the seismic zone characteristics of Kaski and applied as equivalent static forces in both longitudinal and transverse directions. Load combinations incorporated seismic effects for the overall stability of the bridge [13].
- **Other Loads:** Environmental loads such as wind load, temperature effects, and shrinkage/creep effects are also considered in the design process as per IRC guidelines.

2.5.3. Structural analysis techniques

The analysis involved several stages:

- **Deck Slab Analysis:** The deck slab is analyzed as a one-way slab for local bending moments and shear. The effective width method is employed to determine the distribution of concentrated wheel loads over the slab, ensuring accurate design of reinforcement. This method simplifies the complex load distribution by assuming that the wheel load is distributed over a certain effective width of the slab.
- **Box Girder Analysis:** The PSC box girder, as the primary load-carrying element, is analyzed for bending moments, shear forces, and torsional effects under various load combinations. Longitudinal prestressing tendons are designed to counteract tensile stresses induced by external loads and self-weight, ensuring the concrete remains predominantly in compression or experiences minimal tension. The influence of prestressing losses (due to friction, anchorage slip, elastic shortening, creep, and shrinkage) is calculated to determine the effective prestressing force.
- **Limit State Checks:** Both ULS (flexure, shear, torsion, axial compression) and SLS (stress control, crack control, deflection) are checked for all components.

3. Materials and specifications

The material selection aligns with standard bridge engineering practices and IRC codes:

- **Concrete:** M50 grade concrete is specified for the superstructure (deck slab and box girders) due to its high compressive strength and durability, essential for resisting prestressing forces and environmental exposure. M40 grade concrete is designated for substructure components (abutments and foundations).

- **Reinforcing Steel:** Fe500D grade high-strength deformed bars are used for all conventional reinforcement.
- **Prestressing Steel:** High-tensile steel strands with a minimum tensile strength of 1570 N/mm² are utilized for prestressing, selected to minimize relaxation losses and maximize efficiency.
- **Bearing:** Pot PTFE bearings to accommodate rotation and horizontal movement and effective vertical load transfer.

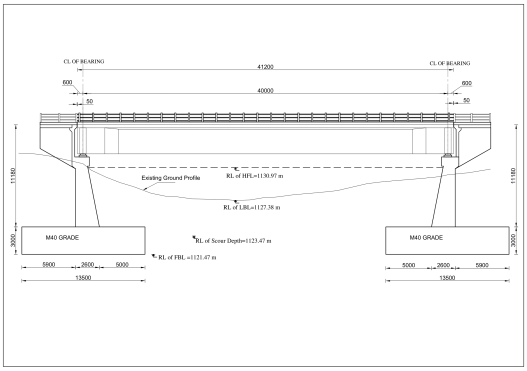

Figure 2: General arrangement of Bridge

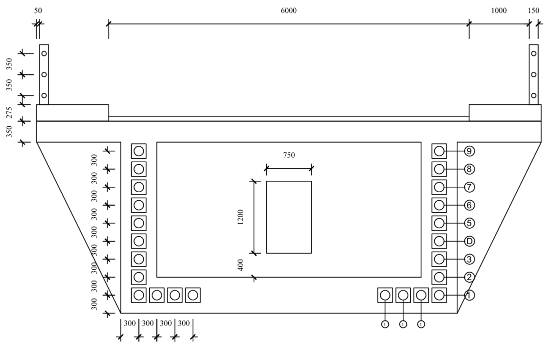

Figure 3: Section at support showing end blocks

4. Component design and result

The detailed design yielded specific dimensions and reinforcement details for all structural elements, following IRC standards. Figure 2 is the general arrangement of the designed bridge.

4.1. Superstructure dimensions and reinforcement

- **Deck Slab:** The typical slab thickness is 350mm. Designed in flexure with a design moment of 151.167 kNm and within permissible limits as suggested by IRC guidelines, 16 mm bars at 125 mm c/c spacing are provided as main rebars, and 12 mm bars at 125 mm c/c spacing are provided as distribution rebars.
- **Cantilever Slab:** Designed for moments and shear from footpath loads and parapet self-weight, and superimposed dead load. The design process is similar to that of the deck slab, with a design moment of 36.295 kNm. 16 mm bars at 200 mm c/c spacing are provided as main rebars, and 12 mm bars at 200 mm c/c spacing are provided as distribution rebars.
- **Box Girder:** Designed for longitudinal bending (flexure) and transverse shear. Prestressing tendons are profiled (e.g., parabolic) to optimize the resisting moment and control stresses within permissible limits. The cross-section dimensions are optimized based on flexural and shear demands. 22 Class II 7 ply 19K13 prestressing cables are used with an effective prestressing force of 2730 kN per cable. This force is strategically applied via parabolic cable profiles to achieve zero or minimal tension in concrete under service loads [14].

  Height of parabolic cable profile from the bottom of the girder (y) is determined using the expression:

$$y = -\frac{4(y_m - y_e)a^2}{\text{span}^2} + \frac{4(y_m - y_e)a}{\text{span}} + y_e \quad (1)$$

where:
y = Height of parabolic cable profile from the bottom of the girder
y_m = Height of parabolic cable profile at midspan from bottom of girder
y_e = Height of parabolic cable profile at supports from bottom of the girder
a = Section at which the height of the parabolic cable profile is desired
span = Total span of the girder

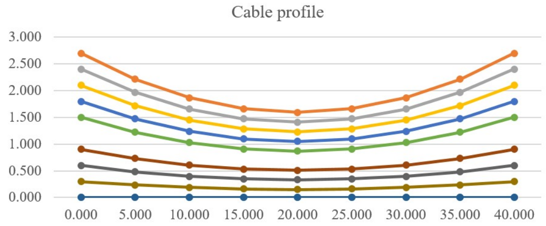

Figure 4: Cable profile for girder

- **Bearings:** Pot bearings are specified to accommodate thermal expansion/contraction and rotational movements of the superstructure while effectively transferring vertical and horizontal loads to the abutments. Different load combinations are considered [5]. The design vertical load per bearing is approximately 500 kN. 4 pot PTFE bearings, among which 2 are fixed (restricting translation but allowing rotation) and the other 2 are free (allowing both translation and rotation), are designed as shown in Figures 5 and 6, respectively.

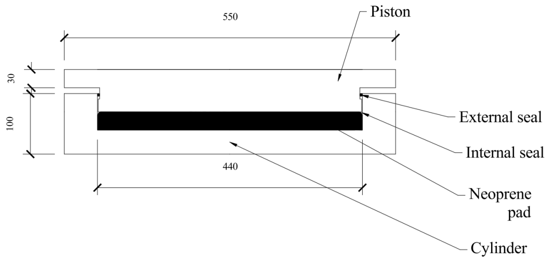

Figure 5: Fixed PTFE Pot Bearing

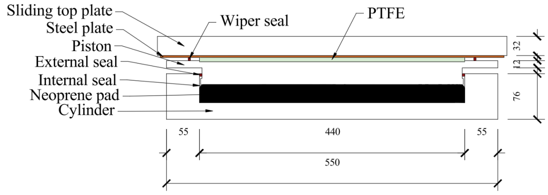

Figure 6: Free PTFE Pot Bearing

4.2. Substructure and foundation design

- **Abutment:** Designed as reinforced concrete cantilever return walls, they resist lateral earth pressure, approach slab loads, and transfer superstructure reactions to the foundation. Stability checks against overturning, sliding, and crack width are performed, with particular attention to seismic forces. The total height from foundation to the final road level (top of back wall) is designed to be 11.28 m. As the axial capacity is calculated to be greater than the maximum axial load, abutment is designed as a flexure member with a maximum bending moment of 39973.82 kNm. 32 mm bars at 100 mm c/c spacing are provided as main rebar, which is well within the permissible limits for shear and crack width. For horizontal reinforcement, 20 mm bars at 130 mm c/c are spaced at 100 mm for vertical reinforcement (at front face). The abutment cap required 16 mm bars at 150 mm c/c spacing on both longitudinal and transverse sides. For the back wall, the rebars are placed at 150 mm c/c, whose diameter is 16 mm for vertical bars and 12 mm for horizontal bars. The loads and moments are analyzed and found safe against overturning and sliding.
- **Foundation:** The foundation design uses an open foundation system, optimized for the site's geological conditions of sandy gravels and boulders, ensuring strong load-bearing capacity and stability. It supports vertical and horizontal forces, including moments from the superstructure, abutment self-load, and environmental loads like seismic forces, adhering to IRC:6-2017 [5] standards. Bearing pressure checks verify safety, with a maximum pressure of 562.5 kN/m². The structural design employs M40 concrete and Fe500D reinforcement, with 28 mm rebars at 130 mm c/c to address flexure and shear demands. A punching shear check confirms the foundation's capacity to resist concentrated loads, preventing shear failure at critical sections. Crack width and minimum reinforcement checks improve durability, while moment of inertia and stress distribution analyses confirm performance under various load combinations, ensuring a reliable foundation for the bridge.

5. Comparison with alternate structural systems

- **I-girder alternative:** The deck would require approximately six to eight girders to achieve the total width of 8.4 m. This option offers comparatively lower torsional stiffness and therefore demands additional cross-bracing and more intricate connection detailing. Overall, the estimated construction cost is about 12–15% higher than the selected box girder solution [15].
- **Segmental PSC alternative:** The use of segmental construction would call for specialized equipment and skilled workmanship, increasing both the complexity of execution and the project schedule. While this method is advantageous for significantly longer spans (typically greater than 60 m), it is less economical for the present 40 m span, with costs estimated to be around 20–25% higher than the adopted box girder [15].

6. Discussion and conclusion

Considering the difficult topography and intricate hydrology of the location, the decision to use a single-span PSC box girder bridge proved to be quite successful in spanning the Mardi River [16]. It is a viable option for medium-span bridges in these conditions due to its exceptional torsional rigidity and effective load distribution capabilities. Thorough hydrological analysis and thoughtfully planned deep foundations guarantee long-term stability. Additionally, the bridge is more resilient to earthquakes that commonly impact Nepal's tectonic topography since seismic design principles are integrated throughout the structure.

The project demonstrates how well IRC standards and the limit state design philosophy can be applied to provide a safe and long-lasting bridge that meets the unique requirements of the site. The study provides insightful information for future bridge construction in mountainous, seismically active areas and highlights the significance of integrating structural analysis with local environmental factors.

7. Limitations

- Simplified thermal load analysis; detailed temperature gradient studies during monsoon and dry seasons would improve bearing and joint design.
- Lack of full-scale prototype testing.

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