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Seismic Performance Analysis of RC Bridge Substructures using Pushover Method

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Abstract: Bridges serve as critical transportation infrastructure, yet many older reinforced concrete bridges lack adequate seismic design, leaving them vulnerable to moderate earthquakes due to insufficient shear capacity, poor confinement, and limited transverse reinforcement. In seismically active Bangladesh—a river-dense region with no bridge-specific seismic code—this study addresses the gap by integrating (BNBC, 2020) hazard data with (AASHTO, 2020) LRFD design provisions for bridge substructures. The research evaluates soil-structure interaction effects, particularly on soft soils, and assesses seismic performance under varying earthquake intensities. Results demonstrate that AASHTO-compliant designs, adapted with BNBC seismic parameters, meet safety objectives for bridge piers in Bangladesh, providing a validated framework for regions lacking localized codes. Future work should explore advanced soil modeling and nonlinear time-history analysis to further refine seismic resilience.

Keywords: *Seismic Performance, Bridge Substructure, Soil-Structure Interaction, AASHTO LRFD, BNBC 2020, Pushover Analysis, Fiber Hinges, Performance-Based Design, Bangladesh Bridges, Nonlinear Static Analysis.*

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I. INTRODUCTION

Bridges play a crucial role in transportation infrastructure, facilitating economic growth and regional connectivity. However, many reinforced concrete (RC) bridge bents constructed before the 1990s were designed with limited seismic provisions, rendering them susceptible to damage even under moderate seismic events (Bazaez & Dusicka, 2017). Common deficiencies—including inadequate shear capacity, insufficient transverse reinforcement, and poor concrete confinement—further exacerbate their vulnerability (Parghi & Alam, 2016).

The dynamic response of bridges during earthquakes is a key determinant of structural safety. Notably, soil-structure interaction (SSI) significantly influences seismic performance, particularly for bridges founded on soft soils. While conventional design approaches often overlook SSI, studies confirm that both ground motion characteristics and foundation behavior critically affect bridge performance during seismic activity (Fawad et al., 2019).

Bangladesh, a river-dense country traversing a north-south corridor, depends heavily on bridges for transportation. However, it lies in a seismically active zone, yet lacks a bridge-specific seismic design code. Current practices predominantly adopt (AASHTO, 2020) guidelines, which do not comprehensively address the region's unique seismic risks. Although the Bangladesh National Building Code (BNBC, 2020) includes seismic provisions, its focus remains on buildings rather than bridges. This study seeks to bridge this gap by: (1) Integrating (BNBC, 2020) seismic provisions into a LRFD-based framework (AASHTO, 2020) for bridge substructure design, (2) Evaluating seismic performance of substructures under varying earthquake intensities to improve resilience and safety of bridges in Bangladesh.

II. METHODOLOGY

The seismic design of bridge substructures requires a robust methodology that accounts for regional seismic hazards, soil-structure interaction, and nonlinear structural behavior. In this study, the design process begins by defining the seismic hazard parameters. The zone coefficients and spectral acceleration values are adopted from (BNBC, 2020), while the site coefficients follow (AASHTO, 2020) guidelines. These parameters are used to construct the design response spectrum, which serves as the basis for seismic analysis. The soil conditions are classified according to the (AASHTO, 2020) Soil Classification system, ensuring site-specific considerations are integrated into the design. Additionally, bridges are categorized into three operational classes based on their functional importance, as prescribed by (AASHTO, 2020).

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To accurately estimate displacement demands, the FEMA 440 Equivalent Linearization (EL) method is employed. This approach refines traditional linear analysis by incorporating nonlinear effects through equivalent damping and effective stiffness parameters. The EL method provides a more realistic approximation of inelastic displacement demands (Δ_{nl}), particularly for structures expected to undergo significant nonlinear deformation during seismic events. This step is critical for ensuring that the bridge can withstand design-level earthquakes without catastrophic failure.

The accurate modeling of soil-structure interaction is critical for assessing the seismic performance of bridge foundations. For lateral soil resistance, the analysis employs p-y curves as specified in API RP 2A, which characterize the nonlinear relationship between lateral pile deflection and soil resistance. The axial load-transfer mechanism is modeled using two complementary approaches from (AASHTO, 2012): t-z curves for skin friction distribution along the pile shaft and Q-z curves for end-bearing capacity at the pile tip. These empirically-derived curves provide a comprehensive framework for simulating:

By implementing these standardized soil models, the analysis captures the essential nonlinear behavior of foundation systems under seismic excitation. This approach ensures that both global bridge response and local soil failure mechanisms are properly accounted for in the performance evaluation.

The structural design follows (AASHTO, 2020) LRFD specifications, with a focus on two primary limit states: the Strength I Limit State for normal and extreme load conditions, and the Extreme Event I Limit State for seismic demands with a 1,000-year return period. The design and detailing of piers and piles adhere to ductility requirements to enhance seismic resilience. Nonlinear pushover analysis is conducted using fiber hinge models to evaluate the structure's performance under progressively increasing lateral loads, identifying potential failure mechanisms and hinge formations.

Performance evaluation is carried out using criteria outlined in (FHWA, 2006), which establishes relationships between seismic hazard levels and bridge performance objectives (e.g., operational, life safety, and collapse prevention). While (AASHTO, 2014) requires only a single-level design for a 1,000-year earthquake, this study extends the analysis to multiple performance levels based on the framework proposed by (Hose and Seible, 1999). This approach ensures that the bridge meets performance expectations across a range of seismic intensities, providing a comprehensive assessment of its resilience.

The methodology concludes with a validation phase, where displacement demands and ductility requirements are checked against the refined spectra derived from the Equivalent Linearization method. This step ensures that the design not only complies with code requirements but also achieves the desired performance objectives under seismic loading. By integrating and AASHTO provisions with advanced analysis techniques, this study provides a systematic framework for the seismic design of bridge substructures in regions with high seismic risk, such as Bangladesh.

III. MODELING AND ANALYSIS

➢ *Bridge Description and Site Conditions*

This study examines a 120-meter-long, three-span prestressed concrete girder bridge crossing the Meghna River in Astagram, Bangladesh. The structure features 40-meter equal spans supported by four rectangular piers, with a 10-meter-wide deck accommodating a 9-meter carriageway. The bridge is founded on AASHTO Soil Type E (soft clay/silt), representing a typical river crossing in Bangladesh that combines common structural features with challenging geotechnical conditions.

These site-specific conditions create a complex soil-structure interaction scenario. The soft clay/silt foundation (Soil Type E) combined with the variable soil stratification and significant scour potential presents unique challenges for seismic performance. The contrast between the stiff sand layers and soft clay interlayer may lead to irregular dynamic behavior, while the substantial scour depth necessitates careful consideration of foundation stability. This combination of typical bridge configuration and challenging subsurface conditions provides valuable insights for seismic assessment of similar river crossings in Bangladesh and other regions with comparable geotechnical profiles.

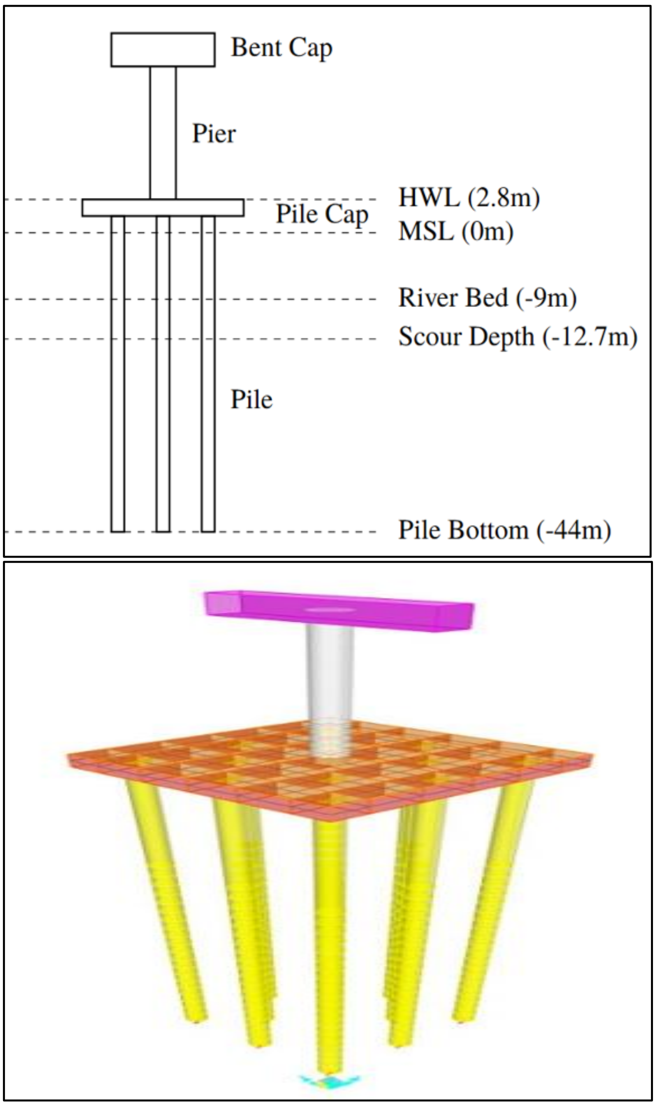

Fig 1 Elevation view and 3D Model of Bridge Substructure

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➢ *Modelling of Soil as Springs*

While SAP2000 lacks native capability for finite element modeling of soil, it permits the use of discrete spring elements to approximate soil-structure interaction. In this study, soil properties were characterized using Standard Penetration Test (SPT-N) values obtained to a depth of 30 meters below the riverbed. The soil springs were implemented at each pile node with the following configuration:

- P-y springs in both Global X and Y directions to represent lateral soil resistance
- T-z springs in Global Z direction to model shaft friction along the pile length
- Q-z spring at the pile tip to simulate end bearing resistance

This modeling approach captures the three-dimensional soil-structure interaction while maintaining computational efficiency. The spring properties were assigned based on the site-specific geotechnical data, with due consideration given to the variation in soil strata with depth.

➢ *Material Property*

The study used standard construction materials with concrete specified at 40 MPa compressive strength and 29.7 GPa elastic modulus, paired with 420 MPa yield strength reinforcement steel having 200 GPa elastic modulus. These properties represent typical bridge construction materials, providing adequate strength for structural demands while ensuring proper ductility for seismic performance. The material specifications were selected to accurately model structural behavior under both service and seismic loading conditions.

➢ *Loads*

The analysis incorporated both gravity and seismic loads to evaluate bridge performance. A uniform gravity load of 255 kN/m (total 10,200 kN per 40m span) was applied, comprising 6,800 kN dead load and 3,400 kN live load. Seismic loads followed (BNBC, 2020) for Soil Type E in Zone 2, using response spectrum analysis with 100%-30% directional combination. Load combinations included Strength I (1.25DL + 1.75LL) and Extreme Event I (1.0DL + 0.7LL + 1.0EQ_X/Y) per (AASHTO, 2020).

➢ *Nonlinear Analysis*

Pushover analysis began with a Nonlinear Gravity load case (100%DL + 25%LL) to establish initial conditions. Lateral displacement was then incrementally applied until failure, assessing ductility, hinge formation, and collapse capacity. The displacement-controlled protocol captured yield points, energy dissipation, and failure mechanisms.

➢ *Hinge Definition and Assignment*

The nonlinear behavior of structural members was modeled in SAP2000 using fiber hinges, which provide a more detailed representation of material behavior compared to conventional auto hinges. Unlike the automated hinge properties defined by ASCE 41-13, fiber hinges explicitly account for the stress-strain response of both concrete and steel, enabling a more precise simulation of member nonlinearity during pushover analysis. For concrete columns, the fiber hinge formulation incorporated uniaxial constitutive models for confined and unconfined concrete, along with reinforcing steel, allowing for direct evaluation of strain demands and damage progression.

This approach facilitated a realistic representation of the structural response, capturing initial elastic behavior, yielding, and post-yield degradation while also providing detailed insights into localized stress and strain distributions. The fiber hinge model effectively tracked the progressive formation of plastic hinges and associated ductility demands during displacement-controlled pushover analysis, offering a comprehensive assessment of structural performance under seismic loading. By explicitly modeling material nonlinearity, the fiber hinge approach enhanced the accuracy of the analysis while maintaining computational efficiency, ensuring a robust evaluation of the structure's seismic behavior beyond the generalized assumptions of code-based auto hinges.

➢ *Pier and Pile Design and Detailing*

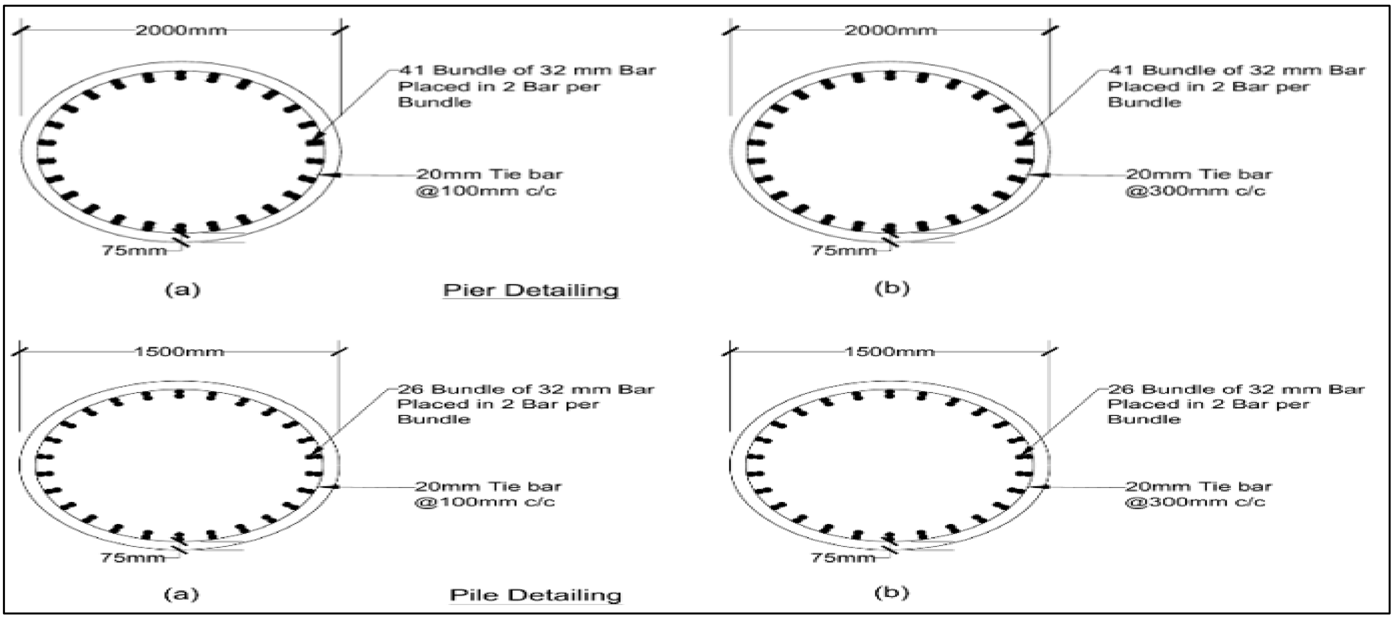

Fig 2 Cross Section Detailing of Pier and Pile (a) Confined Region, (b) Unconfined Region

- *Performance Evaluation from Pushover Curve*

After upon successful completion of the Nonlinear Static (Pushover) Analysis, the static pushover curve representing the relationship between base shear and monitored displacement was generated to characterize the inelastic response of the structure. To evaluate the seismic demand, an elastic response spectrum analysis was conducted and the predefined response spectrum function, thereby establishing the corresponding demand curve. The FEMA 440 Equivalent Linearization (EL) method was adopted to compute the displacement demand at both the Design Basis Earthquake (DBE) and Maximum Credible Earthquake (MCE) levels. This methodology incorporates the inelastic behavior of the structure, including damage accumulation and energy dissipation mechanisms, thereby offering a more precise assessment of seismic performance than conventional linear methods. To verify compliance with performance-based seismic design criteria, the following acceptance limits were superimposed on the pushover curve: Immediate Occupancy (IO), Life Safety (LS), Collapse Prevention (CP). These performance thresholds were derived based on:

- Local component behavior, including hinge formation and ductility demands,
- Global structural response, quantified through pier drift limits,
- Material strain limits for both concrete and reinforcing steel, as mentioned in the (NCHRP, 2013).

The bridge pier under investigation was classified under the "Other/Conventional" operational category, necessitating that it remains within the Collapse Prevention (CP) performance limit under MCE conditions. This implies that while significant damage may be sustained, structural collapse must be precluded.

IV. RESULTS AND DISCUSSION

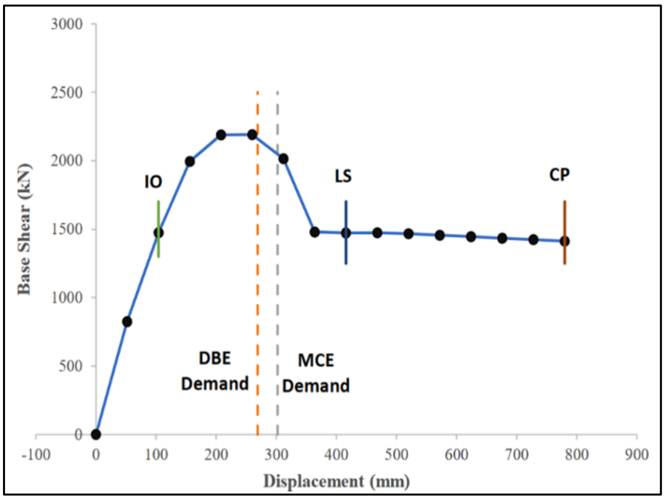

Fig 3 Pushover Curve with Capacity and Demand

The pushover analysis reveals the structure's seismic performance characteristics, demonstrating gradual stiffness degradation and significant ductile capacity beyond the yield point. The base shear-displacement response curve illustrates the bridge's nonlinear behavior, beginning with initial elastic response followed by progressive yielding and stiffness degradation. Notably, both Design Basis Earthquake (DBE) and Maximum Credible Earthquake (MCE) demands remain well below the structure's ultimate capacity, with demand points falling significantly below the established capacity limits. The extended plateau region of the curve confirms substantial ductile capacity, while clearly identified performance levels (Life Safety and Collapse Prevention) validate the design's seismic resilience.

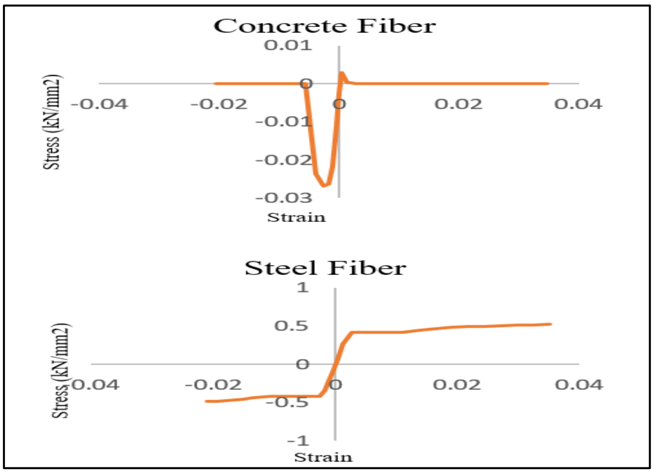

Fig 4 Stress-Strain Curve of Concrete and Steel Fiber

Complementary fiber element analysis further substantiates the design approach, with results indicating concrete crushing as the governing failure mode while reinforcement steel remains within the inelastic range. This failure mechanism confirms effective energy dissipation through controlled ductile behavior, validating the intended seismic performance objectives. The consistent observation of steel reinforcement remaining in the inelastic range during concrete crushing demonstrates proper implementation of capacity design principles.

These results demonstrate the effectiveness of combining AASHTO design provisions with BNBC hazard parameters for bridge construction in seismic regions. The structure achieves the intended performance objectives, balancing strength and ductility to ensure life-safety under extreme events while preventing collapse. The pushover curve's shape and the fiber-level response both confirm that the design successfully accommodates inelastic demands through controlled damage mechanisms, prioritizing repairable damage over catastrophic failure. This approach provides a reliable framework for seismic-resistant bridge design in Bangladesh and similar regions.

V. CONCLUSION

This study demonstrates the effective integration of (BNBC, 2020) for seismic hazard assessment with (AASHTO, 2020) provisions for soil classification, design methodology, and substructure detailing of bridges in Bangladesh. The results confirm that the AASHTO design approach successfully meets performance objectives for the case study bridge, validating its application in regions lacking dedicated bridge codes. The analysis shows bridge piers designed according to AASHTO specifications can achieve satisfactory seismic performance under Bangladesh's seismicity.

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To advance this research, future studies should consider: (1) conducting linear and nonlinear time history analyses to better understand design demands and structural behavior, , and (2) employing advanced finite element software (PLAXIS 3D, ZOSIL, GEOS FEM) for more accurate soil response modeling. These enhancements would provide deeper insights into soil-structure interaction and nonlinear dynamic response, further improving bridge seismic design methodologies for Bangladesh.

The findings support adopting (AASHTO, 2020) as a provisional bridge design standard while emphasizing the need for continued research to develop comprehensive, region-specific bridge design codes that account for Bangladesh's unique seismic and geotechnical conditions. This approach would ensure optimal safety and performance of bridge infrastructure in earthquake-prone regions.

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