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# Innovative design and implementation of the tower foundation for the 1915 Çanakkale Bridge

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ABSTRACT: The 1915 Çanakkale Bridge stands as a hallmark of modern engineering, necessitating innovative foundation solutions to address complex geotechnical challenges. This paper presents the comprehensive design and implementation of the tower foundations, emphasizing the usage of inclusion piles and gravel pads to improve soil conditions, mitigate settlement, and increase lateral resistance. Inclusion piles, specifically thin-walled tubular pipes, play a pivotal role in this design by effectively augmenting the bearing capacity of the foundation through soil reinforcement. These piles are strategically integrated to distribute loads, thereby reducing potential settlement impacts. The gravel pad significantly assists in load distribution from the tower foundation to the inclusion piles and surrounding soil, but also serves as a crucial component by acting as a horizontal fuse between the caisson base and the inclusion piles that diminishes horizontal seismic actions resulting on the inclusion piles. To ensure sufficient load transfer from the gravel pad to the upper part of the piles, the pile heads have been fitted with shear keys and a support ring structure. This paper details the methodologies adopted in designing the foundation system, numerical simulations, field tests, and the performance outcomes observed. In an innovative study, the local buckling behavior of the thin-wall inclusion piles under seismic actions was meticulously analyzed to ensure their structural integrity and performance during seismic events. Similarly, there was detailed focus on the analyses and design of the pile heads to ensure effective load transfer from the gravel pad to the piles. The application of inclusion piles coupled with a gravel pad demonstrates significant efficiency in achieving the desired geotechnical performance and resilience against seismic forces. An in-depth presentation of the design principles, execution challenges, and the strategic implementation that contributed to the successful realization of the tower foundations for the 1915 Çanakkale Bridge is provided.

KEYWORDS: 1915 Çanakkale Bridge, Tower foundations, Inclusion piles, Gravel pad, Caisson foundation, Seismic isolation, Horizontal fuse, Soil-structure interaction.

## 1 INTRODUCTION

The 1915 Çanakkale Bridge, with a world-record 2023 m main span, required a foundation capable of ensuring long-term safety in the highly seismic Çanakkale Strait. The design was dictated by formidable challenges, including deep water and a complex soil profile of soft, normally to slightly over-consolidated Holocene clays with potentially liquefiable sand pockets.

This paper presents the hybrid foundation system developed for the bridge's two towers. The design methodology is the same for both the European and Asian tower foundations, but this paper focuses on the European tower, which was more critical due to a thicker layer of soft Holocene clay. The system integrates a massive reinforced concrete caisson with a composite ground improvement scheme of large-diameter, thin-walled steel inclusion piles and an engineered gravel pad. The central innovation is the dual functionality of the gravel pad, which serves as both a load transfer platform (LTP) and a "horizontal fuse" for seismic isolation. This concept builds upon previous major bridge projects but refines the approach through rigorous verification of each component, ensuring robust performance under extreme seismic loading (Yang, Dobry and Peck, 2001).

## 2 PRECEDENTS IN SEISMIC FOUNDATION DESIGN FOR MAJOR BRIDGES

The foundation concept for the 1915 Çanakkale Bridge marks another step of the evolution from rigid, force-resisting systems to more sophisticated, performance-based approaches that manage and dissipate seismic energy. This evolution is marked by the development of Geotechnical Seismic Isolation (GSI) systems, which introduce a flexible or sliding interface within the foundation to decouple the superstructure from intense ground motions (Chiaro et al., 2024; Tsang, 2009). The design for the Çanakkale Bridge draws upon and advances the principles established by key international precedents.

The Rion-Antirion Bridge in Greece stands as a seminal project in this field. Faced with a highly seismic environment, deep water, weak soils, and the unique challenge of significant potential tectonic movements, its designers pioneered the concept of a "sliding shear fuse" for a major bridge foundation (Pecker and Teyssandier, 1998; Pecker, 2005). The foundation system involved large-diameter gravity caissons resting on a gravel layer, which in turn sat atop a grid of unconnected steel pipe inclusions reinforcing the upper soil layers. This design deliberately created a plane of weakness at the caisson-gravel interface. Under extreme seismic loading or tectonic displacement, this interface was designed to allow sliding, thereby dissipating enormous amounts of energy and limiting the forces transmitted to the piers (Pecker, 2005; Yang, Dobry and Peck, 2001). The Rion-Antirion Bridge established the conceptual viability of using a composite foundation with a gravel layer as a sacrificial fuse, fundamentally shifting the paradigm for seismic foundation design in challenging conditions.

The Osman Gazi Bridge (Izmit Bay) in Turkey provided a critical regional validation of this approach. Constructed in a seismic setting comparable to that of the Çanakkale Strait and in close proximity to the North Anatolian Fault, its tower foundations also employed a hybrid system of a concrete caisson, a thick gravel bed, and steel inclusion piles for soil improvement (Steenfelt, Foged and Augustesen, 2015; Inoue et al., 2025). The design explicitly identified the gravel bed as a base isolation layer, acting as a fuse to provide a controlled sliding surface during high-amplitude earthquakes (Lyngs, Kasper and Bertelsen, 2013; Inoue et al., 2025). The successful implementation of this system on the Osman Gazi Bridge served as a vital precedent, confirming the applicability and effectiveness of the concept within the specific geological and seismic context of Turkey (Steenfelt, Schunk and Zhao, 2023).

The 1915 Çanakkale Bridge foundation represents the next logical step in this evolution, building upon the established principles of its predecessors. It synthesizes the concepts of ground reinforcement with inclusion piles and seismic isolation via a gravel fuse but advances the state-of-the-art through a more profound level of detailed mechanical analysis and component verification. While earlier projects established the system-level concept, the Çanakkale design placed a significant emphasis on rigorously verifying the performance of the individual components that enable the system to function as intended. This includes detailed verification of the shear keys and support rings that ensure load transfer from the gravel to the piles, a sophisticated approach for combining inertial and kinematic loading of the piles and an advanced finite element analysis of the local buckling behavior of the thin-walled piles under soil confinement. This progression from conceptual innovation (Rion-Antirion) to regional application (Osman Gazi) and finally to detailed mechanical refinement and optimization (Çanakkale) demonstrates a maturation of the design philosophy, leading to a highly robust and well-understood foundation system, which enables the bridge to resist a second large earthquake after the non-collapse earthquake event.

## 3 SITE AND GEOTECHNICAL CONDITIONS

A comprehensive geotechnical investigation campaign, including nine sets of boreholes and Cone Penetration Tests with pore pressure measurement (CPTU), was conducted to establish the geological stratification and engineering properties of the soil at the European Tower location. The investigations revealed a layered but relatively uniform sub-seabed profile with nearly horizontal boundaries. The seabed itself is located at a depth of approximately -35 m to -36.5 m TUDKA.

### 3.1 *Subsurface Profile*

The ground profile is characterized by a significant thickness of soft, compressible marine deposits from the Holocene epoch, overlying much stiffer and older mudstones from the Miocene epoch. The primary soil units, simplified for numerical modeling, are:

- CH-H1 (Holocene Fat Clay): A thick layer of soft, high-plasticity clay extending from the dredged level of -37 m TUDKA down to approximately -55 m to -59 m TUDKA. This layer is characterized as normally to slightly over-consolidated.
- CH-H2 (Holocene Fat Clay): A second layer of fat clay, slightly stiffer than the overlying CH-H1, extending to depths of -60 m to -72 m TUDKA.
- CH-M1 and CH-M2 (Miocene Weak Mudstone): A transitional layer of weak to weathered mudstone, representing the upper boundary of the more competent Miocene deposits. They were combined as CH-M12.
- CH-M3 (Miocene Mudstone): A competent layer of mudstone providing the primary bearing stratum for the inclusion piles.

A liquefaction hazard assessment was conducted, which indicated that some discontinuous sand pockets (SM-H2) located at depths greater than 20 m below the original seabed were susceptible to liquefaction under a Safety Evaluation Earthquake (SEE) or greater. However, as these pockets are occasional rather than continuous and are located primarily near the center of the caisson where the inclusion piles are less critical for overall capacity, their effect on the foundation's bearing capacity and stiffness was determined to be very limited.

### 3.2 *Geotechnical Parameters*

Characteristic soil parameters were derived from extensive laboratory and in-situ testing for use in the design analyses. These parameters were selected as cautious estimates of the mean values to account for the large soil masses involved in potential failure mechanisms. Table 1 summarizes the key parameters used for the design. For seismic analyses, soil stiffness was degraded from the small-strain shear modulus (Gmax) to an equivalent linear shear modulus (GSRA) based on site response analyses for the different earthquake levels (FEE, SEE, NCE). For static settlement analyses, the constrained modulus (Eoed) derived from oedometer tests was used.

Table 1. Geotechnical design profile and key parameters at tower foundation European.

| Soil ID | $\gamma$ (kN/m3) | $c_u$ (kPa) | $\varphi'$ (°) | $E_{oed}$ $(MPa)$ | $G_{SRA,NCE}$ $(MPa)$ |
|---|---|---|---|---|---|
| CH-H1 | 17.2 | 2.5+1.7z | 32 | 0.53+0.07z | 5.6 |
| CH-H2 | 18.1 | 36.5+1.9z | 33 | 3.62+0.19z | 22.6 |
| CH-M12 | 19.4 | 85 | 38 | 14.6 | 94.6 |
| CH-M3 | 20.1 | 250 | 40 | 112+2.76z | 176.6+7.04z |
| Gravel | 18.0 | - | 45 | 4.0 | 77 |

Note: z represents depth in meters increasing downwards from the top of the respective layer. Stiffness values for CH-M3 vary with depth.

## 4 FOUNDATION DESIGN CONCEPT

To address the formidable site challenges, the foundation for the European tower was conceived as a hybrid system, integrating a large gravity caisson with an improved ground mass. This composite system is designed to provide robust performance under all service, ultimate, and seismic limit states by leveraging the distinct functions of its three primary components: the concrete caisson, the steel inclusion piles, and the engineered gravel pad.

### 4.1 *System Architecture*

The overall system consists of a large, rectangular reinforced concrete caisson, measuring 83.3 m × 74 m, placed at a foundation level of -37.0 m TUDKA. This caisson rests on a 3 m thick gravel bed, which in turn sits atop a subsoil mass reinforced by a grid of 192 steel inclusion piles (Figure 1). The detailed pile-head-to-gravel interface is shown with greater clarity in Figure 3.

### 4.2 *Steel Inclusion Piles for Ground Reinforcement*

The ground improvement scheme utilizes a grid of 192 large-diameter (2.5 m), thin-walled (20/25 mm) open-ended steel pipes. These elements are driven to the toe elevations of -78 m, -81 m, and -84 m TUDKA, resulting in penetration depths of 41 m to 47 m below the foundation level (Figure 2). They are arranged in a triangular grid with a center-to-center spacing of 6.25 m.

Critically, these elements are not designed as traditional end-bearing or friction piles in the conventional sense. Instead, they function as "rigid inclusions," a ground improvement technique where stiff elements are installed to reinforce a soil mass, creating a composite material with enhanced strength and stiffness (Lauzon, Desgranges and Massé, 2009; Han, 2021). The primary functions of these inclusions are twofold:

1. **Settlement Reduction**: By creating a stiff composite block of soil and steel, the inclusions significantly reduce both the magnitude and duration of consolidation and creep settlements in the soft Holocene clay layers, which would otherwise be excessive for a shallow foundation of this scale.
2. **Load Resistance**: The inclusions provide the ultimate vertical and horizontal bearing capacity for the foundation system, resisting the immense static and dynamic loads that are transmitted from the caisson through the gravel pad.

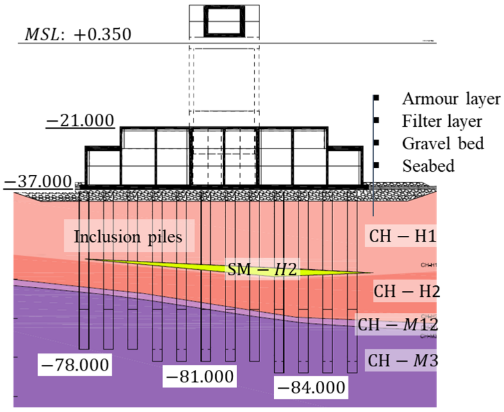

Figure 1. Schematic of the hybrid tower foundation system.

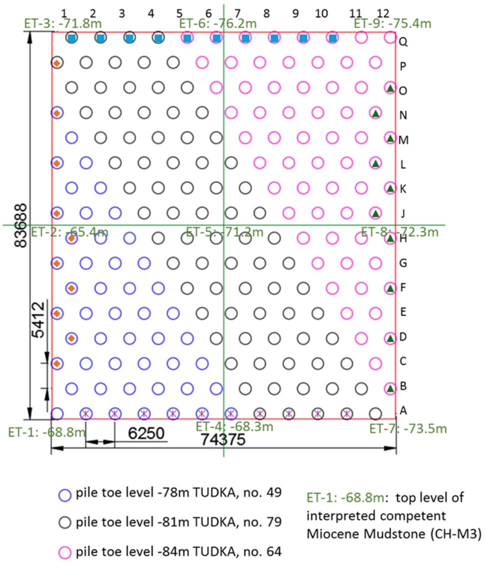

Figure 2. Arrangement of inclusion piles. The piles highlighted with fill represent the locations of the top-10 most critical piles for each of the four governing NCE load combinations

### 4.3 *The Gravel Pad: A Dual-Function Load Transfer Platform and Seismic Fuse*

A 3 m thick layer of compacted, crushed stone (gravel) is placed between the base of the caisson and the top of the improved ground. This gravel pad is a cornerstone of the design, serving two distinct and vital functions.

Firstly, it acts as a Load Transfer Platform (LTP). The gravel pad distributes the enormous vertical loads from the caisson onto the heads of the 192 inclusion piles and the intervening soil. This load transfer is achieved through soil arching, a well-established mechanism in granular materials where stress concentrates over stiffer supports (Blanc et al., 2014). This ensures that the piles are effectively engaged to carry the majority of the load, thereby activating the ground reinforcement system.

Secondly, the interface between the smooth concrete base of the caisson and the gravel pad is engineered to act as a horizontal fuse, a concept central to the foundation's seismic resilience. During an extreme seismic event, such as the No Collapse Earthquake (NCE), this interface is designed to permit sliding if the horizontal seismic forces exceed the frictional capacity of the interface. This sliding action acts as a mechanical fuse, dissipating a significant portion of the seismic energy and, crucially, limiting the peak shear forces and bending moments that are transmitted to the inclusion piles and the tower superstructure. This concept of a sliding shear fuse is a form of Geotechnical Seismic Isolation (GSI) that has been successfully implemented on previous major bridges like Rion-Antirion and Osman Gazi (Pecker, 2005; Steenfelt, Foged and Augustesen, 2015).

### 4.4 *Enhancing Load Transfer: Shear Keys and Support Ring*

A critical detail in the design is ensuring the efficient transfer of vertical load from the gravel of the LTP into the steel inclusion piles, which is needed to reduce settlements sufficiently. Relying solely on skin friction along the short length of pile embedded in the gravel would be insufficient to ensure occurrence of the needed level of arching within the gravel pad.

To solve this, the top 2.05 m of each inclusion pile is fitted with internal steel components designed to mechanically engage the gravel fill inside the pile. This includes three internal shear key rings and, below them, a more substantial 400 mm wide internal support ring structure. An external shear key ring is also provided at the same elevation as the support ring (Figure 3).

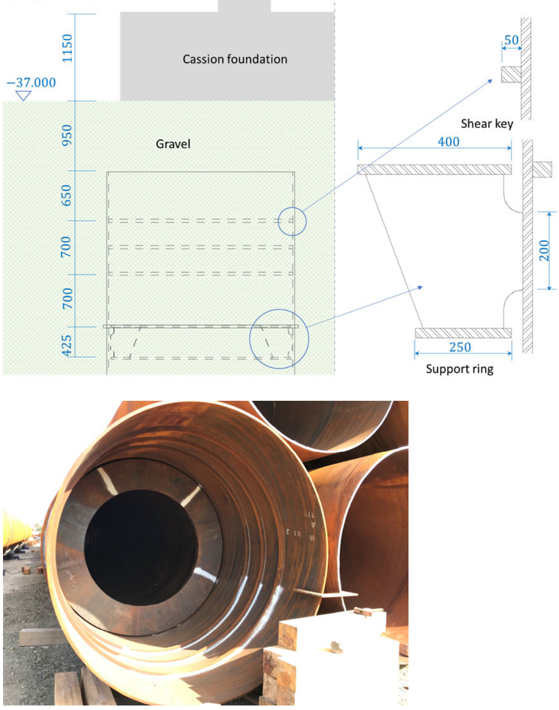

Figure 3. Details of the innovative pile head design for load transfer, drawing and photo.

These elements create a positive, mechanical interlock with the gravel column inside and around the pile head. This robust connection ensures that vertical loads are effectively transferred from the caisson, through the gravel pad, and into the steel inclusions, forcing them to act as the primary load-bearing elements. The structural integrity of these vital components, including their welds, was rigorously verified using detailed Finite Element Analysis (FEA) to ensure they could withstand the high concentrated forces during both construction (pile driving) and in-service seismic events. This attention to the mechanics of load transfer represents a key refinement that ensures the theoretical benefits of the LTP and inclusion system are realized in practice.

## 5 ADVANCED ANALYSIS AND VERIFICATION OF KEY COMPONENTS

The validation of the innovative foundation system for the 1915 Çanakkale Bridge required a suite of advanced analytical techniques that went beyond conventional design practice. These methods were essential to accurately capture the complex, non-linear behavior of the soil, the foundation elements, and their interaction under extreme seismic loading.

### 5.1 *Soil-Structure Interaction (SSI) in the Global Model*

For the global dynamic analysis of the entire bridge structure, the foundation's interaction with the soil was modeled in the COWI in-house software IBDAS using a sophisticated distributed support system rather than a simplified, single 6x6 stiffness matrix. The foundation base was discretized into a grid of nodes, each supported by a set of independent springs and dashpots representing the soil response (see Figure 4). This distributed system, which includes the gapping element, slider, and nonlinear hysteretic spring, is the explicit model for the caisson-to-gravel-bed interaction.

This distributed model consisted of vertical and horizontal elements. The vertical elements included a linear spring and dashpot to capture both material and radiation damping. The horizontal elements were more complex, featuring a non-linear hysteretic spring governed by the Masing rule, a slider element to model the fuse mechanism, and a dashpot for radiation damping. This approach offered significant advantages over traditional methods by allowing for the direct and explicit modeling of critical non-linear phenomena during a time-history analysis, including:

- **Foundation Gapping**: The potential for partial uplift of the caisson base under large overturning moments.
- **Hysteretic Soil Damping**: The energy dissipation within the soil as it undergoes cyclic loading.
- **Interface Sliding**: The activation of the "horizontal fuse" at the caisson-gravel interface, where the sliding capacity is correctly modeled as being dependent on the instantaneous vertical force acting on that portion of the foundation.

The stiffness and damping parameters for this distributed spring model were not assumed but were carefully calibrated. A series of detailed 3D push-over analyses were performed using the geotechnical software Plaxis to simulate the foundation's response to vertical and horizontal loading (Figure 5). The results of these rigorous geotechnical simulations (performed in Plaxis 3D modeling the full caisson, gravel bed, and pile geometry, and using the Mohr-Coulomb model for all soil strata and interfaces with $R_{inter} = 0.67$) were then used to derive the equivalent non-linear properties for the springs in the global IBDAS model, ensuring that the simplified model accurately reflected the complex underlying soil-structure interaction.

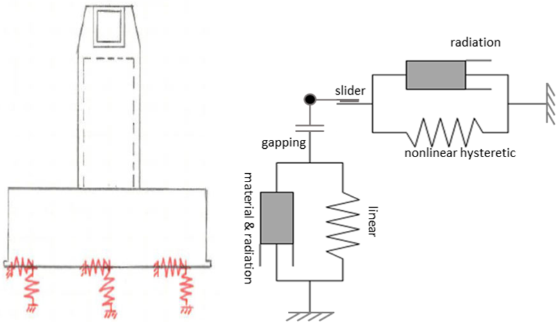

Figure 4. Principle of modelling of tower foundations in global analysis model and Detailed view of each set of distributed springs.

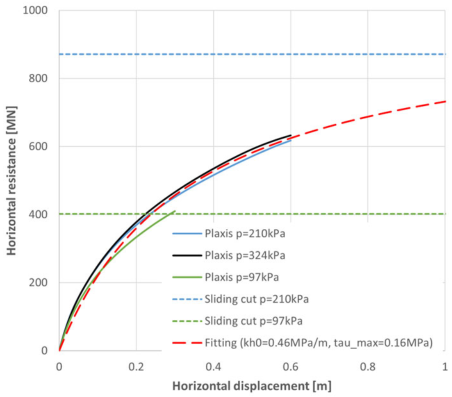

Figure 5. Horizontal foundation resistance-displacement relationship, based on the soil parameters corresponding to NCE.

### 5.2 *Analysis of Thin-Walled Pile Capacity under Seismic Loading*

A key innovation in the foundation design was the use of large-diameter (2.5 m) but relatively thin-walled (20/25 mm) steel inclusion piles. According to Eurocode 3, such proportions classify the pile as a Class 4 cross-section, for which the structural capacity is typically governed by premature local buckling, significantly limiting its allowable bending moment. A standard design approach would have necessitated much thicker, and thus more expensive, piles.

To develop a more realistic and economical design, an advanced Geometrically and Materially Non-linear Imperfect Analysis (GMNIA) was conducted using the ABAQUS software. This detailed finite element model simulated a single pile embedded within a 3D soil domain representing the specific soil stratigraphy, thereby capturing the critical confining effect of the surrounding soil on the pile wall. The Abaqus GMNIA model captured this confining effect by modeling both the external soil and the internal soil plug as 3D solid elements using the Mohr-Coulomb (MC) model. Pile-soil contact was defined using a Coulomb friction model ($\mu = 0.67$) with 'hard' normal contact. To ensure accuracy, a mesh convergence study was performed, which determined that an 80mm shell element size provided the optimal balance of accuracy and computational efficiency. The analysis incorporated several key features:

- **Soil Confinement**: The model included both the external soil and the internal soil plug, which provide lateral support to the pile wall and inhibit outward and inward buckling.
- **Geometric Imperfections**: Initial imperfections in the pile's circular geometry were introduced into the model.

The shape of these imperfections was based on the first eigen-mode shape derived from a Linear Bifurcation Analysis (LBA), and their amplitude was calibrated according to EN 1993-1-6.

- **Material Non-linearity**: The steel was modeled using a non-linear stress-strain curve with strain hardening.

The results of this sophisticated analysis demonstrated conclusively that the lateral confinement provided by the soil significantly enhances the pile's resistance to local buckling. Based on this, a performance-based design criterion was adopted, defining the pile's ultimate bending moment capacity as the moment corresponding to a maximum equivalent plastic strain of 0.8%. This scientifically justified capacity was substantially higher than the conservative value calculated using standard code provisions that neglect soil support. This advanced analysis was fundamental to validating the feasibility and economic efficiency of using thin-walled inclusion piles.

### 5.3 *Combination of Inertial and Kinematic Pile Loading*

During an earthquake, piles in soft soil are subjected to two distinct types of loading that must be combined to determine the total demand. The first is inertial loading, which arises from the inertia of the bridge superstructure as it sways. These forces are transmitted down through the tower, into the caisson, and through the gravel pad to the pile heads (Garala, 2020; Mylonakis, Nikolaou and Gazetas, 1997). The second is kinematic loading, which is induced by the deformation of the surrounding soil itself as seismic waves propagate upward from the bedrock. The curvature imposed on the pile by the moving soil generates significant bending moments, particularly at interfaces between soft and stiff soil layers (Ardita et al., 2010).

For the Çanakkale design, these two effects were analyzed separately and then combined. Inertial forces (axial force, shear, and moment) in each pile were calculated using the 3D Plaxis model subjected to the governing load combinations derived from the global IBDAS analysis. Kinematic bending moments were calculated independently using a 2D FLAC model of the soil profile subjected to the design seismic ground motions. This analysis used the Mohr-Coulomb model combined with the ITASCA Hysteresis Sigmoidal (S3) model to capture the nonlinear hysteretic soil response.

A simple superposition of the peak inertial and peak kinematic moments would be overly conservative, as these peaks do not necessarily occur at the same instant in time. By examining the time histories of the two effects, it was observed that the inertial forces exhibited a slight latency compared to the kinematic moments (see Figure 6). Based on this phase difference, a rational and robust superposition rule was established for the final structural verification of the piles: the total design bending moment was taken as the sum of 100% of the calculated inertial moment and 80% of the calculated kinematic moment. This approach provides a safe-sided yet realistic assessment of the total demand on the piles.

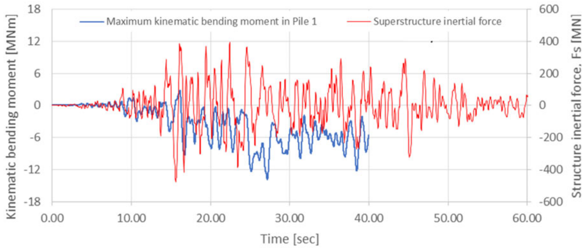

Figure 6. Illustration of simultaneous kinematic bending moment and superstructure inertial force

## 6 SYSTEM PERFORMANCE VERIFICATION AND KEY RESULTS

The comprehensive design was subjected to a multi-tiered verification process to confirm its performance under all specified limit states. This process involved checking the overall geotechnical stability of the foundation system, the structural integrity of each individual pile, and the long-term serviceability with respect to settlement.

### 6.1 *Geotechnical Bearing Capacity and Stability*

The overall stability and bearing capacity of the hybrid foundation system were verified using the 3D Plaxis finite element model. The model was subjected to the most onerous load combinations derived from the global IBDAS analysis, covering the full spectrum of design scenarios:

- **Seismic Limit States**: Functional Evaluation Earthquake (FEE), Safety Evaluation Earthquake (SEE), and No Collapse Earthquake (NCE).
- **Ultimate Limit State (ULS)**: Persistent situations (dead, live and environmental loads) and Accidental situations (ship impact).

For each scenario, the analysis confirmed that the foundation possessed sufficient geotechnical capacity. To quantify the margin of safety, phi/c-reduction analyses (i.e., the Strength Reduction Method, where $\tan\phi'$ and $c'$ are reduced by an equal factor simultaneously) were performed. For the extreme NCE seismic event, the calculated minimum factor of safety against soil failure was greater than 1.3. For the persistent ULS condition, the minimum factor of safety was greater than 2.0. These results demonstrate a robust safety margin against a geotechnical failure. The analysis of the failure mechanism showed that the inclusion piles effectively prevent a deep-seated rotational failure like for a normal shallow foundation. To quantify this contribution, a comparative 'no-pile' analysis was performed. This analysis showed the foundation failing under initial vertical construction loads alone, with a Factor of Safety of approximately 0.6. This result demonstrates that the inclusion piles are essential for preventing a bearing capacity failure.

### 6.2 *Structural Performance of Inclusion Piles*

The final verification step was a structural check of each of the 192 inclusion piles. This check compared the 'Demand' (loads) against the 'Capacity' (resistance). The 'Demand' was calculated by combining 100% of the inertial forces (axial, shear, and moment) from the 3D Plaxis analysis with 80% of the kinematic bending moments from the 2D FLAC analysis, as described in Section 5.3. The 'Capacity' was defined by a unique moment-axial force (M-N) interaction diagram. This M-N diagram was not based on a simplified analytical model; it was the direct result of the advanced Abaqus GMNIA push-over analysis described in Section 5.2. Because the GMNIA model included the entire pile embedded in the full layered soil profile, the varying soil confinement effects were already implicitly captured. The resulting M-N curve represents the pile's true structural capacity at its critical buckling location. The combined demand was then checked against the M-N capacity for all piles under all governing NCE-load combinations.

The results confirmed that all piles satisfy the design criteria. The most heavily loaded piles are those at the periphery of the foundation, which experience the highest combination of axial load and bending moment. While some of these peripheral piles are predicted to undergo minor yielding (with plastic strains remaining below the 0.8% design limit), the plastic deformation has been investigated to be acceptable and does not compromise the pile's function. Figure 2 indicates the locations of the most heavily loaded piles for the governing NCE load combinations, confirming that the largest demands are concentrated at the periphery of the foundation. Crucially, the analysis showed that even after experiencing an NCE event, the piles retain sufficient structural capacity to withstand a subsequent SEE-level earthquake, ensuring the bridge's post-earthquake resilience without requiring underwater inspection or repair.

### 6.3 *Settlement and Serviceability*

The serviceability limit state (SLS) was evaluated by predicting the foundation settlement over the bridge's 100-year design life. This was performed using a 3D Plaxis consolidation analysis that modeled the detailed construction sequence and accounted for long-term creep deformation in the soft clay layers.

The analysis predicted a total settlement at the center of the caisson base of approximately 0.32 m by the completion of construction. The long-term settlement, including primary consolidation and secondary compression (creep), is predicted to reach 0.46 m after 100 years. These settlement magnitudes were evaluated and found to be acceptable for the bridge's structural tolerances and long-term operational requirements, such as navigational clearance. A comprehensive monitoring program was specified to track actual performance during and after construction, allowing for calibration of the models and confirmation of the design assumptions.

## 7 CONCLUSIONS AND IMPLICATIONS FOR PRACTICE

The design and implementation of the tower foundations for the 1915 Çanakkale Bridge represent a significant advancement in geotechnical engineering for major infrastructure in seismically active marine environments. The project successfully addressed a formidable combination of challenges through the development of a novel hybrid foundation system employing details, analyses methods and design approaches.

The key conclusions and implications from this work are:

1. **Successful Design Synthesis**: The foundation demonstrates a highly effective synthesis of ground reinforcement and seismic isolation. The steel inclusion piles create a stiff, composite soil-structure block to control settlement and provide bearing capacity, while the gravel pad acts as both a load transfer platform and a sacrificial seismic fuse.
2. **Indispensable Role of Advanced Modeling**: The project underscores that for structures of this scale, advanced numerical modeling is an essential part of the design process. The use of sophisticated finite element analyses was critical for justifying the use of economical thin-walled piles, calibrating a distributed non-linear spring model for the global analysis, and developing a rational basis for combining inertial and kinematic pile loads.
3. **Contribution to the State-of-the-Art**: This project advances the state-of-the-art in large-scale foundation design by moving beyond conceptual application toward a system rigorously verified at the component level. The methodologies developed offer valuable and transferable insights for the design of future major bridges in similarly challenging environments.
4. **Limitations and Future Research**: The design's advanced modeling also highlighted a key area for future research. The use of decoupled springs in the global model (Section 5.1) is a necessary simplification to simulate the behavior of the gravel bed including the disconnected piles. For this project, the model to simulate the behavior was investigated and calibrated specifically, since the dynamic interaction of disconnected piles in such hybrid systems is not well researched and described. This therefore presents a valuable topic for future academic investigation.

## 8 ACKNOWLEDGEMENTS

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