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Finite Element Analysis and Design of Bridge Pier Pile Foundation Subjected to Dynamic Moving Load And Induced Vibration - A Review

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Abstract: - In modern civil engineering, bridge structures play a vital role in transportation systems, and their safety under dynamic loading conditions has become a major concern. Bridge pile foundations are subjected to various types of dynamic loads such as seismic forces, moving loads, impact loads, hydrodynamic forces, and environmental effects. The behaviour of these foundations becomes complex due to the interaction between structure and surrounding soil. This review paper focuses on analysing previous research studies related to finite element analysis (FEA) of bridge pier pile foundations under dynamic loading conditions. A comprehensive review of recent research articles is carried out to understand the behaviour of pile foundations under different loading scenarios such as earthquake loading, moving load, wave and current forces, impact loading, and soil–structure interaction. The review highlights the key findings, methodologies, and limitations of existing studies. Based on the analysis, major research gaps are identified, particularly in the area of combined dynamic moving load and induced vibration, realistic soil modelling, pile group behaviour, and resonance analysis. The study concludes that although significant research has been conducted using advanced numerical techniques, there is still a need for integrated, realistic, and multi-loading condition analysis using 3D finite element modelling. The findings of this review paper provide a strong foundation for future research in the field of bridge pile foundation design and analysis.

Keywords: - Finite Element Analysis, Bridge Pier, Pile Foundation, Dynamic Loading, Moving Load, Seismic Analysis, Soil–Structure Interaction, Vibration Analysis

I. INTRODUCTION

Bridge structures are one of the most important components of transportation infrastructure. With increasing traffic loads, high-speed transportation systems, and construction of bridges in complex environments such as coastal regions and seismic zones, the design of bridge foundations has become more challenging. Pile foundations are widely used in bridge construction because they can transfer heavy loads safely to deeper soil layers.

In real-life conditions, bridge pile foundations are subjected to various dynamic loads such as:

- Earthquake loads
- Moving vehicle and train loads
- Wave and current forces
- Impact loads
- Environmental effects

These loads create vibrations and dynamic responses in the structure, which can lead to structural damage, excessive displacement, and even failure if not properly analysed.

In recent years, Finite Element Method (FEM) has become a powerful tool for analysing complex structural behaviour. Many researchers have used FEM to study dynamic response, soil–structure interaction, and vibration characteristics of bridge pile foundations.

II. LITERATURE REVIEW

Many researchers have studied the behavior of bridge pile foundations under different loading conditions. The important findings from previous studies are discussed below.

[1] Dynamic Response Analysis of Hollow Thin-Walled Pier Rigid-Frame Bridge under Rockfall Impacts (2025) By Yangyang Mo, Yanlin Han, Jin Zhang, Zhongyao Zhang and Wendong Wu – Analysed the dynamic response and damage behaviour of hollow thin-walled rigid-frame bridge piers subjected to rockfall impact loading using advanced finite element modelling in LS-DYNA software. The study focused on understanding the effect of impact energy, rockfall size, reinforcement detailing, and impact location on structural performance. The analysis evaluated parameters such as displacement, impact force, shear damage, and crack development within the pier structure. The results showed that increasing rockfall diameter significantly increases displacement and damage intensity, especially when the impact occurs near the base of the pier. It was observed that higher reinforcement ratios help in reducing damage by localizing failure zones, while decreasing stirrup spacing improves resistance against shear damage. The study also developed a power-law relationship between peak impact force and impact energy, providing a predictive model for design purposes. The research concluded that impact loading due to rockfall is a critical factor in mountainous bridge design, and proper structural detailing along with advanced numerical analysis is essential to improve impact resistance and ensure safety.

[2] Seismic Response and Vulnerability Assessment of the Pile-Supported Bridge Pier in Seasonally Frozen Regions (2025) By Shengsheng Yu, Mingyi Zhang, Xiyin Zhang and Wanping Wang – Analysed the seismic response and vulnerability of pile-supported bridge piers under seasonal frozen and thawed soil conditions using a nonlinear seismic analysis model. The study evaluated the influence of frozen soil layers on structural behaviour based on reliability theory. The analysis considered parameters such as acceleration, displacement, and bending moment of both pier and pile foundation under seismic loading. The results showed that frozen soil reduces lateral displacement of the pier top by approximately 80%, thereby improving structural stability against earthquake-induced damage. However, it was observed that frozen soil increases acceleration response at the pier top due to reduced damping effect. The study also revealed that bending moment in the bridge pier increases in frozen conditions, while bending moment in the pile foundation decreases, reducing overall vulnerability. The research concluded that soil condition, especially seasonal freezing, has a significant impact on seismic behaviour and must be considered in the design and safety assessment of bridge pile foundations in cold regions.

[3] Dynamic Response and Vibration Control of Deep-water Bridge Piers under Ship Wave Excitation (2025) By Changqing Wu, Minhui Li, Hua Luo, Tian Hu, Shiming Yi and Guanghui Wang – Analysed the dynamic response of deep-water bridge piers subjected to ship wave excitation using both theoretical and finite element modelling approaches. The study developed a time-domain model for ship wave loads based on classical Morison equation and linear wave theory, and a detailed finite element model was created in ANSYS software to simulate the behaviour of bridge piers under wave loading conditions. The research considered important parameters such as ship speed, wave height, wave frequency, and structural natural frequency to evaluate their effect on structural response. The results showed that ship speed has a significant influence on wave characteristics, where increase in speed leads to higher wave height and load amplitude, while frequency decreases. It was observed that when the wave load frequency approaches the natural frequency of the bridge pier, resonance occurs, resulting in very high displacement and acceleration, which can be dangerous for structural safety. The study further proposed vibration control measures such as installation of tuned liquid dampers (TLD) and rigid connection between twin piers. The analysis indicated that TLD reduces vibration response by more than 60%, while rigid connection reduces transverse vibration by more than 80%. However, these methods are costly and time-consuming. Therefore, the study recommended a practical solution of controlling ship speed to avoid resonance conditions and reduce dynamic effects. The study concluded that ship wave excitation is a critical factor in deep-water bridge pier design and must be properly considered along with effective vibration control techniques for ensuring safety and stability.

[4] Examining the Structural Design of Deep Pile Foundation Bridge under Different Directions of Water Movement (2025) By Ahmed Saeed Hakim – Analysed the structural behaviour of deep-water pile foundation bridge piers subjected to varying directions of water movement including current and wave forces using advanced numerical simulation techniques. The study was carried out using ABAQUS software to model the interaction between current and wave forces acting in different directions such as 0°, 45°, 90°, 135°, and 180°. The analysis focused on evaluating dynamic response parameters such as displacement and acceleration of the pile foundation system under multiple loading conditions. The numerical results were validated using previously available experimental studies to ensure accuracy and reliability. The findings showed that the presence of water significantly affects the natural frequency of the bridge pier, increasing its stiffness characteristics. It was observed that the maximum dynamic response occurs when the current and wave forces act in the longitudinal direction (90°), compared to other directional combinations. The study also revealed that the directional interaction between current and wave forces plays a crucial role in influencing structural response and cannot be neglected in design. The research concluded that proper consideration of directional water forces is essential for the safe and efficient design of deep-water pile foundation bridges, especially in marine environments where such forces are dominant.

[5] Structural Finite Element Analysis of Bridge Piers with Consideration of Hydrodynamic Forces and Earthquake Effects for a Sustainable Approach (2025) By Qahtan Adnan Saber, Riyadh Alsultani, Ahmed Ashor Al-Saadi, Ibtisam R. Karim, Saleh I. Khassaf and others – Analysed the dynamic behaviour of bridge piers considering combined effects of hydrodynamic forces and earthquake loading using advanced three-dimensional finite element modelling techniques. The study was carried out using DIANA software with parallel processing to simulate soil–structure interaction, including nonlinear behaviour of soil and concrete. Hydrodynamic forces due to current and wave action were applied as distributed loads using Morison's formula and fifth-order Stokes wave theory. The analysis evaluated key structural response parameters such as displacement, acceleration, bending moment, shear force, and hydrodynamic pressure under varying conditions of flow velocity, wave characteristics, and seismic intensity. The results showed that earthquake-induced hydrodynamic pressure significantly alters the structural behaviour of bridge piers by increasing internal forces at lower regions and causing higher displacement and acceleration at the top of the pier. It was observed that the combined effect of wave and seismic forces produces more critical conditions compared to individual loading cases. The study concluded that hydrodynamic and seismic interaction must be considered in the sustainable design of bridge pile foundations, and advanced finite element analysis is essential for accurate prediction of structural response under complex environmental loading.

[6] Research on the Dynamic Characteristics of a New Bridge-and-Station Integrated Elevated Structure (2025) By Kaijian Hu, Xiaojing Sun, Ruoteng Yang, Rui Han and Meng Ma – Analysed the dynamic characteristics and vibration response of a newly developed bridge-station integrated elevated structure used in high-speed railway systems. The study used both field measurements and numerical simulation techniques to evaluate vibration behaviour under train-induced dynamic loading. A detailed finite element model was developed and validated using actual vibration data collected from existing stations. Various parameters such as train speed, structural configuration, and operational conditions were considered to study their effect on vibration response. The results showed that structural joints significantly influence the transmission path of vibration energy, thereby affecting overall structural response. It was observed that vibration levels increase with increase in train speed and are higher under double-track operation compared to single-track operation. The study further indicated that when train speed exceeds 200 km/h with double-track operation or 350 km/h with single-track operation, the vibration level in the waiting hall exceeds permissible limits, which may affect passenger comfort and structural safety. The research concluded that proper structural configuration, vibration control measures, and accurate dynamic analysis are essential for ensuring safe and comfortable operation of bridge-station integrated structures under high-speed train loading conditions.

[7] Dynamic Response of Bridge Pile Foundations under Pile-Soil-Fault Interaction in Seismic Areas (2025) By Yujie Li, Zhongju Feng, Fuchun Wang, Jiang Guan and Xiaoqian Ma – Analysed the dynamic behaviour of bridge pile foundations considering the combined effect of pile–soil–fault interaction in seismic regions using advanced finite element modelling techniques. The study was carried out using a detailed numerical model of the Haiwen Bridge pile foundation system, where different seismic wave intensities ranging from 0.2 g to 0.6 g were applied to simulate earthquake conditions. The model also considered different distances between the pile foundation and geological fault to understand their influence on structural response. The analysis included multiple parameters such as pile acceleration, displacement, bending moment, and shear force, and detailed simulation results were obtained through mesh modelling and dynamic time history analysis. The results showed that the soil layer above bedrock significantly amplifies pile acceleration, while the amplification effect reduces with increase in seismic intensity. It was also observed that bedrock has comparatively less influence on acceleration response. The study further revealed that maximum bending moments occur at the interface of soil and bedrock, while maximum shear forces are concentrated at the pile top and at soft–hard soil boundaries. The displacement pattern indicated that piles behave like elastic long members under seismic loading. Additionally, the mechanical behaviour of piles located on the upper and lower sides of the fault showed significant variation due to fault movement and stress redistribution. The research also included sensitivity analysis, which concluded that the distance between pile and fault has more influence than seismic intensity on the dynamic response of the foundation system. The study highlighted that the effect of fault extends up to a region nearly 10 times the pile diameter, which is very critical for design consideration.

[8] Dynamic Response Characteristics and Pile Damage Identification of High-Piled Wharves under Dynamic Loading (2024) By Xubing Xu, Xiaole Di, Yonglai Zheng, Anni Liu, Chenyu Hou and Xin Lan – Analysed the dynamic response and damage behaviour of pile foundation systems in high-piled wharf structures subjected to impact loading using numerical simulation and finite element modelling techniques. The study was carried out using FLAC 3D software to simulate ship impact loads and evaluate the structural behaviour under different loading scenarios. The analysis considered parameters such as bending moment, axial force, shear force, displacement, and stress distribution within the pile foundation system. The results showed that dynamic loading produces a significant amplification effect, with a dynamic amplification factor of approximately 1.5, indicating that impact loads must be carefully considered in design. It was observed that impact loads have a major influence on bending moments of piles, especially in inclined piles, while axial forces are less affected. The study also revealed that high-speed or unexpected ship collisions can cause severe cracking and structural damage in pile foundations. Additionally, modal flexibility analysis was used effectively to identify damage locations within the pile system, where higher changes in modal flexibility correspond to greater damage severity. The research concluded that dynamic loading and impact effects play a crucial role in pile foundation performance, and advanced numerical analysis techniques are essential for damage prediction and structural safety assessment.

[9] Railway Bridge Dynamics Considering Piled Foundations in Soft Soil (2024) By Borong Peng, Lei Xu, David P. Connolly, Zheng Li, Xuhui He, Yuanjie Xiao and Yunlong Guo – Analysed the dynamic behaviour of railway bridge systems considering the influence of piled foundations in soft soil using a coupled train–track–bridge–pile–soil interaction model. The study developed a comprehensive numerical framework combining finite element method and multi-body dynamics to simulate the interaction between train loading and structural components. The model included both superstructure (train-track-bridge interaction) and substructure (pier-cap-pile-soil system), which were coupled using bearing forces and multi-time-step integration for improved computational efficiency. The results were validated using ABAQUS software to ensure accuracy. The analysis evaluated vibration transmission, acceleration response, and energy distribution within the system. It was observed that when pile foundations are considered, low-frequency vibrations (below 7 Hz) dominate the system response. The study also showed that higher train speeds significantly increase vibration levels in piles and surrounding soil, particularly at frequencies related to axle spacing. The research concluded that considering pile foundations and soft soil conditions is essential for accurate prediction of railway bridge dynamics, and coupled interaction models provide better understanding of vibration behaviour and structural performance.

[10] Dynamic Response Analysis of Coastal Bridge Members Exposed to Water Forces and Earthquakes (2024) By Riyadh Alsultani, Ibtisam R. Karim, Saleh I. Khassaf and Ahmed Ashor Al-Saadi – Analysed the dynamic response of coastal bridge pile foundations subjected to combined effects of water forces and earthquake loading using advanced numerical modelling techniques. The study focused on reinforced concrete pile foundation bridge piers located in deep water regions, where structures are exposed to hydrodynamic forces due to waves, currents, and seismic excitation. A detailed finite element model was developed using DIANA software, incorporating nonlinear behaviour of soil and concrete along with parallel computation techniques for accurate simulation. The wave forces were calculated using Stokes's fifth-order wave theory and Morison's hydrodynamic pressure formula, and applied as distributed loads on the pile foundation system. The analysis evaluated parameters such as displacement, internal forces, and vibration characteristics under combined loading conditions. The results showed that hydrodynamic pressure significantly increases bending moments and shear forces in pile foundations during earthquake conditions. It was observed that interaction between water forces and seismic loads amplifies the dynamic response of the structure, which can affect stability and safety. The study concluded that combined current-wave-earthquake effects must be considered in design of coastal bridge pile foundations, and advanced finite element analysis is essential for accurate prediction of structural behaviour under complex loading conditions.

[11] Dynamic Response Analysis of Coastal Piled Bridge Pier Subjected to Current, Wave and Earthquake Actions with Different Structure Orientations (2023) By Riyadh Alsultani, Ibtisam R. Karim and Saleh I. Khassaf – Analysed the dynamic response of coastal bridge pier pile foundations under combined effects of water current, wave action, and earthquake loading considering different structural orientations ranging from 0° to 90°. The study was carried out using an innovative experimental setup known as Reality Water–Structure–Earthquake Interaction Test (RWSEIT), along with a detailed three-dimensional numerical model to validate the experimental results.

Various parameters such as water depth, current velocity, wave characteristics, earthquake amplitude, and structural orientation were considered to evaluate their influence on structural behaviour. The analysis included measurement of peak displacement and peak acceleration of the pile-supported bridge pier under different loading conditions. The results showed that fluid–structure interaction (FSI) plays a significant role in influencing the dynamic response of coastal pile foundations, and the effect becomes more critical when combined with seismic forces. It was observed that structural orientation greatly affects displacement and acceleration response, with certain angles producing higher dynamic amplification. The numerical model results closely matched the experimental findings, confirming the accuracy of the modelling approach. The study concluded that combined effects of wave, current, and earthquake loads must be considered in the design of coastal bridge pile foundations, and proper orientation of structure can significantly improve stability and performance under dynamic loading conditions.

[12] Analysis of the Influence of Deep Foundation Excavation on Adjacent Viaduct Pile Foundation Considering Train Dynamic Loads (2023) By Xiaohua Bao, Zilong Cheng, Chuang Lv, Jun Shen, Xiangsheng Chen and Hongzhi Cui – Analysed the effect of deep foundation excavation on nearby viaduct pile foundations considering the influence of train-induced dynamic loads using finite element modelling techniques. The study developed a detailed three-dimensional numerical model incorporating soil behaviour using the modified Cam-Clay model, and evaluated the interaction between excavation, soil, and pile foundation under different working conditions. Six different cases were analysed considering variations in excavation depth and train dynamic loading. The analysis focused on parameters such as soil settlement, horizontal displacement of piles, bending moment, and internal forces. The results showed that excavation significantly affects the stability of surrounding soil and pile foundation system, and the presence of train dynamic load further aggravates the deformation behaviour. It was observed that soil settlement increases by approximately 49% under train loading, while horizontal displacement at pile top increases up to 51%. The study also revealed that dynamic loading increases negative bending moments in piles, leading to higher structural stress. The research concluded that combined effects of excavation and dynamic loads must be carefully considered in urban infrastructure projects to ensure safety and prevent damage to adjacent bridge pile foundations.

[13] Structural Analysis of Bridges and Pile Foundation Subjected to Seismic Loads (2022) By Rajesh Kumar Singhal and Pradyumna Dashora – Analysed the structural performance of bridge and pile foundation systems under seismic loading conditions using numerical modelling techniques. The study focused on evaluating the effect of different pile foundation materials such as structural steel, carbon fibre reinforced steel, and epoxy fibre reinforced steel on the dynamic behaviour of bridge structures. Finite element modelling was carried out using ANSYS software, where soil–structure interaction was also considered to simulate realistic conditions. The analysis evaluated parameters such as nodal displacement and vibration response under seismic loading. The results showed that material properties significantly influence the structural response, with carbon fibre reinforced steel exhibiting better performance in terms of reduced displacement and improved structural stability compared to other materials. It was observed that maximum nodal displacement was lowest for carbon fibre structural steel and highest for conventional structural steel. The study concluded that selection of appropriate material for pile foundation plays a crucial role in improving seismic performance and durability of bridge structures.

Advancing Knowledge Across Disciplines

[14] A Substructure Approach for Analyzing Pile Foundation and Soil Vibrations due to Train Running over Viaduct and its Validation (2022) By Ying Wu, Xuecheng Bian, Chong Cheng and Jianqun Jiang – Analysed the vibration response of pile foundation and surrounding soil due to train-induced dynamic loads acting on viaduct structures using a substructure-based computational approach. The study developed a coupled train–viaduct–pile foundation–soil interaction model, where the train–viaduct system was solved using dynamic stiffness integration method, and the pile–soil system was simplified using Fourier decomposition technique. The three-dimensional interaction problem was reduced into multiple two-dimensional axisymmetric finite element models for efficient computation. The model incorporated equivalent stiffness of pile groups and considered displacement compatibility at the interface of pier and pile foundation. The results were validated using field measurements obtained from vibration testing on actual railway systems. The study showed that the proposed method accurately predicts vibration behaviour of pile foundations and surrounding soil. It was observed that vibration frequencies at the pier top are generally below 100 Hz, while ground surface vibrations are below 30 Hz. The study concluded that the developed substructure approach is effective for analysing dynamic interaction and can be used for predicting vibration-induced settlement and environmental impact in high-speed railway bridge systems.

[15] Dynamic Analyses of Pile-Supported Bridges Including Soil-Structure Interaction under Stochastic Ice Loads (2020) By Tianyu Wu and Wenliang Qiu – Analysed the dynamic response of pile-supported bridge structures subjected to stochastic ice loads considering soil–structure interaction using advanced finite element modelling techniques. The study developed a comprehensive bridge analysis model based on real stochastic ice load spectrum to simulate the random nature of ice forces acting on offshore bridges. Soil behaviour was modelled using API-based cyclic p–y, t–z, and Q–z spring models to represent pile–soil interaction accurately. The dynamic analysis was carried out in the time domain to evaluate structural response parameters such as displacement, vibration, and internal forces under varying environmental conditions. The study also investigated the influence of important factors such as undrained soil strength and water depth on the dynamic performance of bridge structures. The results showed that bridges located in deep water experience significantly higher dynamic responses compared to those in shallow water conditions. It was observed that soil–structure interaction plays a crucial role in influencing vibration characteristics and cannot be neglected in analysis. The study concluded that stochastic ice loads are critical for offshore bridge design, and advanced dynamic analysis is necessary to identify the most critical loading conditions and ensure structural safety.

[16] Study on Dynamic Behavior of Bridge Pier by Impact Load Test Considering Scour (2020) By Myungjae Lee, Mintaek Yoo, Hyun-Seok Jung, Ki Hyun Kim and Il-Wha Lee – Investigated the dynamic behaviour of bridge piers using impact load testing while considering the effect of scour around the foundation. The study involved both full-scale model testing and field experiments, where impact loads were applied in different directions such as along bridge axis, pier length, and outside direction to study structural response. The effect of surcharge load ranging from 0 to 250 kN and simulated scour depth of 1 m was also analysed. Acceleration response was recorded using sensors, and natural frequencies were determined using Fast Fourier Transform (FFT) analysis. The results showed that scour significantly reduces the natural frequency of the pier, indicating loss of stiffness and stability. It was observed that the first vibration mode is highly affected by both surcharge load and scour condition, while the second mode helps in evaluating structural stability and the third mode indicates direction of scour. The study concluded that dynamic testing methods can effectively detect early damage and instability in bridge pier foundations and emphasized the importance of considering scour effects in design and maintenance of bridge structures.

[17] Dynamic Analysis of Metro Rail Bridge Subjected to Moving Loads Considering Soil–Structure Interaction (2018) By Hitesh Bhure, Gayatri Sidh and Anand Gharad – Analysed the dynamic response of metro rail bridge structures subjected to moving loads by considering soil–structure interaction using finite element modelling techniques. The study modelled the bridge superstructure, piers, and substructure using shell elements, while rails and piles were modelled using frame elements in SAP2000 software. Two different models were analysed, namely fixed base model and complete pile foundation model, to compare the influence of soil flexibility on structural response. The interaction between deck and piers was simulated using link supports, and soil stiffness was evaluated based on IS 2911:2010 provisions. Dynamic analysis was performed using the Newmark-β method, considering a damping ratio of 5%. The results showed that train speed is a very important parameter influencing the dynamic response of the bridge structure. It was observed that resonance occurs at lower speeds in the pile-supported model compared to the fixed base model due to soil flexibility effects. The study concluded that proper consideration of soil–structure interaction and moving load effects is essential for accurate prediction of bridge behaviour, and full three-dimensional dynamic analysis is necessary for safe and efficient design of bridge structures under moving load conditions.

[18] Dynamic Interaction between Bridge Pier and its Large Pile Foundation Considering Earthquake and Scour Depths (2016) By Yan Xu, Yu Shang and Aijun Ye – Analysed the dynamic interaction between bridge pier and large pile foundation considering the combined effects of earthquake loading and scour depth using a simplified two-degree-of-freedom analytical model. The study focused on understanding how scour, which increases the unsupported length of piles, affects the dynamic characteristics and seismic performance of bridge substructures. The analysis evaluated parameters such as vibration period, resonance behaviour, and lateral load capacity of the pile-supported bridge system. The results showed that scour significantly alters the dynamic response by increasing flexibility and reducing lateral load carrying capacity of the foundation. It was observed that the presence of large pile cap mass contributes to strong resonance effects between the pier and pile foundation system under seismic loading. The study also proposed an approximate method to determine the most critical equivalent pile length considering scour depth, which helps in identifying worst-case seismic conditions. The methodology was validated using an actual bridge case study, confirming its accuracy and practical applicability. The study concluded that the effect of scour must be carefully considered in seismic design of bridge pile foundations, as it plays a major role in influencing dynamic response and structural safety.

[19] Effect of Soil–Foundation–Structure Interaction and Pier Column Non-Linearity on Seismic Response of Bridges Supported on Shallow Foundations (2016) By Muhammad Tariq A. Chaudhary – Analysed the seismic response of bridge structures considering the combined effects of soil–foundation–structure interaction (SSI) and non-linear behaviour of pier columns using finite element modelling techniques. The study was carried out on a four-span bridge model subjected to different ground motion records and varying rock conditions. Soil interaction was simulated using Winkler spring approach, while the non-linear behaviour of reinforced concrete pier columns was represented using an equivalent linear model. The analysis evaluated key response parameters such as displacement, base shear, and overall structural behaviour under seismic loading conditions. The results showed that soil–foundation–structure interaction plays a significant role and cannot be neglected, especially under certain soil and rock conditions. It was observed that pier column non-linearity has a more dominant effect on structural response compared to SSI, particularly in terms of displacement and base shear. The study also investigated the effect of foundation rocking, which was found to have minimal influence due to high rocking stiffness of properly designed foundations. The research concluded that both SSI and structural non-linearity must be considered in seismic analysis for accurate prediction of bridge behaviour and safe design.

[20] Networked Pseudodynamic Testing of Bridge Pier and Precast Pile Foundation (2012) By Y. Xiao, Y.R. Guo, P.S. Zhu, S. Kunnath and G.R. Martin – Investigated the seismic response of bridge pier and precast concrete pile foundation using an advanced networked pseudo-dynamic testing approach. The study utilized an internet-based platform called NetSLab, which connects different laboratories and computational systems to perform hybrid simulations combining numerical modelling and physical testing. In this research, the bridge pier column was analysed numerically, while a full-scale prestressed precast pile model was tested physically under simulated earthquake loading conditions. The analysis considered moment distribution along the pile and ignored pile group effects for simplification. The results showed that seismic loading can cause significant damage in precast pile foundations, especially due to sudden spalling of thick concrete cover, which leads to unstable structural response. It was observed that near-fault earthquake motions produce more severe effects compared to far-field ground motions. The study also demonstrated that hybrid testing techniques provide more realistic and accurate results compared to conventional methods. The research concluded that proper seismic design and detailing of pile foundations is essential to avoid failure, and advanced testing methods like networked pseudo-dynamic testing can significantly improve understanding of structural behaviour under earthquake loading.

[21] Seismic Response Analysis of the Large Bridge Pier Supported by Group Pile Foundation Considering the Effect of Wave and Current Action (2008) By Bai De-gui, Chen Guo-xing and Wang Zhi-hua – Analysed the seismic response of large bridge piers supported by group pile foundations considering the combined effects of wave and current forces using three-dimensional finite element modelling in ABAQUS software. The study modelled the pile–soil–pier system with soil represented using nonlinear viscous-plastic elements and piles represented using beam elements incorporating dynamic plastic damage behaviour of concrete. Hydrodynamic forces were applied using Morison's equation along with Stokes fifth-order wave theory to simulate wave action. The analysis evaluated response parameters such as displacement, acceleration, shear force, and bending moment under seismic loading combined with water forces. The results showed that wave and current actions significantly increase the peak values of displacement, shear force, and bending moment in pile foundations, while having relatively less effect on acceleration response. It was observed that wave height influences the seismic response depending on earthquake characteristics, whereas current velocity has a strong effect on displacement behaviour, increasing displacement in the flow direction and reducing it in the opposite direction. The study concluded that combined wave and current effects must be considered in seismic analysis and design of bridge pile foundations, especially for large structures located in water bodies.

III. RESEARCH GAP

From the detailed review it is clearly observed that a large number of studies have been carried out on bridge pile foundations under different types of loading conditions such as seismic loads, hydrodynamic forces, impact loads, and train-induced dynamic loads. Many researchers have successfully used advanced tools like finite element analysis to study soil–structure interaction, vibration characteristics, and stress distribution in pile-supported bridge systems. However, despite the extensive research available, there still exist several important gaps which need further investigation, especially in the context of modern bridge engineering where loading conditions are becoming more complex and demanding. One of the major research gaps identified is the lack of comprehensive studies on combined dynamic moving load and induced vibration effects on pile foundations. Most of the existing studies focus either on

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seismic loading or on moving loads such as train or vehicle loads independently. Very few studies consider the combined effect of moving loads along with induced vibration and dynamic amplification on bridge pile foundations. In real-life conditions, bridges are subjected to continuous moving traffic loads which generate vibrations, and these vibrations interact with the foundation system. This combined behaviour is not fully explored in previous research, leading to a gap in understanding the actual field performance of bridge pile foundations. Another important gap is related to limited consideration of realistic soil–structure interaction under dynamic loading conditions. Although many studies include soil–structure interaction using simplified models such as Winkler springs or linear elastic soil assumptions, the actual behaviour of soil is highly nonlinear and time-dependent. The influence of soil damping, hysteresis behaviour, and variation in soil properties with depth is often neglected or simplified. Therefore, there is a need for more detailed modelling of soil behaviour under dynamic and moving loads to achieve accurate prediction of structural response.

It is also observed that most research works are focused on either single pile or simplified pile group models, while in actual bridge construction, complex pile group configurations are used.
The interaction between piles within a group, known as pile group effect, significantly influences load distribution, settlement, and vibration characteristics. However, this effect is not adequately addressed in many previous studies, especially under dynamic moving load conditions. This creates a gap in understanding the behaviour of real bridge foundations under actual field loading. Another significant gap is the limited research on frequency-based analysis and resonance behaviour of pile foundation systems under moving loads. Some studies have discussed natural frequency and vibration modes, but the relationship between moving load frequency, structural natural frequency, and resonance conditions is not fully explored. In modern bridges, where high-speed vehicles or trains are involved, resonance can lead to excessive vibration and possible structural damage. Hence, there is a need for detailed investigation of resonance effects in pile-supported bridge systems.

In addition, experimental validation of numerical models is limited in many studies. While finite element modelling provides powerful tools for analysis, the accuracy of results depends on validation through field data or laboratory experiments. Many studies rely only on simulation results without proper validation, which reduces the reliability of conclusions. Therefore, there is a need for more experimental studies or field monitoring data to validate analytical and numerical models. Another gap is the lack of integrated analysis considering multiple real-life loading conditions simultaneously, such as moving load, vibration, seismic effect, and environmental loads like water flow or temperature variation. Most of the existing research considers these loads separately. However, in practical scenarios, bridge foundations are subjected to a combination of these effects, which may lead to more critical conditions than individual loads. This indicates the necessity of developing a comprehensive analysis approach that considers multiple loading conditions together. Furthermore, it is found that material behaviour and advanced construction materials for pile foundations are not extensively studied under dynamic conditions. Although some research has compared different materials, there is still a need to evaluate modern materials such as fibre-reinforced composites under dynamic and vibration loading to improve structural performance and durability. Finally, a major gap lies in the application of advanced finite element techniques for dynamic moving load analysis with realistic boundary conditions and full 3D modelling. Many studies use simplified models to reduce computational effort, but this may lead to inaccurate results. With the advancement of computational power, it is now possible to perform detailed 3D simulations, which are still underutilized in this field.

Conclusion of Research Gap:
From the above discussion, it can be concluded that although significant research has been carried out in the field of bridge pile foundation analysis, there is still a strong need for:
1. Combined study of moving load and induced vibration
2. Advanced modelling of soil–structure interaction
3. Consideration of pile group behaviour
4. Detailed frequency and resonance analysis
5. Integration of multiple loading conditions
6. Use of advanced materials and 3D FEM modelling
7. Proper experimental validation

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CONCLUSION

From this review study, the following conclusions are drawn:
1. Bridge pile foundations are highly affected by dynamic loads
2. Soil–structure interaction plays a critical role
3. Moving loads and vibration are important but less studied together
4. Advanced materials improve structural performance
5. FEM is a powerful tool but requires validation
6. Combined loading analysis is necessary for realistic design

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