Design and Analysis of Prestressed Cantilever Pier Caps: For Gravity Loads using CSi Bridge Software

Namrata A. Salvi[1], P. R. Barbude[2], S. A. Rasal[3], R. R. Rele[4]

[1]Post Graduate Student, Dept. of Civil Engineering, Datta Meghe College of Engineering, Airoli, Navi Mumbai 400708, Maharashtra, India

[2,3] Assistant Professor, Dept. of Civil Engineering, Datta Meghe College of Engineering, Airoli, Navi Mumbai 400708, Maharashtra, India

[4]Dept. of Bridge Engineering, R. R. Consulting Engineers, Mumbai, India

***Abstract*—Prestressed cantilever pier caps are crucial structural components in modern bridge engineering, providing support stability and controlling deformation in bridge decks. The present study investigates the design and analysis of a prestressed cantilever pier cap using CSI Bridge software to evaluate the structural impact of prestressing tendons on both bridge deck deformation and bearing performance. A comprehensive design procedure is established, combining manual analytical calculations with finite element modeling (FEM). Prestress forces and their spatial distribution within the pier cap are determined and incorporated into the CSI Bridge model. Structural response including stress distribution, displacement profiles, and support reactions is examined under varied loading scenarios.**

Comparative assessments between theoretical results and CSI Bridge simulations are performed to verify accuracy and reliability of software predictions regarding prestress effects. Particular emphasis is placed on how prestressing influences deck deflection and bearing reaction behavior, offering insight into deformation control and support demands. Key findings from the present study demonstrate that appropriately arranged prestressing tendons can significantly reduce deck deflection, optimize bearing load distributions, and enhance overall structural durability, all while maintaining efficient use of material. Results confirm a close correlation between manual and software-based calculations when modeling assumptions align. Where discrepancies arise, they highlight the importance of refined tendon layout design and careful interpretation of software limitations. The present study contributes a practical engineering workflow for pier cap design that bridges theoretical design principles with applied software modeling. Recommendations are provided for tendon placement strategies, modeling fidelity in CSI Bridge, and aligning analysis outputs with recognized concrete design codes (e.g. AASHTO, Eurocode, IRC). Ultimately, this work aims to advance the reliability,economy, and structural performance of prestressed cantilever pier caps in modern bridge engineering.

***Index Terms*—Prestressed Cantilever Pier Cap, CSI Bridge Software, Deck Deformation, Bridge Bearings, Structural Analysis, Prestressing Tendons, Finite Element Modelling**.

I. INTRODUCTION

Modern bridge infrastructure demands innovative and efficient solutions to accommodate increasing traffic loads, complex geometries, and tight construction schedules. Among these solutions, prestressed cantilever pier caps have emerged as a vital structural component, especially in elevated metro corridors and highway flyovers. Serving as the crucial link between a bridge's superstructure and substructure, pier caps transfer loads from decks and girders to the supporting piers. Prestressing, a technique that introduces internal compressive forces into concrete, significantly enhances the performance of these caps by counteracting tensile stresses and improving flexural capacity. In cantilever configurations, post-tensioned tendons help minimize cracking and deformation while ensuring durability under asymmetric or eccentric loading conditions. Prestressing also influences bearing behavior and deck deformation, leading to reduced vertical deflections and more uniform load distribution at support points. This is particularly important in metro systems with curved or bifurcated alignments, where flexible cantilever arm design is needed without compromising structural stability.

Bridges, as essential infrastructure, span physical obstacles such as water bodies, valleys, roads, or railways, providing uninterrupted passage and facilitating transportation and communication. Their design varies based on function, terrain, materials, and budget, with each type tailored to specific engineering challenges. Over time, bridge engineering has evolved with advancements in materials, design methodologies, and construction techniques. One of the key substructure components is the pier cap, which transfers loads from the superstructure to the supporting columns. Cantilever pier caps are widely used to support girders while reducing the need for intermediate supports. However, traditional reinforced concrete cantilever pier caps often suffer from excessive deflections and cracking under heavy loads, raising concerns about long-term durability and maintenance.

To overcome these limitations, prestressing has gained prominence as a reliable method to enhance the structural efficiency of cantilever pier caps. By introducing pre-applied compressive forces, prestressing reduces tensile stresses, deflections, and cracking, thereby improving overall performance. Moreover, prestressing affects related components such as bearings and bridge decks, altering stress distribution and deformation patterns. Understanding the interaction between prestress, bearing behavior, and deck deformation is essential for optimizing bridge designs and ensuring long-term serviceability. This study aims to investigate the design of prestressed cantilever pier caps and evaluate their influence on bearing performance and deck deformation. Through a comprehensive analysis, the research seeks to fill existing knowledge gaps and offer insights that contribute to more efficient and resilient bridge structures.

Bridges are subjected to various loading conditions, including dead loads, live loads, thermal effects, and dynamic forces from vehicular movement. The cantilever pier cap plays a critical role in maintaining the stability and durability of the entire bridge system. Conventional reinforced concrete pier caps often experience significant deflections and tensile stresses, leading to cracking, increased maintenance costs, and potential serviceability issues. Prestressing has proven to be an effective solution for enhancing structural capacity and reducing these adverse effects. However, its application introduces complexities such as changes in stress distribution, bearing behavior, and deck deformation. While extensive research exists on prestressed bridge components, limited studies focus specifically on cantilever pier caps and their associated elements. This research aims to address that gap by conducting an in-depth study on the design and behavior of prestressed cantilever pier caps, assessing their impact on bearings and deck deformation, and providing valuable guidance for future bridge design optimization.

.

II. REVIEW OF LITERATURE

The evolution of prestressed cantilever pier caps in bridge engineering has been significantly influenced by the demands of urban infrastructure, where constraints in space, high axial loads, and complex geometries call for advanced structural solutions. Prestressing particularly post-tensioning has become a widely adopted method for enhancing the structural efficiency of cantilever pier caps. It improves crack control, flexural capacity, and span reach, while reducing the depth of structural members, making it ideal for metro and highway projects.

Recent studies have focused on optimizing design parameters for these systems. Nikhil Pawar *et al.* (2024) analyzed prestressed cantilever pier caps, highlighting the role of eccentricity, prestress force optimization, and code compliance. Their work emphasized the sustainability and structural benefits of prestressing over traditional RCC solutions. Reinforcing this, Jiang Yu and Hongtao Xu (2023) explored prestressed framed piers for complex bridge geometries, such as acute-angle and parallel alignments. They stressed the importance of coordinating cap beam and column stiffness, tendon arrangement, and casting techniques, while accounting for the impact of foundation stiffness on prestress- induced moments and thermal effects.

Seismic resilience has been a major area of investigation. Renwei Zhang *et al.* (2024) tested assembled concrete piers with hybrid joints, showing that circular steel tube shear keys outperformed cross- shaped ones in energy dissipation and joint durability. ABAQUS-based finite element models closely matched their experimental results. In a related study, Md. Taohidul Islam *et al.* (2024) conducted parametric analyses on 3D finite element models of self-centering piers, revealing that prestress force and concrete strength greatly influenced lateral load behavior, whereas duct diameter had negligible effect. Similarly,

S. Kocakaplan Sezgin *et al.* (2024) examined precast post-tensioned segmental piers incorporating Shape Memory Alloy (SMA) bars. Their study revealed that SMA bars significantly improved seismic drift control and recentering behavior, especially in slender piers prone to second-order effects. They also found that pulse periods aligned with the natural frequency increased seismic risk.

Structural damage prediction under seismic loads has also been extensively researched. Javier F. Taipe et al. (2023) conducted nonlinear pushover analyses to define six displacement-based damage states, identifying pier aspect ratio and subgrade stiffness as the most critical parameters. Their predictive model for spalling displacement demonstrated strong accuracy, deviating only 20% from observed data. Complementing this, Rajesh Rele *et al.* (2022) investigated semi-integral piers with monolithic connections, which exhibited approximately 50% reduction in bending moments and improved post- earthquake serviceability when compared to traditional bearing-supported piers.

Real-world vulnerability assessments further contextualize the findings. Luo Hua *et al.* (2022) performed seismic vulnerability analyses of long-span rigid-frame bridges and found increased damage probability under near-field earthquakes, especially at slight to moderate levels. Despite this, the bridges retained good ductility. Experimental validation was conducted by Siva Avudaiappan *et al.* (2021), who used quarter-scale pier-to-cap models under thermal and seismic conditions. Their results confirmed elastic behavior of reinforcement and minimal cracking, with close correlation between experimental and ANSYS simulation results.

In terms of performance-based design, Sai Bhavith EV et al. (2020) evaluated the response reduction factor

(R) for cantilever piers. They concluded that Indian code values might underestimate the structure's actual capacity, especially in higher seismic zones where ductility and overstrength are reduced. In physical testing, Hussam K. *et al.* (2020) demonstrated that seismic accelerations amplify from pier base to crest during shaking table tests. Observed liquefaction and overturning underscored the importance of modeling soil-structure interaction.The influence of shear lag in large structural elements has also been studied. Rajesh Rele *et al.* (2020) found that in multi-cell box girders, stress distribution is non-uniform—especially at web-flange junctions—and worsens with wider cantilevers and longer spans, prompting the need for refined stress analysis. Following real-world seismic events, Selcuk Bas *et al.* (2020) compiled a damage database from 140 bridges in Türkiye. Common issues included bearing failures, girder cracking, and plastic hinging at pier bases. This comprehensive review aids vulnerability prediction and design improvement.

Innovative systems for seismic resilience have been developed. Rajesh Rele *et al.* (2019) proposed a rocking pier foundation system using SMA bars and elastomeric pads. Their nonlinear time history analysis showed significant reductions in moments and displacements with enhanced recentering capacity. Preeti Pandey and V. K. Shukla (2019) highlighted the importance of evaluating seismic performance using multiple analytical methods. Their comparison of linear static, response spectrum, and pushover analyses revealed discrepancies that could influence final design reliability.

From a construction standpoint, prestressing is crucial in space-constrained environments. Prem Pal Bansal and Siddharth Yadav (2018) demonstrated that prestressed pier caps for six-lane flyovers significantly reduced section depths and increased load resistance. Pappu Baniya et al. (2018) introduced STM-CAP, a strut-and-tie modeling tool that accurately estimated shear capacity in deep pier caps where sectional design methods often fail. For integral bridges, Eleftheria D. *et al.* (2018) showed that prestress affects moment distribution, especially due to tendon profile geometry. They advocated for inclusion of prestressing effects in seismic modeling of monolithic structures.

Earlier, Rajesh Rele *et al.* (2017) developed a resilient pier with SMA bars and elastomeric pads that minimized damage and enhanced post-earthquake usability. His study, along with S. Talukdar (2013), validated finite element models in SAP2000 for prestressed multi-cell box girders, accounting for time-dependent losses like creep and shrinkage. Parametric studies demonstrated that transverse behavior in prestressed sections could be accurately captured using modern FE methods.

In terms of fundamental understanding, Huili Wang *et al.* (2011) showed through nonlinear time history analysis that prestressed RC piers experience lower residual displacements and greater recentering capacity than non-prestressed counterparts. Tendon position and reinforcement ratios were found to significantly impact structural stiffness and deformation capacity. Going further back, Rui Faria *et al.* (2000) introduced a damage mechanics-based model for hollow RC piers, which accurately captured cyclic degradation. This was reinforced by Y. Xiao *et al.* (2000), who utilized a hybrid web-based testing system to evaluate precast pier elements. Their observations of concrete spalling and instability under near-fault motions highlighted the seismic vulnerabilities of thick concrete covers.

Altogether, this rich body of literature underscores the growing reliance on prestressed cantilever pier caps as efficient, resilient, and adaptable structural solutions. Their ability to manage large spans, resist seismic forces, and conform to complex geometries makes them indispensable in modern transportation infrastructure. The inclusion of advanced materials like SMA bars, the use of hybrid joints, and the development of tools like STM-CAP represent significant steps forward in both design precision and structural performance.

III. OBJECTIVES OF THE STUDY

The primary objective of this study is to design a cantilever prestressed pier cap and evaluate the structural benefits of prestressing, particularly its influence on bridge deck deformation and bearing performance.

The study aims to assess the effectiveness of various prestressing tendon configurations during the staged construction process, focusing on their impact on stress distribution, deflection behavior, and crack control within the pier cap.

Additionally, the research seeks to understand how prestressing improves the interaction between the pier cap, bearings, and the deck slab. Using CSI Bridge software, the study involves modeling, analysis, and design of the prestressed system under gravity and live loads, adhering to relevant design standards such as IRS and IRC. Ultimately, the objective is to identify an optimized and cost-effective prestressing strategy that enhances structural efficiency, durability, and service life of bridge pier cap systems.

METHOD OF ANALYSIS

The bridge under study is a Prestressed concrete structure designed to accommodate vehicular traffic by using CSi Bridge software. It features a total length of 80 meters (Continuous bridge with span 40m each) and a width of 27.41 meters, ensuring adequate space for multiple traffic lanes and safety shoulders.

The design of Prestressed Pier cap is done using CSi bridge software as per the all the provisions of the code to demonstrate code-equivalency. The pier cap is designed to resist Dead, SIDL & Live Load only.

Two models were prepared as per given Bridge specifications for the detailed Analysis of Pier cap as well as to overview the effect of Prestress on the Deck Deformation and Bearing Codes used for the design of Pier Cap are: IRC:6-2017 (For Live Load of Vehicular Movement), Standard Specifications and Code of Practice for Road Bridges. IRC:112 2020 (For Serviceability Limits of Stress and Deflection) Code of practice for concrete road bridges.

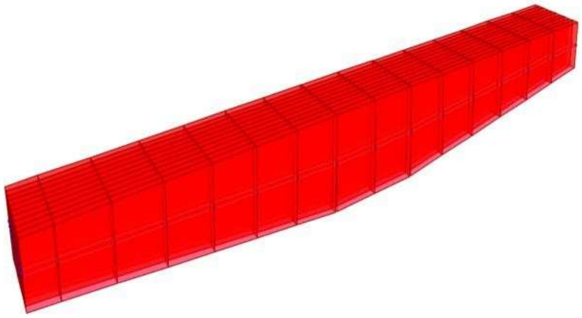


Fig. 1: Model 1- Pier Cap Model for Design and Analysis

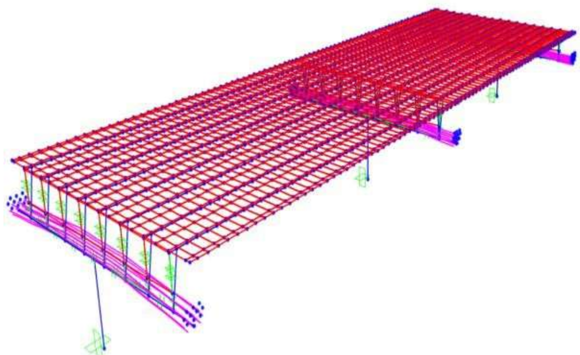


Fig. 2: Model 2-Continuous Bridge Model to review the Effect of Prestress on Deck Deformation and Bearing

(a) Loads for the Design

For the modelling phase, the following loads were considered. This study concentrated on DL, SIDL & LL due to Vehicle only

1. Self-weight Calculations

The Self weight is calculated by CSi Bridge Modeler for each structural element using Density of Concrete As 2.5t/M^3

2. Super Imposed Dead Load

Wearing Coat load = 0.2 t/m^2 (Applied as area load in CSI BRIDGE)

Crash barrier load = 1.1 t/m (Applied as line load in CSI BRIDGE)

3. Live Load due to Vehicle

For the Live load, the moving load option is used from the CSi Bridge software in which the program creates a different pattern of loading for each time step. The load applied to the structure is determined by the longitudinal position of each vehicle in its lane at the current time from its starting position. For each individual concentrated load, consistent joint loads are calculated at the corner of any loaded shell element on the deck.

For multi-lane bridges and culverts, each Class 70R loading shall be considered to occupy two lanes and no other vehicle shall be allowed in these two lanes. The passing/crossing vehicle can only be allowed on lanes other than these two lanes Class 70R loading is applicable only for bridges having carriageway width of 5.3 m and above (i.e. 1.2 × 2 + 2.9 = 5.3). The minimum clearance between the road face of the kerb and the outer edge of the wheel or track, ‘C, shall be

1.2 m.For single lane bridges having carriageway width less than 5.3 m, one lane of Class A shall be considered to occupy 2.3 m. Remaining width of carriageway shall be loaded with 500 Kg/m^2 For multi-lane bridges each Class A loading shall be considered to occupy single lane for design purpose.

(b) Stage Stressing Sequence for Analysis

The following Construction stages are considered Stage 1: Self Weight of Pier Cap: Casting of Pier Cap Stage 2: PT Stage 1 (When the structure achieved at least 75% Strength)

Cable 4 and 7 are stressed

Cable 8 and 10 are stressed

Stage 3: DL of I Girder: I girder erected

Stage 4: DL of Deck Slab: Casting of Deck Slab and Diaphragm of I girderStage 5: PT Stage 2 (When the structure achieved at least 75% Strength)

Cable 1 and 3 are stressed, Cable 2 is stressed Cable 5 and 6 are stressed

Stage 6: SIDL: SIDL due to crash barrier, wearing course etc.

Stage 7: LL 70R Vehicle: L L from 70R Vehicle Stage 8: Long Term: Long term effects due to creep and shrinkage are considered for 100 years.

(c) Material Properties and Bridge Details

For the modeling phase, the following material properties and bridge details were utilized

1. Properties of Concrete

Table 1: Properties of Concrete

Characteristic Concrete Strength (Super Structure) fck	= 30 MPa
Modulus of Elasticity (E)	= 27386 MPa
Characteristic Concrete Strength (Sub Structure) fck	= 50 MPa
Modulus of Elasticity (E)	= 35355 MPa
Poisson's Ratio (μ)	= 0.15
Density (ς)	= 2.5 t/m^3
Concrete Strength at Transfer (fci)	= 40 MPa

2. Properties of Prestressing Steel

Prestressing steel will be conforming to requirements of IS:14268, Class 2 low relaxation uncoated stress relieved strands with following properties:

Table 2: Properties of prestressing steel

Nominal Area of Strands (As)	= 140 mm^2
Diameter of strand (d)	= 15.2 mm
Ultimate Stress (fpu)	= 1860 MPa
Maximum Jacking Stress (0.765fpu)	= 1422.90 MPa
Maximum Jacking Load	= 20.16 ton
Modulus of Elasticity (Eps)	= 200000 MPa
Type of Duct	= HDPE
Length Effect Coefficient-Wobble (ω)	= 0.002
Curvature Effect Coefficient-Friction	= 0.17
Anchorage Slip	= 6mm

3. Reinforcement Material Properties Reinforcement Steel

Grade of steel - fy = 550 MPa

Modulus of Elasticity: - Es = 200000 MPa

4. Bridge Details

For 2 No's of 70R Vehicle (1 no of 70R Vehicle covers 2 lane area) + Class AA, Six Lane bridge with Carriageway width of 7.5 m each.

Table 3: Details of Bridge

Width of Bridge	= 27.41 m
Length of Bridge	= 80 m continuous bridge with two spans. 40m each
Cantilever length of Pier cap	= 11.705 m Each side
Deck slab thickness	= 0.26 m
Total depth of Pier cap	= 3 m
Varying depth of cantilever	= 1.8 m to 3 m
Width of Pier cap	= 2.9 m
Pier dimensions	= 4 m × 2.2 m (3 nos)

IV. RESULTS AND DISCUSSION

The detailed analysis is done using two models (Model 1 and Model 2), both prepared by using CSI software. The results concerning stresses are discussed here with Stage wise Stresses in Pier Cap.

1) Stresses at Stage 1: Self Weight of pier cap

Table 4: Stresses at Stage 1(Self Weight of pier cap)

Sr No.	Distance mm	S11 Top Center N/mm²	S11 Bottom Center N/mm²
1	0	0	0
2	1025	0.04	-0.04
	2785	0.253	-0.253
6	4545	0.59	-0.59
8	6305	1.004	-1.004
10	8065	1.467	-1.467
12	9825	1.961	-1.961
14	11705	2.511	-2.511
16	13705	2.411	-2.411
18	15705	2.511	-2.511
20	17655.83	1.941	-1.941
22	19606.67	1.396	-1.396
24	21557.5	0.892	-0.892
26	23508.33	0.456	-0.456
28	25459.17	0.133	-0.133
30	27410	0	0

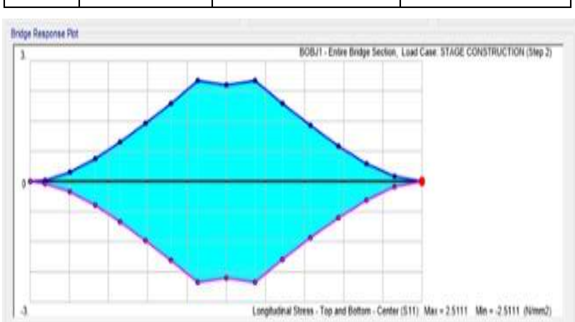


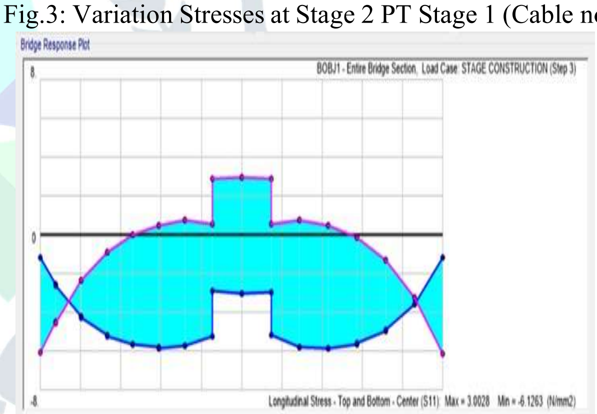
Fig.3: Variation of Stresses at Stage 1(Self Weight of pier cap)

2) Stresses at Stage 2 PT Stage 1 (Cable no 4,7,8 and 10 are stressed):

Table 5: Stresses at Stage 2 – PT Stage 1 (Cable no 4,7,8 and 10 are stressed)

Sr No.	Distance mm	S11 Top Center N/mm²	S11 Bottom Center N/mm²
1	0	-1.158	-6.056
2	1025	-2.529	-4.433
4	2785	-4.221	-2.294
6	4545	-5.175	-0.864
8	6305	-5.652	0.026
10	8065	-5.802	0.535
12	9825	-5.727	0.773
14	11705	-5.198	0.572
16	13705	-3	3.003
18	15705	-2.916	2.909
20	17655.83	-5.763	0.799
22	19606.67	-5.845	0.514
24	1557.5	-5.608	-0.133
26	23508.33	-4.928	-1.297
28	25459.17	-3.565	-3.227
30	27410	-1.145	-6.126

Fig.3: Variation Stresses at Stage 2 PT Stage 1 (Cable no 4,7,8



and 10 are stressed)

3) Stresses at Stage 3 and 4 –DL of I girder and Deck slab:

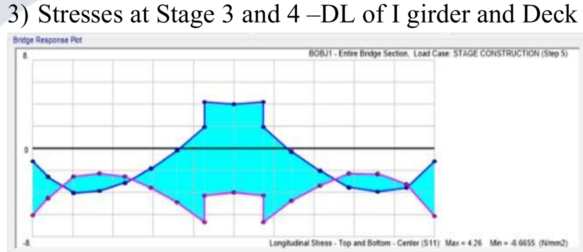


Fig.4: Variation Stresses at Stage 3 and 4 (DL of I girder and Deck slab)

Table 6: Stresses at Stage 3 and 4 (DL of I girder and Deck slab)

Sr No.	Distance mm	S11 Top Center N/mm²	S11 Bottom Center N/mm²
1	0	-1.158	-6.056
2	1025	-2.529	-4.433
4	2785	-3.977	-2.538
6	4545	-3.816	-2.23

8	6305	-3.096	-2.552
10	8065	-1.766	-3.547
12	9825	-0.165	-4.861
14	11705	1.934	-6.661
16	13705	4.004	-4
18	15705	4.259	-4.264
20	17655.83	-0.303	-4.753
22	19606.67	-2.023	-3.366
24	21557.5	-3.545	-2.226
26	23508.33	-3.945	-2.289
28	25459.17	-3.584	-3.208
30	27410	-1.145	-6.126

4) Stresses at Stage 5 - PT Stage 2 (Cable no 1,2,3,5 and 6 are Stressed):

Table 7: Stresses at Stage 5 - PT Stage 2 (Cable no 1,2,3,5 and 6 are Stressed)

Sr No.	Distance mm	S11 Top Center N/mm^2	S11 Bottom Center N/mm^2
1	0	-9.791	-6.73
2	1025	-11.809	-3.947
4	2785	-14.135	-0.54
6	4545	-14.375	0.809
8	6305	-13.825	1.21
10	8065	-12.528	0.719
12	9825	-10.857	-0.251
14	11705	-8.399	-1.981
16	13705	-3.611	3.612
18	15705	-3.366	3.352
20	17655.83	-11.039	-0.087
22	19606.67	-12.867	0.917
24	21557.5	-14.315	1.447
26	23508.33	-14.446	0.473
28	25459.17	-13.48	-1.815
30	27410	-9.773	-6.802

Fig.5: Stresses at Stage 5 - PT Stage 2

(Cable no 1,2,3,5 and 6 are Stressed)

5) Stresses at Stage 6 - SDL from Super-Structure:

Table 8: Stresses at Stage 6 - SDL from Super-Structure

Sr No.	Distance mm	S11 Top Center N/mm^2	S11 Bottom Center N/mm^2
1	0	-9.791	-6.73
2	1025	-11.809	-3.947
4	2785	-14.041	-0.635
6	4545	-13.857	0.28
8	6305	-12.969	0.331
10	8065	-11.379	-0.466
12	9825	-9.46	-1.696
14	11705	-6.78	-3.66
16	13705	-1.982	1.984
18	15705	-1.722	1.708
20	17655.83	-9.666	-1.515
22	19606.67	-11.769	-0.224
24	21557.5	-13.566	0.669
26	23508.33	-14.076	0.089
28	25459.17	-13.488	-1.808
30	27410	-9.773	-6.802

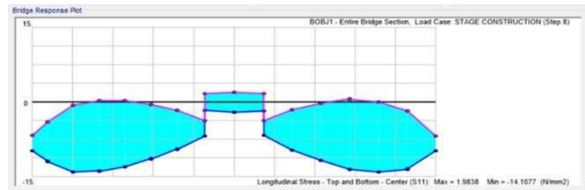
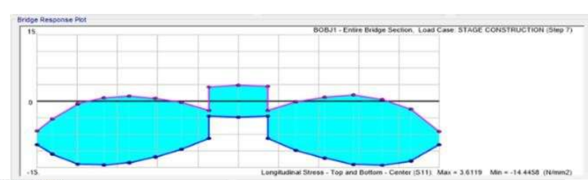


Fig.5: Variation of Stresses at Stage 6 - SDL from Super-Structure

6) Stresses at Stage 7 - LL from Super-Structure

Table 9: Stresses at Stage 7 - LL from Super-Structure

Sr No.	Distance mm	S11 Top Center N/mm^2	S11 Bottom Center N/mm^2
1	0	-9.791	-6.73
2	1025	-11.809	-3.947
	2785	-13.981	-0.696
	4545	-13.523	-0.061
8	6305	-12.326	-0.329
10	8065	-10.337	-1.541
12	9825	-8.08	-3.123
14	11705	-5.099	-5.4
16	13705	-0.319	0.323
18	15705	-0.017	2.89E-03
20	17655.83	-8.316	-2.92
22	19606.67	-10.793	-1.239
24	21557.5	-13.065	-0.0457
26	23508.33	-13.838	-0.157
28	25459.17	-13.494	-1.803
30	27410	-9.773	-6.802



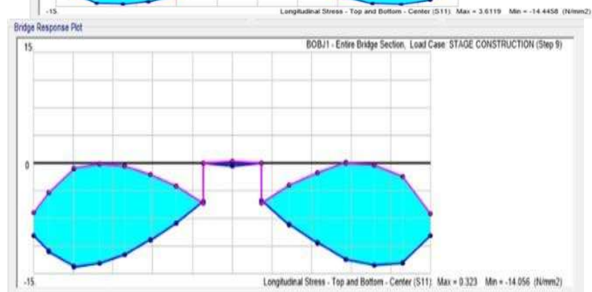


Fig.6: Variation of Stresses at Stage 7 - LL from Super-Structure

7) Stresses at Stage 8 – Long Term (upto 100 Years)

Table 10: Stresses at Stage 8-Long Term (upto 100 Years)

Sr No.	Distance mm	S11 Top Center N/mm^2	S11 Bottom Center N/mm^2
1	0	-9.791	-6.73
2	1025	-11.809	-3.947
4	2785	-13.981	-0.696
6	4545	-13.523	-0.061
8	6305	-12.326	-0.329
10	8065	-10.337	-1.541
12	9825	-8.08	-3.123
14	11705	-5.099	-5.4
16	13705	-0.319	0.323
18	15705	-0.017	2.89E-03
20	17655.83	-8.316	-2.92
22	19606.67	-10.793	-1.239
24	21557.5	-13.065	0.147
26	23508.33	-13.838	-0.157
28	25459.17	-13.494	-1.803
30	27410	-9.773	-6.802

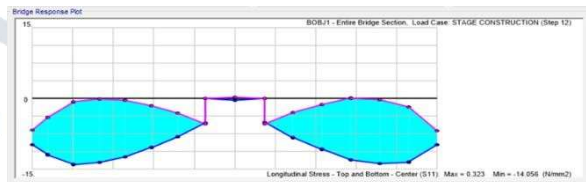


Fig.7: Stresses at Stage 8-Long Term (upto 100 Years)

Checking of Stresses During Construction Stage as per IRC 112:2020 Clause 12.2

1. Compressive Stress Limits for Concrete

Maximum compressive stress in concrete under rare combinations of loads shall be limited to 0.48 fck, in order to keep the longitudinal cracks, micro cracks or creep within acceptable limits.

0.48 fck = 0.48 × 50 = -24 Mpa

2. Tensile Stress Limits for Concrete

For crack width calculations, the mean tensile strength of concrete, fctm, is used. This value is empirical and related to the characteristic compressive strength. fctm = 0.3(fck)2/3 for fck up to M50 = 4.07 Mpa *Stresses during Construction Stages are within allowable limit, Hence Pier Cap is Safe*.

V. CONCLUSION

Across all eight stages of the stress analysis, the prestressed concrete pier cap displays a well- controlled evolution of internal stresses, strategically engineered to resist a complex combination of loads across its service life.

In *Stage 1*, the stresses originate purely from the pier cap's self-weight, beginning and ending at neutral conditions, with symmetrical compressive stresses concentrated around mid-span. This sets the baseline structural behavior before intervention.

With the introduction of *Stage 2* prestressing (Cables 4, 7, 8, 10), the stress profile shifts notably transforming large compression zones into tension pockets, particularly at the bottom center. This shows the start of active internal reinforcement, reshaping force distribution.

Stages 3 and *4*, which include dead loads from the I-Girder and deck slab, induce renewed compressive stresses. The top center experiences a transition into tension mid-span, while the bottom remains largely compressed, highlighting the impact of added mass and flexural effects.

The second round of prestressing in *Stage 5* (Cables 1, 2, 3, 5, 6) strengthens the overall response, generating substantial compression at the top and lifting the bottom into tension across wider sections. This marks a peak in the structural balance achieved by internal force adjustment.

Stage 6 introduces superimposed dead loads from the superstructure, subtly altering the stress pattern. While compressive forces are still dominant, the bottom center continues to show transitions into tension, maintaining equilibrium between added weight and prestress benefit.

The onset of live loads in *Stage 7* reflects how dynamic actions influence the stress regime. Compressive stresses are redistributed once again, with brief transitions to tension at mid-span. Yet, the system resists overstressing and maintains internal harmony. Finally, in *Stage 8*, the long-term projection over 100 years considering creep, shrinkage, and relaxation closely mirrors *Stage 7*. Minimal differences affirm the pier cap's long-term durability, reliability, and resilience against aging effects.

The pier cap effectively transforms from a purely gravity driven structure to a highly optimized prestressed element. Strategic cable tensioning phases, calculated load sequencing, and consistent force redistribution ensure safe serviceability, balanced stress profiles, and lasting performance over its lifespan. This integrated design response underscores the robust engineering behind modern prestressed concrete infrastructure.

REFERENCES

[1] Renwei Zhang, Liqun Zheng, Hai Zhong, Shuangshuang Qin (2024): "Seismic behaviour of assembled concrete bridge piers with hybrid joint connections", Research Square, DOI: Md. Taohidul Islam,

[2] Devabrata Dutta and Nazrul Islam (2024): "On the significant design parameters of self-centering concrete bridge piers", 7th International Conference on Civil Engineering for Sustainable Development (ICCESD2024), Bangladesh

[3] S. Kocakaplan Sezgin, E. Ahmad and M.M. Kashani (2024): "Seismic vulnerability assessment of precast post-tensioned segmental piers", 18th World Conference on Earthquake Engineering, WCEE2024, Milan

[4] Javier F. Taipe, Victor I. Fernandez-Davila (2023):

"Displacement-based seismic performance of RC bridge pier" Advances in Bridge Engineering (2023) 4:17

[5] Jiang YU a and Hongtao XU (2023): "Research on the Design of Long Span Prestressed Bridge Piers" Hydraulic and Civil Engineering Technology VIII M. Yang et al. (Eds.)

[6] Nikhil Pawar, S.R. Suryawanshi, V. P. Bhusare and Y. R. Suryavanshi, (2023): "Advantages of prestressed cantilever pier caps in metro rapid transit systems: a versatile solution for curved alignments", International Journal of Applied Engineering and Technology, ISSN: 2633-4828, Vol. 5 No.4, December, 2023.

[7] Rajesh R. Rele, Adwait Panindre and Prashant Barbude. (2022): "Seismic performance of bridge pier with integral connections" Bridge Structures, DOI:10.3233/BRS-220194 IOS Press, ISSN 1573-2487/$35.00 © 2022 IOS Press

[8] Luo Hua, Liang Yongyan, Feng Jianqiang, Li Bin and Liu Wenjuan (2022): "Seismic Vulnerability Analysis of Long Span Prestressed Concrete Continuous Rigid Frame Bridge" Journal of Engineering Science and Technology Review 15 (6) (2022) 35 -41

[9] Siva Avudaiappan, Kinson Prabu, Deban Selvaraj, Kiran Raja, Paul Oluwaseun Awoyera and Erick I Saavedra Flores (2021): "Performance of Pier-to-Pier Cap Connections of Integral Bridges under Thermal and Seismic Loads" Hindawi, Advances in Civil Engineering Volume 2021, Article ID 5580841,

[10] Sai Bhavith EV, V Samba Murthy Sudhindra, Mohan Ganesh G (2020): "A Study on behaviour of Bridge piers in various seismic zonal conditions" International Journal of Advanced Research in Engineering and Technology (IJARET) Volume 11, Issue 1, January 2020, pp. 129-138,

[11] Hussam K. Al-Aayedi, Asad H. Aldefae and Mohammed S. Shamkhi (2020): "Seismic performance of bridge piers" ICEAT 2020, IOP Conference Series Materials Science and Engineering · July 2020 DOI: 10.1088/1757- 899X/870/1/012069

[12] Rajesh R. Rele (2020): "Shear lag effect in multi- cell box girders" International Journal of Advance Engineering and Research Development Volume 7, Issue 05, May -2020 Scientific Journal of Impact Factor (SJIF): 5.71

[13] Selcuk Bas, Jeffrey Hunt, M. EERI, (2020): "Seismic performance and damage assessment of bridges during the 2023 Kahramanmaras, Turkiye earthquakes (Mw = 7.8, Mw=7.6)", Earthquake Spectra 1–25 sagepub.com/journals-permissions

[14] Rajesh R. Rele, Pradeep Kumar Dammala, Subhamoy Bhattacharya, Ranjan Balmukund (2019): "Seismic behaviour of rocking bridge pier supported by elastomeric pads on pile foundation" Soil Dynamics and Earthquake Engineering, journal homepage:

[15] Preeti Pandey, Vijay Kumar Shukla (2019): "Case Study of Seismic Evaluation Prestressed Concrete on Bridges" International Journal of Science and Research (IJSR) ISSN: 2319-7064, SJIF (2019): 7.583, Volume 9 Issue 11, www.ijsr.net,

[16] Dr. Prem Pal Bansal, Siddharth Yadav (2018): "A Study in Design and Comparison of reinforced, prestressed and partially prestressed pier cap over a rectangular hammerhead pier", Thapar Institute of Engineering & Technology

[17] Pappu Baniya, Anish Sharma, Dr. Serhan Guner (2018): "Evaluation of Reserve Shear Capacity of Bridge Pier Caps Using the Deep Beam Theory" The Ohio Department of Transportation, Office of Statewide Planning and Research State Job Number: 135499

[18] Eleftheria D. Goutzika, Sotiria P. Stefanidou, Vassilis K. Papanikolaou (2018) "The Effect of Deck Prestress actions on the Seismic Performance of R/C bridges", 16th European conference on Earthquake Engineering, Conference Paper on June 2018

[19] Rajesh R. Rele, Pradeep D, Stergios A. Mitoulis, Subhamoy Bhattacharya (2017) "Seismic Response of Resilient Pier on Pile Foundation", Indian Geotechnical Conference 2017 GeoNEst, 14-16 December 2017, IIT Guwahati, India

[20] Rajesh Ranjan Rele and S. Talukdar (2013): "Longitudinal & Transverse analysis of Multi-

Cell Prestressed Concrete Box Girder", Journal of the Indian Roads Congress, July-September 2013, Paper No. 596

[21] Huili Wanga, H. Wang, S.F. Qin, W.J. Xu (2011): "Seismic Analysis of Prestressed Bridge Pier Based on Fiber Section", 1877-7058 © 2011 Published by Elsevier Ltd. doi: 10.1016/j.proeng.2011.11.2026

[22] Rui FARIA, Nelson VILA POUCA And Raimundo Delgado (2000): "Seismic behaviour of R/C bridge piers: Numerical Simulation and Experimental validation", 12WC2000 0673.