Assessment of Tilt Effects on Stress Distribution in Bridge Piers: A Review Study

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Abstract. Stress flow in bridge piers is significantly influenced by tilt behaviour, especially when the vehicle loads are applied. These substructures are repeatedly subjected to static and dynamic forces, generating complex stress responses. Tilt phenomena, which can be caused by uneven load distribution, foundation settlement, or increasing structural degradation, have emerged as important factors in determining the stress flows through piers. This paper presents a comprehensive literature review covering the development of studies on stress behaviour in piers with an emphasis on tilt-induced effects. Studies are categorised according to theoretical approaches to stress analysis, dynamic loading conditions, tilt mechanisms, and structural health monitoring techniques. Furthermore, the study also evaluates the effectiveness of current numerical methods, including finite element analysis and field monitoring, in capturing stress variations due to tilt. It emphasizes the importance of incorporating tilt effects into structural assessments and points to future advancements in pier health monitoring systems.

Keywords: Stress distribution, tilt behaviour, numerical modelling, finite element analysis, substructure stability.

1 Introduction

Railway bridges represent a vital component of national transportation networks, ensuring the movement of goods and passengers over varied terrains. The substructure of these bridges, particularly the piers, plays a critical role in transferring loads safely to the foundation. Traditionally, design approaches have assumed that vertical alignment and uniform stress distribution exist within piers. However, real-world deviations, especially those involving geometric tilting due to foundation settlement, scour, seismic activity, or prolonged degradation, have challenged this assumption. The tilt phenomenon is no longer incidental it is a fundamental factor in understanding stress distribution and structural safety.

With many railway bridges worldwide exceeding their intended design lives, the need to evaluate their health under modern operational demands has intensified. Increasing axle loads, faster train operations, environmental influences, and subsoil variability have made bridge piers more vulnerable to progressive tilting. Even a few degrees of inclination can cause significant redistribution of stresses, resulting in unanticipated cracking, concentration zones, or even structural failure. As observed in the Storebaelt Link project, Steenfelt & Kristensen (2023)[1], long-term tilting can develop incrementally but has profound consequences on stress behavior under service loads.

Simultaneously, advancements in sensor-based monitoring, finite element modelling, and machine learning have opened new avenues for studying how tilt alters pier response over time. Real-time monitoring systems equipped with tilt sensors, digital inclinometers, and vibration-based assessment tools now offer granular insight into how internal forces evolve under tilt conditions. Combined with 3D numerical simulations and probabilistic assessment techniques, engineers are now better positioned to predict, manage, and mitigate tilt-induced risks.

This review consolidates key global studies that examine the tilt–stress relationship in railway bridge piers. By synthesizing findings across experimental, analytical, and monitoring-based research, the paper provides a unified technical narrative. It aims to guide future bridge health monitoring, retrofitting, and design practices to account for tilt effects more explicitly, particularly in aging rail infrastructure that demands resilience under dynamic loading and uncertain soil–structure interactions.

2 Influence of Tilt on Structural Behaviour of Railway Bridge Piers

The performance of bridge piers is fundamentally tied to their geometry and load-bearing characteristics. In an ideal scenario, piers are vertically aligned, allowing axial loads to be uniformly transmitted to the foundation. However, in practice, piers are often subjected to tilting due to differential settlements, scour, nearby construction activities, seismic movements, or prolonged degradation of foundation materials. This geometric alteration disrupts the uniformity of internal stress flow and introduces eccentricities that significantly alter structural behavior. Long-term case studies offer compelling evidence of the cumulative effect of tilt on structural performance. One of the most extensive efforts was conducted by Steenfelt & Kristensen (2023) [1], who monitored 62 piers of the West Bridge on the Storebaelt Link for over 25 years. Their findings revealed that even in stiff clay till foundations, small tilt increments influenced the stress patterns and required attention under Ultimate Limit State (ULS) conditions. These results underscore the need to treat tilt not as an anomaly, but as a progressive structural condition. Gikas et al. (2019) [2] provided further clarity through a nine-month monitoring study of tall piers in a multi-span beam bridge using high-resolution digital inclinometers. Their observations confirmed that tilt was not static it varied in response to vehicle loadings, temperature, and seasonal changes. This dynamic behaviour resulted in non-uniform lateral displacements and increased stress gradients across the pier cross-section.

Similarly, Xiao Feng et al. [3] employed Fiber Bragg Grating (FBG) tiltmeters to capture both angular changes and vibration-induced responses, providing real-time insight into the structural response during vehicle crossing.

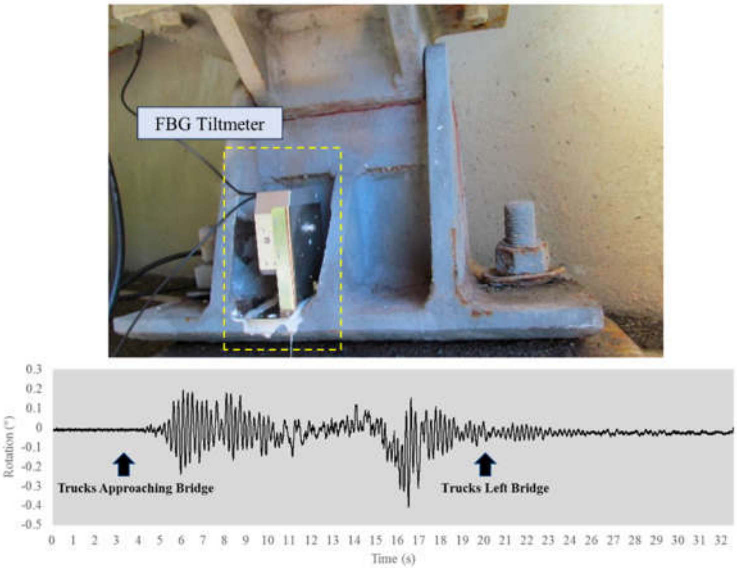

Fig. 1. Sample tilt data trend from Xiao Feng et al. (2017) showing angular shifts during truck passages

Theoretical and computational modelling studies validate these observations. Building on the need to understand the structural impact of pier tilt, Ahmadi and Kashani [4] conducted simulations to analyse the nonlinear behaviour of segmental precast post-tensioned bridge piers subjected to tilt-induced eccentric loading. Their study revealed that even a modest tilt could significantly reduce dynamic stiffness and introduce energy dissipation mechanisms absent in perfectly vertical piers. Notably, their findings indicated that tilted piers are more susceptible to seismic amplification, particularly in geometrically tapered configurations where stress concentrations tend to intensify.

Following this, Chengyin Liu et al. (2020)[5] investigated how temporary construction loads can trigger tilt-related deformations. Using a detailed three-dimensional finite element (FE) model, they simulated the effect of a temporary roadway built beneath a bridge, revealing that such loading led to notable lateral deflections and stress redistributions in both piers and foundation piles. Their findings were reinforced by field measurements, underlining how even short-term construction activities can induce tilt and stress anomalies, particularly in sensitive structural zones. This insight becomes especially relevant in aging bridges or regions prone to foundation degradation, where tilt often evolves in conjunction with scour phenomena. In this context, Ebrahim Akhlaghi et al. (2020)[6] provided a comprehensive review of theoretical and experimental scour studies, establishing a clear link between foundation erosion and progressive tilt development. Furthering this understanding, Mario Moreno et al. (2016)[7] carried out 48 long-duration physical model tests on complex bridge pier systems and demonstrated that pile cap design and pile group configuration significantly influence scour depth and tilt behavior.

Building upon these findings, Ciancimino et al. (2022)[8] emphasized that scour-induced tilt leads to accelerated stress concentration in caisson foundations, particularly under high-flow hydraulic conditions. Their study underscores the importance of conducting integrated analyses that consider both scour progression and structural response, especially for piers in rivers or coastal environments.

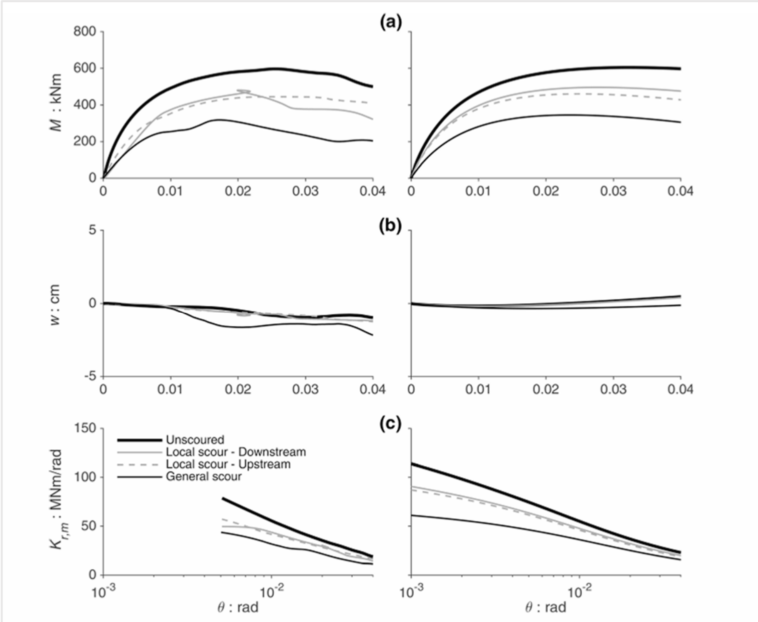

Fig. 2. Relationship between scour progression and pier tilt adapted from Ciancimino et al. (2022)

3 Advancements in Structural Health Monitoring

With advances in real-time Structural Health Monitoring (SHM) technologies, engineers can now continuously track the evolution of pier tilt and its impact on structural integrity, even in historic structures. Polepally et al. (2023)[9] exemplified this progress by combining SHM instrumentation, deploying wireless accelerometers on a 93-year-old masonry railway bridge, with model-driven approaches to detect vibrational anomalies correlated with pier tilt. By cross-verifying these anomalies with numerical models, they could relate tilt data to ambient vibrations and underlying soil conditions, allowing for the identification and prioritization of at-risk spans for retrofitting. This research demonstrates how even heritage structures can be seamlessly integrated into the digital era, enhancing their safety and longevity without compromising their historical value.

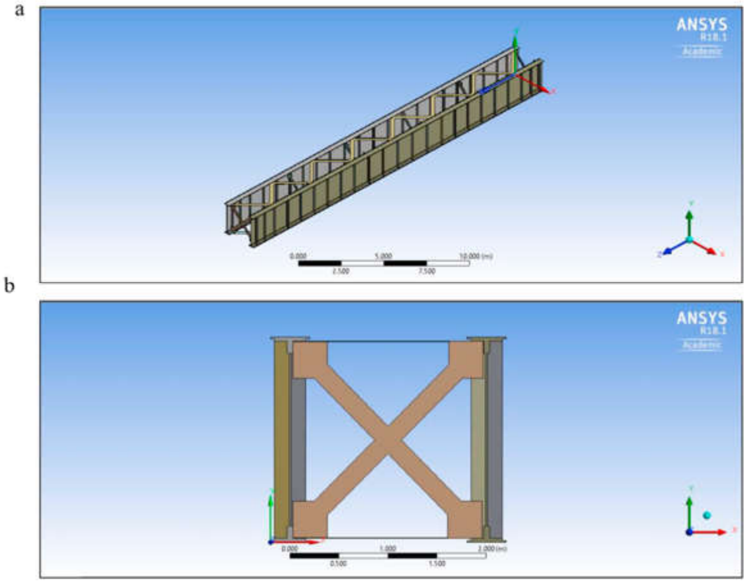

Fig. 3. Integrated SHM strategy for masonry pier stress analysis adapted from Polepally et al. (2023)

In India, Banerji and Chikermane (2011, 2014) [10]-[11] developed a robust, practical framework for tilt-based life estimation of railway bridges. Their initial study utilized field-calibrated numerical models and short-duration monitoring data to estimate the fatigue life of steel bridges subjected to elevated axle loads, effectively predicting remaining service life by accounting for stresses associated with developing tilt. Building on this, their 2014 research extended the methodology to concrete and masonry bridges, introducing tilt-based damage indicators as part of a comprehensive life extension strategy. Applied across more than 125,000 bridges, their work established tilt not only as a symptom of deterioration but also as a quantifiable parameter for predicting performance decline and guiding targeted interventions. The evolution of SHM technologies has further enhanced the scalability and effectiveness of such approaches.

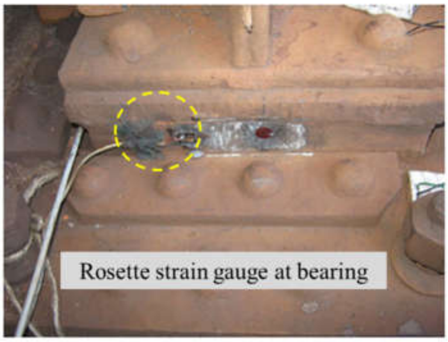

Fig. 4a. Rosette strain gauge at bridge bearing

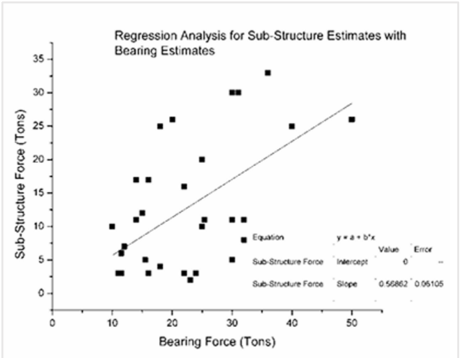

Fig. 4b. Regression analysis of forces studies by Banerji and Chikermane (2011,2014)

To make tilt monitoring more accessible and scalable, Bhatta and Dang (2024) [12]presented a state-of-the-art review of IoT-enabled structural health monitoring (SHM) systems. They highlighted how low-power, cloud-connected wireless sensors and edge computing enable real-time tracking of tilt and structural response across extensive bridge networks, significantly reducing the need for manual inspections and paving the way for integration of tilt data into predictive maintenance strategies. Their review emphasized that these cost-effective systems can efficiently monitor tilt in large-scale bridge inventories, but also acknowledged persistent challenges such as sensor calibration, data security, energy constraints, and environmental noise. Addressing these technical hurdles will be crucial for the widespread, reliable application of IoT-based monitoring in bridge management.

Most recently, Chuang Wang et al. (2024)[13] introduced a sparse-sensor methodology that uses a single vibration transducer to extract train-induced modal responses. These responses were then used to assess tilt-related stiffness degradation in piers. Their approach, validated on the Songhua River bridge, proved to be highly reliable even under freeze-thaw environmental conditions, demonstrating its potential for wide-scale application in SHM systems.

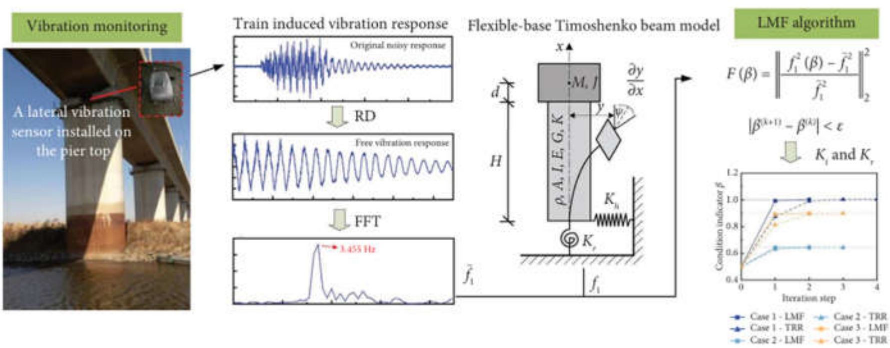

Fig. 5. Sparse-sensor methodology for tilt assessment technique adapted from Chuang Wang et al. (2024)

Together, these studies reveal that tilt is not a secondary condition but a transformative geometric parameter that influences how piers bear, redistribute, and resist loads. Its effects permeate across materials, load cases, environmental exposures, and design configurations. Whether captured through long-term monitoring, field experiments, or probabilistic simulations, tilt consistently emerges as a key variable in defining the stress performance of railway bridge piers.

4 Advancements in Predictive Modelling and Retrofitting Solutions

As tilt in bridge piers becomes increasingly recognized as a governing factor in stress redistribution and structural safety, advancements in monitoring, modelling, and evaluation strategies have evolved significantly. Traditional static assessments and visual inspections are insufficient for capturing the time-dependent and dynamic implications of pier tilt, particularly in aging infrastructure subjected to heavier loads and extreme environmental conditions. The convergence of smart sensing technologies, robust numerical modelling, and data-driven prediction tools now offers a multidisciplinary framework for tracking tilt-induced behaviour with greater precision and foresight.

Advancing further into the realm of analytics, Lai et al. (2024)[14] conducted a stochastic analysis of the bending capacity of precast prestressed concrete piers using Monte Carlo simulation and machine learning. They identified tilt as a significant variable influencing the statistical variability of pier strength. Their study revealed that parameters such as the modulus of elasticity of prestressing steel and the compressive strength of concrete contributed more to performance uncertainty under tilt than other variables, including constant axial loads. The research demonstrated how probabilistic models could bridge the gap between theoretical prediction and real-world performance, especially when tilt alters load paths unexpectedly.

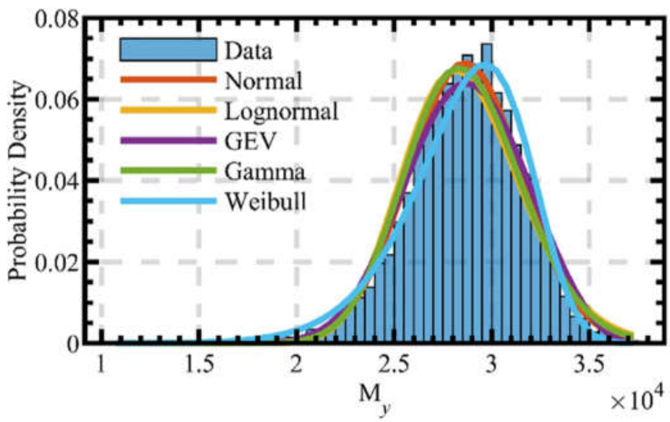

Fig. 6. Monte Carlo simulation of tilt-based bending variability adapted from Lai et al. (2024)

Building upon such diagnostic perspectives, Vagnoli et al. (2021)[15], who reviewed various structural health monitoring (SHM) techniques and fault detection systems for Europe's aging railway bridges. With over 35% of the continent's 300,000 railway bridges being more than a century old, they highlighted that traditional inspection methods often fall short in early identification of tilt-induced failures. In their comparative analysis, Vagnoli et al. assessed tilt monitoring strategies and found that combining model-updating approaches such as finite element (FE) model correlation with data-driven tools like Artificial Neural Networks (ANNs) and Bayesian Belief Networks (BBNs) creates a hybrid methodology. This hybrid approach offers more accurate and reliable tilt-based damage prognosis than relying on either method alone.

Moving beyond detection, monitoring serves as a foundation for designing effective intervention strategies when tilt is identified. Pan et al. (2023)[16] addressed this challenge by proposing and field-validating an in-situ replacement method for tilted piers and caps, employing a 3D ABAQUS-based support system. This technique simulates and facilitates the replacement or repair of tilt-affected elements while preserving the original load paths and stress states, thereby enabling structural renewal under live traffic or active railway conditions. Their successful deployment represents a significant advancement in sustainable bridge management, demonstrating that tilt-sensitive retrofitting techniques can restore structural integrity with minimal service disruption, a crucial step toward resilient and long-lasting infrastructure.

Looking ahead, integration between field-based instrumentation and advanced modelling tools holds the key to future resilience. Real-time feedback from tilt sensors can be used to update FE models and forecast stress evolution. With the rise of digital twins in civil infrastructure, bridges can now be managed as live systems, where tilt is not just monitored but dynamically analysed in conjunction with traffic, weather, and structural data.

In conclusion, the advances in monitoring and modelling tilt effects have reshaped how bridge piers are evaluated and managed. From SHM networks and sparse-sensor frameworks to machine learning and numerical simulation, the toolkit available to engineers is now more powerful than ever. As aging railway infrastructure continues to face increasing demands, these technologies will play a central role in maintaining structural integrity, ensuring safety, and extending service life. Tilt, once a passive indicator of settlement, is now a central player in the story of bridge resilience.

5 Future Prospects and Recommendations

Tilt in bridge piers has evolved from being a secondary concern to a central structural challenge, especially in aging railway infrastructure. While recent advances in monitoring and modelling have addressed many complexities, several key areas remain underexplored. Future research must focus on converting tilt analysis into a proactive, predictive, and cost-effective process.

5.1 Intelligent Monitoring and Modelling Integration

Future developments must prioritize integrating tilt data from SHM systems with real-time analytics and machine learning. Although field sensors capture valuable displacement and vibration trends, these data streams are seldom processed into actionable insights. Algorithms trained on large datasets combining FE model outputs with sensor histories can detect stress trajectory changes early and forecast failure risks. Furthermore, developing digital twin frameworks can enable continuous model updating and stress simulations under progressive tilt. Coupled soil structure interaction models must also evolve to include scour, liquefaction, and non-linear ground behaviour to better reflect real foundation responses under tilt.

5.2 Practical Implementation and Design Frameworks

Field application of tilt-based insights remains limited. Defining standardized, code-based tilt thresholds under varying loading and foundation conditions is necessary to guide design and maintenance decisions. At the same time, the need for durable, energy-efficient tilt sensors, especially for remote sites, must be addressed through innovations in IoT and energy-harvesting technologies. Research into targeted retrofitting solutions such as fiber-reinforced polymers, micro-piling, or base reshaping will enable cost-effective restoration of distressed piers. Pilot projects and real-world validations of these methods will accelerate adoption, particularly in developing regions with budget constraints.

Together, these directions aim to shift tilt assessment from a diagnostic to a predictive discipline, ensuring the long-term performance and safety of railway bridges worldwide.

6 Conclusion

This review has explored the complicated role of tilt in influencing stress distribution and structural performance in railway bridge piers. Drawing from experimental studies, long-term monitoring programs, and advanced numerical simulations, the findings reinforce that tilt is not merely a geometrical imperfection, it is a governing parameter that affects how loads are transferred, redistributed, and resisted within a pier foundation system.

Tilt alters internal force paths, introduces eccentricities, and often leads to stress concentration zones that conventional design models fail to predict. Case studies across Europe, China, and India have demonstrated that tilt is both progressive and dynamic, interacting with environmental loads, foundation conditions, and operational stresses. Whether caused by scour, differential settlement, seismic events, or aging foundations, the presence of tilt significantly impacts serviceability and safety margins. Monitoring systems ranging from inclinometers and tiltmeters to IoT-based wireless sensors have shown considerable promise in detecting and tracking tilt-induced deformations. When combined with finite element models and machine learning techniques, these tools offer engineers a path toward predictive diagnostics and real-time response strategies. Recent efforts to create digital twins and probabilistic models further illustrate how tilt can be integrated into lifecycle performance assessment. However, critical gaps remain. These include the lack of standardized tilt limits for railway piers, underdeveloped soil structure interaction models under tilt conditions, and limited field implementation of tilt-specific retrofitting solutions. Addressing these challenges will require interdisciplinary collaboration, stronger code-based guidance, and innovations in sensor technology and data analytics.

In conclusion, tilt must be treated as a primary design and evaluation parameter in both existing and new railway bridge infrastructure. By embedding tilt awareness into monitoring frameworks, analysis models, and retrofitting strategies, the engineering community can advance toward more resilient, adaptive, and safer railway systems.

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