**STUDY OF VARIATION OF FORCES IN PILES AND PIERS BY CHANGING PIER HEIGHT OF A BALANCED CANTILEVER BRIDGE UNDER AN ACTION OF A PRE-DEFINED COMPENSATION FORCE APPLIED EXTERNALLY**

Tushar, Ravi Sachdeva, Dibakar Saha, Partha Pratim Banerjee

Noida, Uttar Pradesh, India

[tubhardwaj@ayesa.com](mailto:tubhardwaj@ayesa.com), [rsachdeva@ayesa.com](mailto:rsachdeva@ayesa.com), [disaha@ayesa.com](mailto:disaha@ayesa.com), [pbanerjee@ayesa.com](mailto:pbanerjee@ayesa.com)

**Abstract.** A balanced cantilever construction primarily involves cast-in-situ segments having reinforcement and prestressing cables continuity, cast using a travelling gantry (also called as form-traveller). The design and construction both are very challenging tasks because the complexities are directly related to the casting of each segment in consecutive construction stages. Nowadays, many cantilever bridges are being constructed with an integral design, where the superstructure is directly connected to the piers through rigid moment connections instead of using bearings. This method presents additional challenges for designers because of the increased complexity involved.

Once the design of superstructure is finalized, challenges emerge in the substructure and foundation design of these bridges. After the key segment casting is completed, the secondary forces due to tendons stressed and the creep & shrinkage start playing a significant role in design of the foundation and substructure. Sometimes, these forces are governing and are so huge that designing the pile foundations and the pier becomes a very uneconomical. This case is mostly common when the height of the pier is very small, making it stiffer, attracts higher lateral forces. To cater this constraint, a very innovative method is being used now (previously in foreign nations and now in India as well). This method is the application of the pre-defined compensation force in the opposite direction of the main cantilever span, just before the casting of the key segment to provide outward deflection of substructure before development of secondary forces. The aim of this paper is to study the variation of forces taking place in piles and piers (of a sample model) under the application of the pre-defined compensation force for varying pier height models. The study will also cover the effects of varying lengths of main cantilever spans on the forces of foundation and substructure of the bridge under the pre-defined compensation force. This variation of the forces will help us to establish a relation between this pre-defined compensation force, pier height and the main spans lengths.

**Keywords:** Balance Cantilever Bridge, Creep & Shrinkage, Construction Stages, Cast-In-Situ segments, Pre-Compensation Force

# Introduction

This study focuses on a bridge designed with a span configuration of 47m-74m-26.25m, where the main span extends to 74m, and the back spans are 47m and 26.25m, respectively. The bridge forms a crucial part of the metro transit network in a major city in India, serving as an essential element in urban transportation. The alignment has a mild curvature of around 1000m. Its superstructure is integrally connected to piers. In general, integral balance cantilever bridges have twin leaf piers for it’s own flexibility in horizontal direction, but in this case single pier has been used, which adds to the complexity of the structural analysis.

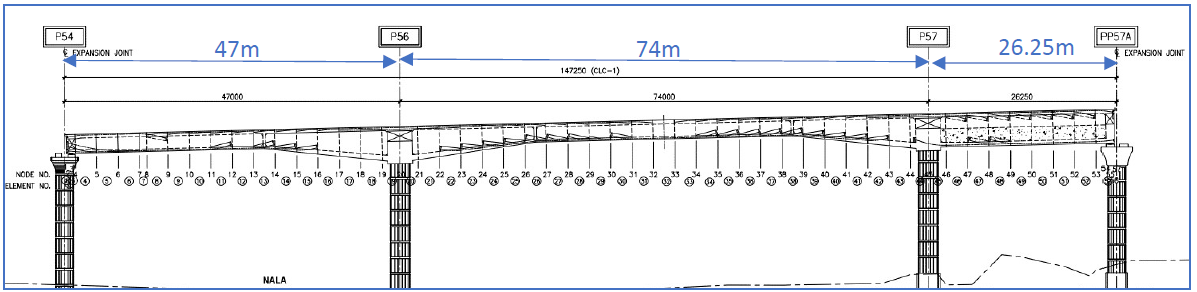


Figure 1: Elevation showing general arrangement of the bridge

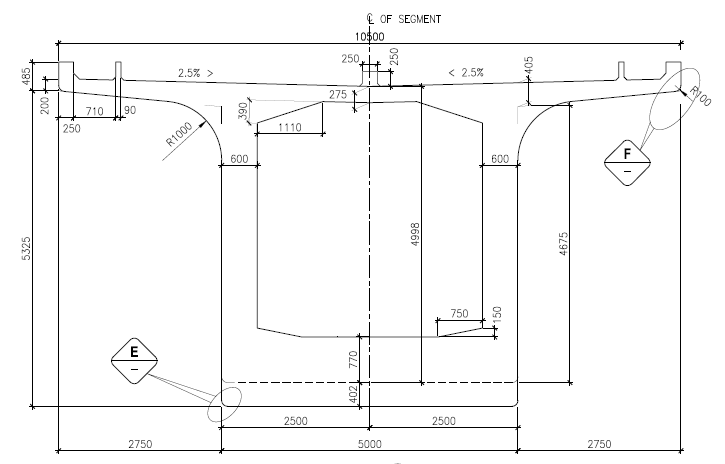


Figure 2: Superstructure section at support (at face of integral pier)

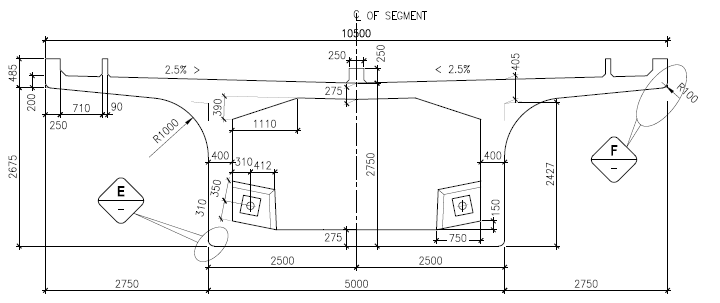


Figure 3: Superstructure section at mid span (at stitch segment location)

To accurately model and analyse the bridge, Midas Civil 2024, a sophisticated finite element method (FEM) based software, was utilized. This software is particularly adept at simulating construction stages in detail, offering the ability to activate and deactivate boundary conditions, loads, and elements as needed throughout the process. This flexibility allows for a more nuanced and realistic simulation of the bridge's construction and overall performance. Additionally, Midas Civil captures critical time-dependent properties and parameters such as creep and shrinkage variation, as well as the characteristic strength of concrete over time. The side spans are supported on the adjacent piers through bearings (left side being a single pier and right side being a portal frame). The depth of the cantilever construction is maximum near support, and it is minimum near key segment. Due to site requirements, the pile layout had to kept unsymmetrical w.r.t. superstructure and the alignment.

The span arrangement and the pile layout of all the piers is shown in Figure-1 to Figure – 3.

Elastic Links to simulate bearing support

Elastic Links to simulate bearing support

Integral connection through rigid type elastic links

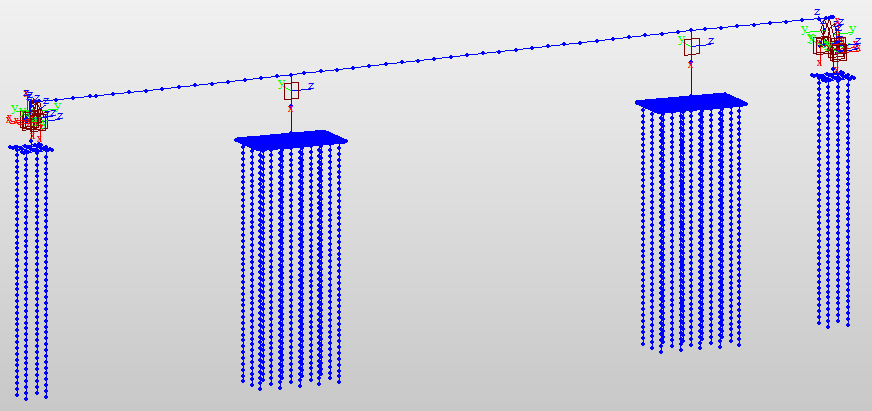


Figure-4: 3D Mathematical Model of the Bridge

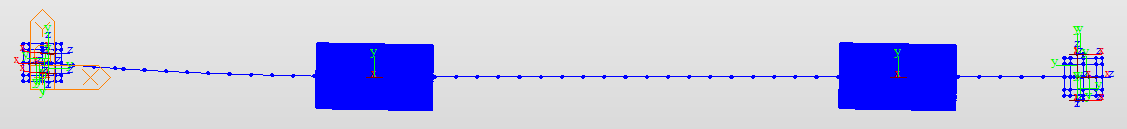


Figure-5: Plan view of Mathematical Model of the Bridge

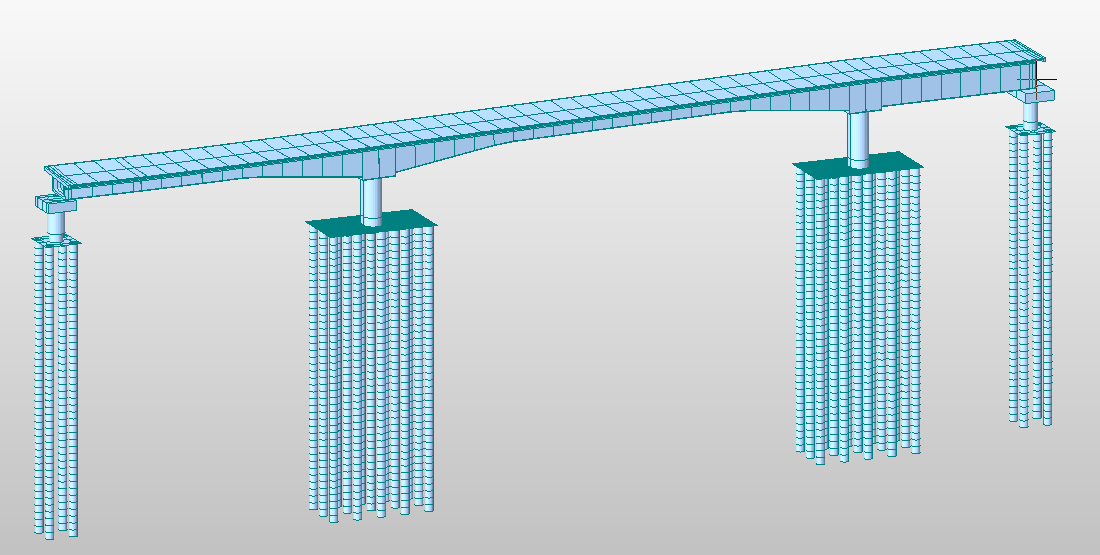


Figure-6: Rendering View of Mathematical Model of the Bridge

1. **Methodology of construction (Construction stages) and loads considered:**

The major construction stages followed for this bridge are mentioned below:

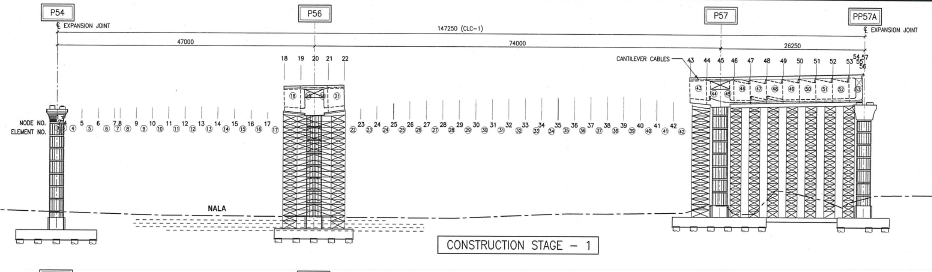


Figure-7: Construction stage-1

A diagram of a construction site

Description automatically generated

Figure-8: Intermediate Construction Stage

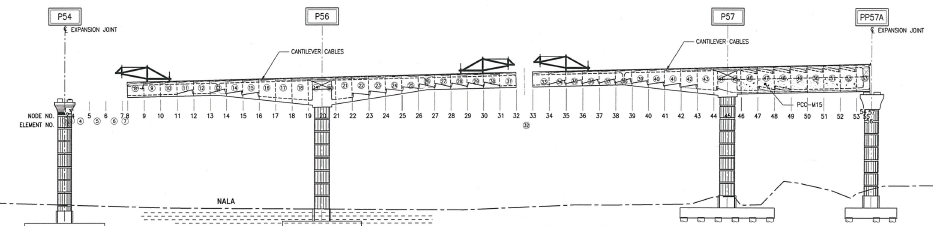


Figure-9: Intermediate Construction Stage showing cantilever segment casting

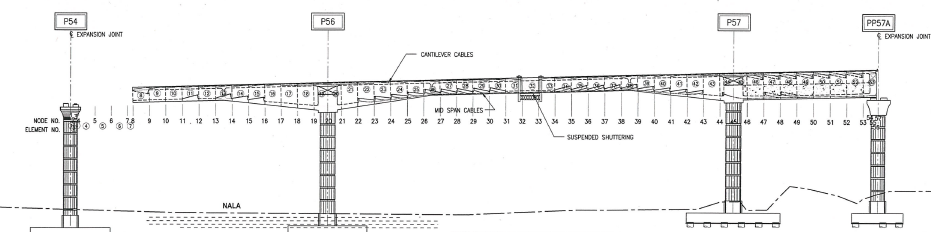


Figure-10: Intermediate Construction Stage showing key segment casting

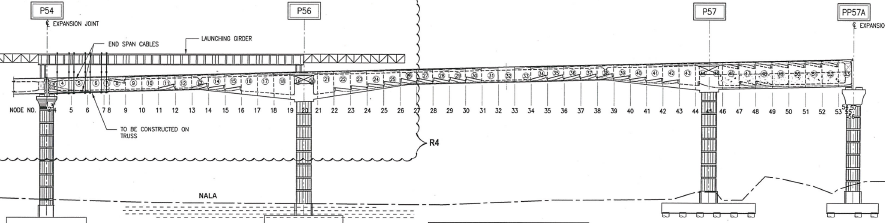


Figure-11: Stage showing side span casting using LG & suspended truss

Since this is an incremental cast-in-situ segment construction, similar separate stages are created in Midas civil as shown in below image. One of the side spans (26m) is completely cast-in-situ on staging and there are total 3 nos. of form travelers (having 50T weight each) which have been used in the incremental construction technique.

A blue and white diagram of a building

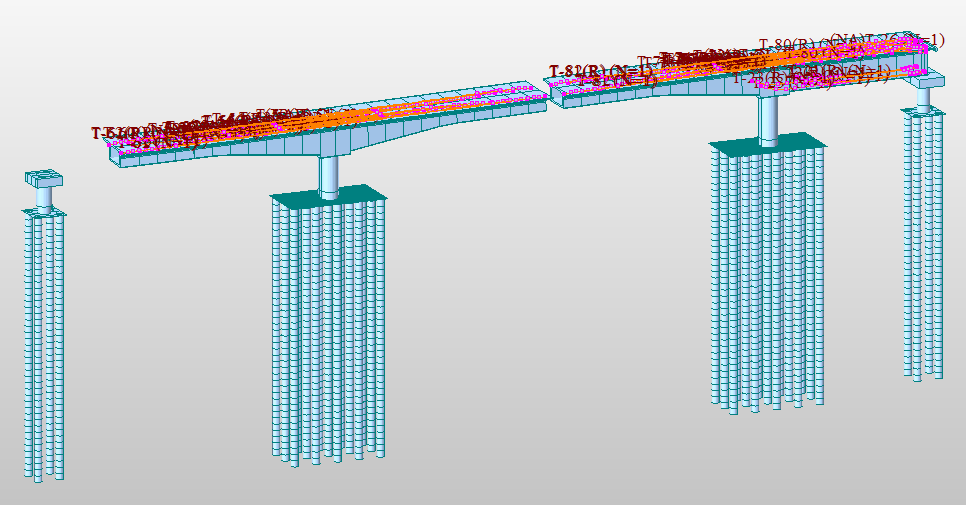
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Figure-12: Stages of Construction in Midas Model

Apart from this form traveler load, the self-weight of each segment (auto-activation in Midas upon defining), the prestressing load (19T15 and 12T15) and the construction stage live load (50kg/sqm) were considered appropriately in the model. The load of blisters and deviator blocks has been applied as nodal load at respective location.

To avoid uplift scenario in the smaller side back-span an additional load of 85kN/m has been applied to act as counterweight using M15-fill within the box.

Apart from these loads, a local pre-compensation force has been applied in two sets of models (out of 3 explained in next heading) at the COG of the penultimate segment just before the casting of the key segment and just after this key segment is cast and it attains the required strength, this pre-compensation force is removed. In the following 2 cases covered up, 75T and 150T of pre-compensation force is used.

Since this stage is mostly confined to construction stages, the service stage loads are not being described here in this section.

1. **Description of Cases Covered in Study**

The cases covered in this study are as follows:

* 1. Analysis using no pre-compensation force.
  2. Analysis using 750kN force.
  3. Analysis using 1500kN force.

For all these three cases listed above, 5 separate models have been prepared with 6.0 m, 9.0 m, 12.0 m, 15.0 m, 18.0 m and 21.0 m pier heights (total 15 Midas Civil models). Results of the substructure & foundation supporting 47m and 74m span in the last stage of construction (after 100 years) are then compared to obtain a pattern of how these results vary with pier height and with the magnitude of the pre-compensation force. The forces taken to compare the results are axial forces, bending moments and shear forces in piles.

1. **Results:**

|  |  |  |  |
| --- | --- | --- | --- |
| Axial Forces in Piles (on the outer side of P56 towards P54)-kN | | | |
| Pier Height (m) | At PCF=0kN | At PCF=750kN | At PCF=1500kN |
| 6 | 1510 | 1655 | 1799 |
| 9 | 1646 | 1811 | 1976 |
| 12 | 1770 | 1955 | 2140 |
| 15 | 1879 | 2083 | 2288 |
| 18 | 1974 | 2198 | 2421 |
| 21 | 2057 | 2299 | 2542 |
| Bending Moments in Piles (on the outer side of P56 towards P54) -kNm | | | |
| Pier Height (m) | At PCF=0kN | At PCF=750kN | At PCF=1500kN |
| 6 | 602.8 | 502 | 401.1 |
| 9 | 264.3 | 171 | 78 |
| 12 | 116 | 147 | 178.6 |
| 15 | 204 | 229 | 279 |
| 18 | 266 | 304 | 377 |
| 21 | 312.5 | 379 | 446 |

|  |  |  |  |
| --- | --- | --- | --- |
| Bending Moment at Pier Bottom-kNm | | | |
| Pier Height (m) | At PCF=0kN | At PCF=750kN | At PCF=1500kN |
| 6 | 17920 | 11464 | 5009 |
| 9 | 17957 | 10194 | 2433 |
| 12 | 16785 | 7767 | 3759 |
| 15 | 15297 | 5065 | 6742 |
| 18 | 13845 | 2430 | 9925 |
| 21 | 12542 | 1186 | 13102 |

|  |  |  |  |
| --- | --- | --- | --- |
| Bending Moment at Pier Top--kNm | | | |
| Pier Height (m) | At PCF=0kN | At PCF=750kN | At PCF=1500kN |
| 6 | 25946 | 27898 | 29850 |
| 9 | 26367 | 27998 | 29623 |
| 12 | 25092 | 26469 | 27847 |
| 15 | 23283 | 24466 | 25649 |
| 18 | 21425 | 22453 | 23482 |
| 21 | 19691 | 20596 | 21500 |

|  |  |  |  |
| --- | --- | --- | --- |
| Shear Force at Pier Bottom-kN | | | |
| Pier Height (m) | At PCF=0kN | At PCF=750kN | At PCF=1500kN |
| 6 | 6050 | 5429.3 | 4808 |
| 9 | 4324 | 3725.8 | 3127 |
| 12 | 3160 | 2584 | 2007 |
| 15 | 2374 | 1817 | 1260 |
| 18 | 1832 | 1293 | 753 |
| 21 | 1449 | 924.3 | 400 |

Tables 1 to 5: Results of the analysis

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Fig.13: Variation of axial forces in piles due to various PCF

Fig.14: Variation of BM in piles due to various PCF

Fig.15: Variation of BM at pier bottom due to various PCF

Fig.16: Variation of BM at pier top due to various PCF

Fig.17: Variation of SF of pier due to various PCF

1. **Conclusion:**

The analysis of the graphs indicates that when no pre-compensation force is applied, an increase in pier height leads to higher axial compression in the piles, while the bending moment (BM) initially decreases up to a certain height of the pier. However, beyond this point, the BM starts to rise again. The introduction of pre-compensation force plays a key role in reducing the bending moments, thereby making the piles more economical. However, this benefit is limited to a specific pier height. Once this critical height is exceeded, the bending moments increase again, which can make the design less cost-effective. It is also important to note that higher levels of pre-compensation force result in a lower critical pier height, meaning that beyond this height, the piles become less economical at a quicker rate.

A similar trend is observed in the behaviour of the piers. Without pre-compensation force, the bending moment at the bottom of the pier decreases as the pier height increases. In contrast, at the top of the pier, the bending moment initially shows a slight increase but eventually decreases as the pier height continues to rise. This pattern remains consistent even when a 750kN pre-compensation force is applied. However, when a higher pre-compensation force of 1500kN is used, the bending moment at the bottom of the pier decreases slightly as the height increases from 6m to 9m, but then begins to rise sharply as the pier height continues to increase beyond this point.

From these observations, it can be inferred that applying a pre-compensation force is highly effective in reducing bending moments in both piles and pier bases, leading to a more economical structural design. This reduction in bending moments, however, only holds up to a specific pier height. Beyond this critical height, the effectiveness of the pre-compensation force diminishes, and the bending moments in the piles and piers begin to increase again, which could make the design uneconomical. As the pre-compensation force increases, the height at which this transition occurs becomes lower, meaning that higher forces require more careful design considerations at lower pier heights to maintain cost efficiency.

Therefore, it is crucial to determine the appropriate pre-compensation force based on the specific height of the pier in the design process. The use of pre-compensation forces can significantly optimize the design by reducing bending moments, but understanding the limitations of this benefit in relation to pier height is essential for ensuring a balance between structural performance and cost-efficiency. Designing with this in mind will help avoid the point at which the piles and piers become uneconomical due to increasing bending moments after reaching a certain height.

These optimization results can lead to the use of less material or smaller cross-sections, contributing to cost savings and a more efficient design. However, the benefits and trade-offs of this approach require careful consideration by the structural design engineer. This process involves several iterations and adjustments to find a balance that optimizes the structure. The goal is to achieve a force value that reduces the bending moments in critical areas, like piers and pile caps, while also ensuring the overall stability and performance of the structure. Through this careful optimization, engineers can achieve a design that is both economical and structurally sound.