

Review

Review of Dynamic Response and Pier Damage Mechanisms in Girder Bridges Under Bidirectional Seismic Excitations: Critical Role of Vertical Components in Near-Field Effects

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Abstract

This paper systematically reviews bridge structural dynamics and pier damage mechanisms under seismic excitation over recent decades, addressing four key aspects: (1) the structural response of simply supported bridges subjected to horizontal seismic forces and corresponding damage in shear keys and piers; (2) the impact of near-fault vertical ground motion on vertical constraint degradation and its contribution to pier damage; (3) the failure mechanisms of piers under bidirectional coupled seismic excitations; (4) recent advances in innovative design concepts, structural configurations, and material applications for seismic-resistant piers. Eventually, the limitations of current research are identified, and potential future research directions and methodologies are proposed.

Keywords: girder bridges; near fault vertical earthquake; bidirectional coupled seismic excitations; pier damage



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1. Introduction

Bridge piers, as primary load-bearing components in bridge systems, not only directly disrupt transportation networks but also severely impede post-earthquake emergency response operations. Historical evidence from major seismic events consistently demonstrates that rehabilitating severely damaged bridges involves complicated and time-consuming reconstruction processes, thereby resulting in substantial economic losses and increased social management burdens. The earliest documented case of bridge seismic damage occurred during the 1906 San Francisco earthquake, when the Pajaro Railway Bridge became inoperable due to significant horizontal displacement and torsional failure of its piers. Similarly, five other bridges lost functionality as piers slid toward the river centers, combined with either horizontal displacement or torsional failure [1]. The 1948 Fukui earthquake damaged 247 bridges, including four complete collapses. Post-earthquake analysis identified substructure failure, particularly pier overturning, as the primary damage mechanism. Although the girders underwent substantial displacements, adequate support lengths prevented more severe failures, such as unseating [2]. During the 1964 Niigata earthquake in Japan, extensive soil liquefaction triggered significant damage to the Showa Highway Bridge. Liquefaction-induced sliding of the left bank caused significant pier displacement, leading to bending failure of two central

piers, with one exhibiting 93 cm residual displacement and the collapse of five of the bridge's twelve spans. Subsequently, the 1995 Great Hanshin Earthquake witnessed the bending failure of reinforced concrete piers on the Fukae section of the Hanshin Expressway, which triggered the progressive collapse of 18 consecutive bridge spans [3]. Similar failure patterns emerged during the 2008 Wenchuan earthquake, particularly near the fault zone. A survey of 1657 bridges revealed that girder bridges accounted for 1370 cases (82.7%), with over 16% sustained moderate-to-severe damage characterized mainly by girder falling and pier failure [4,5]. These cases underscore two fundamental imperatives in bridge seismic design: structural safety preservation through ductile detailing and capacity-protected components during seismic events and enabling rapid functional recovery through repairable damage control and modular construction. This approach is essential for enhancing regional disaster resilience and optimizing post-disaster reconstruction, thereby mitigating socioeconomic disruptions.

Existing research establishes a relatively comprehensive theoretical framework and design specifications for the seismic performance of bridge structures under horizontal ground motions. However, significant deficiencies remain in addressing vertical seismic actions primarily due to two cognitive limitations: (1) The conventional assumption that the peak vertical ground acceleration (PGA) typically constitutes only 30–60% of the horizontal component ($V/H = 0.3\text{--}0.6$), implying its effects are adequately covered within the safety margin of structural vertical bearing capacity [6,7]. (2) Current seismic design codes (e.g., Turkish Earthquake Code TEC-1998 and GB50011-2010) are predominantly based on far-field earthquake statistics, with only limited provisions for near-fault ground motion effects and corresponding design methodologies available in a few national standards, such as the United States, Europe, and Japan [8–11]. These specifications also fail to adequately account for the potential for vertical ground motions to exceed horizontal components in near-fault regions.

However, post-earthquake investigations and computational simulations conducted over the past three decades have revealed that vertical seismic actions can significantly exacerbate horizontal pounding forces and increase pier damage risks through three mechanisms: (1) inducing girder–bearing separation [12–14]; (2) amplifying axial force fluctuations in piers [15–18]; (3) altering structural dynamic characteristics [14,19]. These critical dynamic coupling effects remain overlooked in contemporary seismic design frameworks.

This study systematically reviews research progress in the seismic design for bridge piers, examining structural responses and failure mechanisms under horizontal, vertical, and bidirectional coupled seismic excitations. It comprehensively summarizes the development trends in seismic mitigation and isolation techniques for bridge piers from the perspectives of materials, structural, and technological applications. Meanwhile, current seismic analysis methods tend to underestimate the risk of bearing–girder separation induced by vertical seismic components, leading to insufficient prediction of amplified transverse pounding forces. To address this limitation, this paper proposes an integrated analytical framework and validation methodology designed to accurately quantify these interaction effects. The findings contribute to enhancing the seismic performance assessment system for bridge piers by incorporating essential critical vertical excitation-induced interactions. The organizational framework of this review is shown in Figure 1.

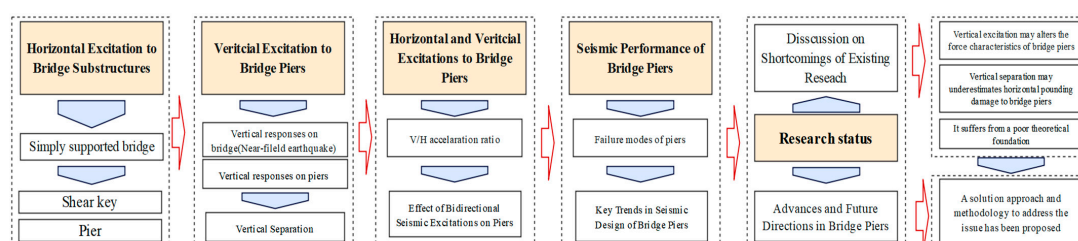


Figure 1. Framework of this review.

2. Impact of Horizontal Seismic Excitation on Bridge Substructure

Under horizontal seismic excitation, the seismic resistance of highway and railway bridges predominantly hinges on the synergistic interaction among pier-bearing-shear key assemblies (Figure 2). This collaborative mechanism serves to constrain girder displacement and prevent unseating failure. Specifically, bearings generally exhibit failure prior to primary structural members. Following damage, significant relative displacement ensues between the superstructure and substructure. To mitigate transverse unseating or misalignment, shear keys are conventionally installed on both sides of bridge abutments and bent caps. Nevertheless, owing to the limited structural dimensions of shear keys, they are typically regarded as “secondary components” within the bridge systems. Consequently, seismic analyses of bridge structures overlook the ramifications of damage occurring proximity to shear keys [20,21]. Field observations from actual seismic damage reveal that when horizontal seismic excitation intensity exceeds the design threshold, the pounding force between shear keys and girders intensifies precipitously. This excessive impact force not only fails to effectively restrain girder displacement but also propagates amplified horizontal forces to piers through shear key collisions or bearings. This, in turn, precipitates severe cumulative damage in substructures [22,23].

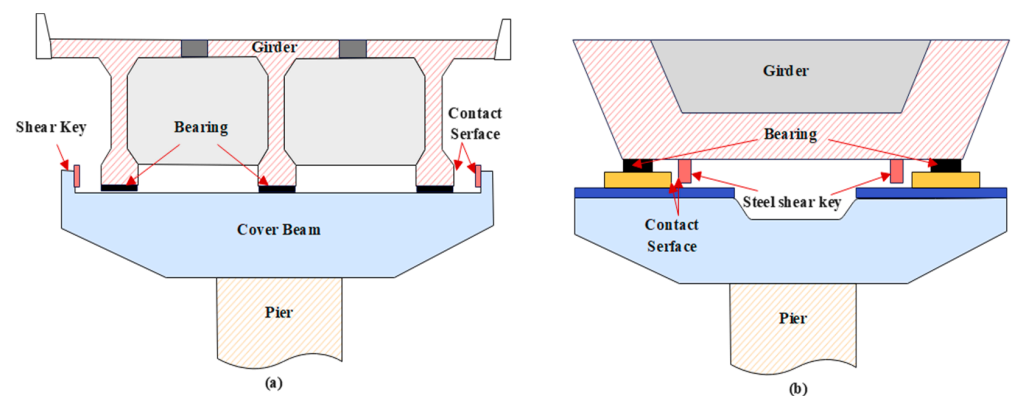


Figure 2. Arrangement of shear keys for highway and railway bridge (a) highway bridge; (b) railway bridge.

2.1. The Impact of Horizontal Seismic to Shear Keys

Under horizontal seismic excitation, the collision-induced damage in bridge structures primarily manifests through interactions between adjacent spans and the dynamic response of the girder–shear key system, with the collision mechanism between the girder and shear keys being particularly critical. As the core component for restraining transverse displacement, the design performance of shear keys directly influences the mitigation of girder unseating risks [24,25]. Historical seismic damage investigations have demonstrated the prevalent failure of conventional shear keys under strong earthquakes: During the 1994 Northridge earthquake, exterior transverse shear keys suffered extensive shear failures due to impact [26,27] (Figure 3a). The seismic damage analysis of over 5000 bridges during the 2008 Wenchuan earthquake revealed that brittle shear failure of shear keys was one of the typical failure modes [28] (Figure 3b). Some earthquake cases in Chile and Iceland further validated the severity of such failure [29,30] (Figure 3c). Currently, with the widespread application of elastomeric bearings in small-to-medium span girder bridges, this weak constraint significantly increases the risk of transverse unseating of the superstructure [31,32].



Figure 3. Various shear key seismic failures (a) Northridge Earthquake [33]; (b) Wenchuan Earthquake [28]; (c) Chile Earthquake [34].

2.1.1. Failure Models of Shear Key

In response to various seismic failure observed in shear keys, researchers have conducted extensive investigations. Megally et al. [24] pioneered experimental tests on 7 internal and 6 external shear keys designed as sacrificial components, identifying three distinct failure modes, diagonal tension failure (Figure 4a), flexural failure (Figure 4b), and sliding shear-friction failure (Figure 4c), along with corresponding bearing capacity calculation formulas. The influence of the depth-to-height ratio (α) and the reinforcement ratio on the bearing capacity of the shear key was investigated. The results indicate that the bearing capacity increases as α decreases.

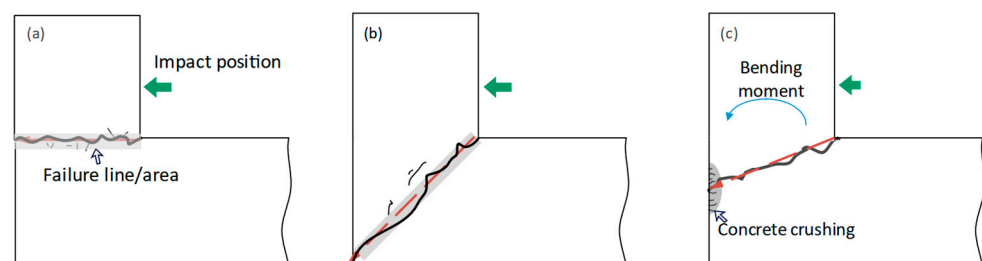


Figure 4. Three failure modes of the shear keys (a) diagonal tension failure; (b) flexural failure; (c) sliding shear-friction failure (redrawn based on [24]).

Building on above findings, Bozorgzadeh et al. conducted an in-depth investigation into the failure mechanisms of concrete exterior shear keys. Through experimental data from 12 reinforced concrete exterior shear key impact tests, they validated Megally's conclusions while performing a comparative analysis of failure mechanisms relative to reinforcement configurations, ultimately proposing specific optimization pathways [35]. Increasingly, researchers have conducted parametric tests on shear keys, yielding significant findings. Among these, Xu Lueqing et al. discovered through experiments on 6 groups of exterior shear keys that the longitudinal reinforcement ratio substantially influences bearing capacity, whereas reinforcement placement exhibits negligible effects [36]. Zheng et al. investigated the relationship between shear key bearing capacity and both thickness and stirrup configurations through quasi-static tests, revealing that bearing capacity increases proportionally with thickness; however, shear keys with open stirrups exhibit comparable ultimate strength yet are prone to brittle failure, consequently undermining seismic performance [37]. In contrast,

Xu Liangjin's test on 8 concrete shear keys revealed that height and bent cap horizontal reinforcement quantity exhibited negligible effects on ultimate bearing capacity [38]. Wang et al. experimentally demonstrated that for prefabricated reinforced concrete shear keys subjected to high-intensity seismic actions the probability of diagonal shear failure exceeds 80% [39]. Table 1 below summarizes relevant experimental research progress on shear key bearing capacity over the past three decades.

Table 1. Experimental study on shear key bearing capacity and influencing factors.

	Author(s)	Number of Specimens	Research Parameter(s)	References
1	Bozorgzadeh et al.	12	Reinforcement ratio and location	[35]
2	Zheng et al.	4	Thickness, stirrup and reinforcement ratio	[40]
3	Xu et al.	12	Longitudinal reinforcement ratio, loading height, and other factors	[36,41,42]
4	Xu Jinliang	8	Concrete strength, stirrup configuration	[38]
5	Kottari et al.	12	Location and smoothness of the sliding surface	[43]
6	Han et al.	12	Concrete strength, and horizontal tie reinforcement ratio and location	[44,45]
7	Meng et al.	4	Initial gap	[46]

Based on the experimental studies on shear keys, the following conclusions can be drawn: (1) The longitudinal reinforcement ratio exerts a significant influence on the shear key's bearing capacity. An increase in the longitudinal reinforcement ratio markedly enhances its load-carrying capability. (2) A strong correlation exists between the shear key's bearing capacity and the shear reinforcement ratio, with the capacity showing improvement as the reinforcement ratio increases. (3) Increases in both concrete strength and shear key thickness contribute to an enhanced bearing capacity; however, their impact on structural ductility remains limited. (4) The force transferred from the shear key to the cap beam or pile cap is primarily resisted by the horizontal tie reinforcement at the top of the cap beam. Sufficient horizontal tie reinforcement can effectively inhibit the propagation of diagonal cracks and prevent shear failure, although its strength has an insignificant effect on the ultimate bearing capacity of the shear key. (5) The prevailing view suggests that the bearing capacity of shear keys tends to decrease with an increasing loading height, although this perspective remains contentious. (6) No clear correlation has been established between the collision force exerted on shear keys and the initial spacing.

Ongoing investigation into the mechanical behavior of shear keys has led to the continuous development and emergence of diverse seismic damping and isolation technologies for these components. In 2001, Megally et al. pioneered the concept of sliding-type seismic shear keys, demonstrating superior energy dissipation capacity and post-earthquake repairability compared to monolithic shear keys, which has been widely adopted in engineering practice [24]. Concurrently, Fan et al. proposed a rubber-buffered shear key (Figure 5a) applied in Sichuan highway bridges, which validated its seismic resistance during the Wenchuan earthquake, China [47]. Adhering to the "multi-defense lines and staged energy dissipation" concept, Wang et al. designed dual-layer shear keys (inner and outer) (Figure 5b) and validated their efficacy via finite element analysis, demonstrating superior seismic performance [48]. Concurrently, based on shear key damage patterns observed in the Wenchuan earthquake, Xiang et al. proposed optimized friction-based energy-dissipating shear keys, which significantly reduced sensitivity to bearing friction coefficient variations while effectively restraining girder displacement compared to conventional reinforced concrete counterparts (Figure 5c) [49]. Bhuiyan et al. recommended an

energy-dissipating shear key directly utilizing Shape Memory Alloys (SMA) to leverage their superior energy dissipation capacity [50]. Simultaneously, Wu et al. developed prefabricated Ultra-High Performance Concrete (UHPC) shear keys, with full-scale experiments demonstrating that post-tensioned UHPC achieved 2.47 times the ultimate shear capacity of conventional RC counterparts while exhibiting minimal crack width and superior self-centering capacity (Figure 5d) [51].

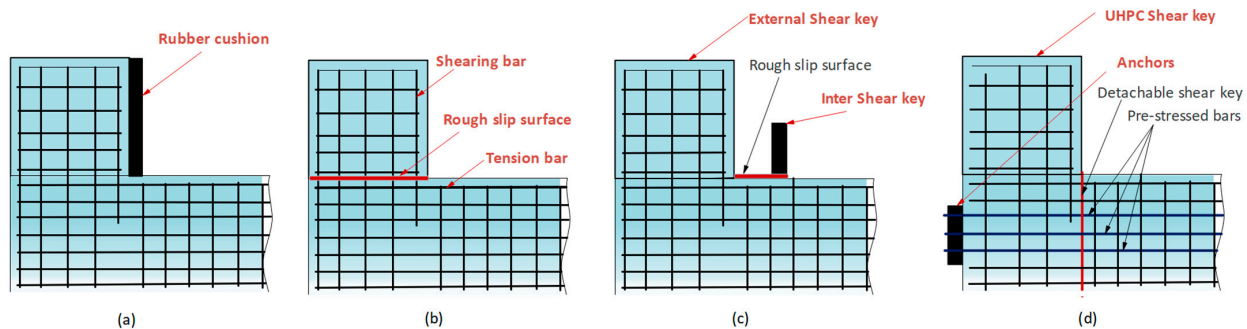


Figure 5. Forms of new shear keys (a) rubber-buffered shear key [47]; (b) dual-layer shear key [48]; (c) friction-based energy-dissipating shear key [49]; (d) UHPC shear key [51].

Beyond concrete shear keys, steel counterparts have gained increasing research attention owing to their plastic energy dissipation and ease of repair. The concept of utilizing steel damping devices for structural reinforcement and seismic isolation was initially proposed in the early 1970s [52]. Subsequent studies have proliferated, with emerging steel shear key types primarily categorized into three configurations: X-shaped steel shear keys, H-shaped shear keys, and steel plate shear keys (Figure 6). In 1991, Ciampi pioneered the use of steel structures as damping energy dissipation devices to protect bridges during earthquakes, prompting extensive testing of various dampers by subsequent researchers [53]. By 2011, Vasseghi proposed replacing traditional concrete shear keys with X-shaped steel shear keys for bridge reinforcement, experimentally demonstrating their superior seismic performance [54]. For H-shaped steel shear keys, Tang et al. conducted slotted connection tests on multiple configurations, revealing that double-row perforated stiffened shear keys exhibit significantly higher shear resistance than single-row perforated variants [55]. Zhu et al. leveraged the mechanical advantages of H-shaped to develop a novel H-shaped steel shear key, establishing theoretical bending-curvature-displacement relationships and validating them via finite element fitting, thereby advancing theoretical framework for shear key bearing capacity [56]. Wei et al. introduced an Equal Strength Mild Steel Tenons (ESMST) elastoplastic shear key, providing exceptional seismic resilience for railway bridges [57].

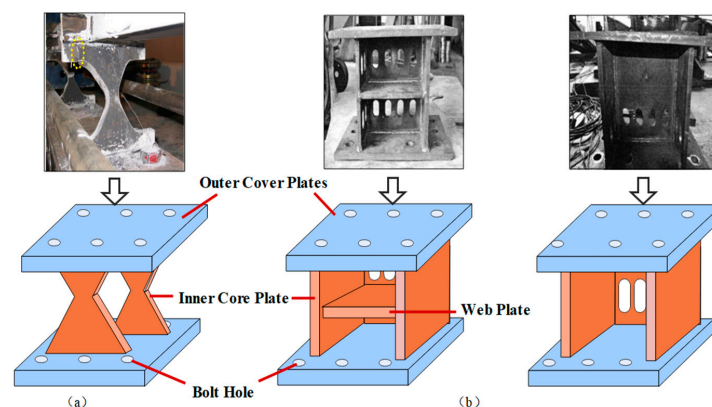


Figure 6. Structural drawing of X-shaped (a) and H-shaped (b) steel shear keys (redrawn based on [53–55]).

2.1.2. Seismic Shear Key Design Methodology in Earthquake-Prone Countries

As a “fusing” component in bridge seismic systems, restrainers effectively dissipate seismic energy through sacrificial failure mechanisms. Based on typical seismic damage characteristics and historical earthquake experiences, countries have proposed differentiated design requirements for shear keys. The United States has pioneered research on lateral impact behavior of shear keys, establishing a systematic and well-developed design framework. According to the South Carolina Department of Transportation (SCDOT) Highway Bridge Specifications, shear keys are categorized into concrete shear keys and steel shear keys, with distinct shear capacity requirements specified for each. Notably, the recommended dimensions of shear keys in the SCDOT specifications are significantly smaller than those in the California Department of Transportation (Caltrans) standards, making them unsuitable as standalone sacrificial components and necessitating supplementary seismic restraint measures [58]. The American Association of State Highway Officials (AASHTO) Bridge Design Specifications further clarify the “fuse” function of seismic shear keys, classifying them into internal and external shear keys and recommending external shear keys as the preferred choice for new constructions. Additionally, the specifications provide detailed load-bearing capacity requirements for shear keys at different structural locations [59]. The California Department of Transportation (Caltrans) specifications, based on experimental research by Megally et al. from the University of California [24,35], proposed a series of shear key parameter indicators and classified shear keys into two categories: seismic isolation type (sliding type) and non-seismic isolation type (integral type).

In light of the installation location of the shear key at the abutment/beam cap, the shear resistance capacity of integral type shear key must satisfy the following formula [60].

$$V_C = \left[0.75 \sum V_{pile}, \alpha P_{dl}^{\sup} \right]_{\min} \quad (1)$$

where $0.75 \sum V_{pile}$ is the sum of shear resistance of piles, $P_{dl}^{\sup}$ represents the axial permanent load effect of the abutment, satisfying $V_C = 0.3 P_{dl}^{\sup}$ when the spread footing is adopted.

For seismic isolation-type shear keys, the cross-sectional area of shear reinforcement (A_s) penetrating the contact surface and the quantity of horizontal stirrups on the bent cap surface shall satisfy:

$$\begin{aligned} A_{sk} &= V_C / (1.8 f_{ye}) \\ A_{sh} &= 2 A_{sk}^{iso} \quad (provided) \end{aligned} \quad (2)$$

where f_{ye} denotes as the shear capacity of shear reinforcements, and $A_{sk}^{iso} \quad (provided)$ is the area of shear reinforcements.

Additionally, the design provisions for shear keys are covered in the U.S. standards ASCE-7, ACI 318, and FHWA specifications [61–63].

In the 1972 Japanese “Specifications for Highway Bridges—Seismic Design with Commentary”, anti-unseating devices were mandated by requiring limiters at beam ends to prevent girder collapse. Following the 1995 Great Hanshin Earthquake, the updated Specifications for Highway Bridges—Part V: Seismic Design with Commentary emphasized holistic structural seismic performance, classifying continuous beam connections and bearings as primary structural components. This revision specifically addressed connection integrity between girders, girders and abutments, and girders and piers [64].

Connection methods between beams and abutments or bearings, as specified in the *New Zealand Bridge Manual* (1994), include connection bolts, shear keys, and specially designed bearings, which shall be selected based on design requirements [65]. Elastomeric bearings with shear bolts are not recommended. When loose connections are adopted between girders and bearings, lateral restraint devices must be provided.

As a seismically active country, China has accumulated extensive experience in seismic engineering; however, the design of bridge shear keys has long been underemphasized. The current Specifications for Seismic Design of Highway Bridges (JTG/T B02-01-2008) only mandates transverse displacement control measures for simply supported and continuous girder bridges in regions with seismic fortification intensity of VII degrees or higher, without specifying detailed design methodologies [66]. Similarly, while the Code for Seismic Design of Railway Engineering (GB 50111-2006) mandates the installation of shear keys in seismic zones to prevent girder unseating, it fails to provide specific design parameters or detailed construction specifications [67].

A comparative analysis of seismic design standards across multiple seismic-prone nations reveals that, apart from systematic provisions for shear key bearing capacity calculations and failure mechanisms in codes such as the AASHTO (Washington, DC, USA), most countries still exhibit systematic deficiencies in shear key design specifications, urgently requiring refinement of their technical guidance systems (refer to Table 2).

Table 2. Comparative analysis of shear key (retraining block) design provisions in seismic codes of earthquake-prone countries and regions.

Country /Region	Design and Structural Requirements of Shear Key (Retaining Block)				
	Constructional Measure	Design of Classification	Bearing Capacity	Layout of Reinforcement	Other Requirements
American	√	√	√	√	√
Japan	√	√	—	—	—
China	√	—	—	—	—
New Zealand	√	—	—	—	—
European Union	√	—	—	—	√

Note: “√” indicates “present”; “—” indicates “absent”.

2.2. The Impact of Horizontal Seismic to Bridge Piers

Although shear keys effectively restrain girder displacement, excessive horizontal collision forces can significantly amplify shear forces and bending moments at pier bases, thereby increasing the risk of pier damage [22]. Early research has confirmed that this collision issue primarily stems from the relative sliding effect caused by insufficient constraint between rubber bearings and pier caps in highway girder bridges during earthquakes [10,13,31,47,68].

In 2007, Nielson et al. conducted numerical analyses on various types of girder bridges (steel and RC girder bridges), revealing that transverse seismic excitation significantly influences bridge responses. Specifically, the stiffness of fixed bearings critically affects pier ductility, and they proposed critical stiffness thresholds for these bearings [69]. Concurrently, Fan Lichu et al. experimentally analyzed the mechanism of lateral sliding between girders and piers, preliminarily establishing dynamic response patterns and structural impacts of laminated rubber bearings during sliding [10,47]. Wang et al. investigated extensive bridge seismic damage cases, demonstrating that excessive transverse restraint by shear keys not only fails to mitigate girder displacement but also adversely affects piers. Researchers identified the strong constraint from shear keys as the primary cause of diagonal cracks in piers of the Baihuahu bridge during the Wenchuan earthquake [70,71]. Xu et al. noted that the stiffness of shear keys significantly exceeds that of laminated rubber bearings. Consequently, researchers recommended modeling the transverse connection as a fixed constraint in analytical frameworks [72]. Meng et al. conducted shake-table tests on a 1:6-scale model of 32 m standard-span high-speed railway simply supported bridge. The

results demonstrated that transverse pounding effectively restricts relative displacement between the girder and shear keys, yet amplifies the bending moment response at pier bases and the acceleration response of the girder by over 50% [46]. Li et al. investigated the interaction between shear keys and bearings in a multi-span continuous bridge, revealing that shear key strength markedly amplifies internal forces in short piers, with shorter piers exhibiting greater sensitivity to variations in shear key strength [73]. Similarly, Pi et al. analyzed coupling relationships through a bearing-shear key-pier interaction model, concluding that shear key design strength should not be excessively increased for short piers [74]. Subsequently, Ma et al. conducted finite element simulations to investigate the effects of restraint shear keys on highway continuous bridge piers, with results indicating that such restraints amplify seismic forces in piers, thereby increasing their vulnerability to earthquake-induced damage [75]. Table 3 summarized the current research progress on the influence of shear keys on pier damage.

Table 3. Factors influencing the failure of shear keys.

Author(s)	Research Model(s)	Factors	References
Wang et al.	Baihuahu Bridge	Excessively high strength of shear keys can adversely affect the piers	[70,71]
Meng et al.	A 1:6-scale model of high-speed railway simply supported bridge	Transverse shear keys effectively restrain girder displacement; but significantly increases the bending moment at the pier bottom.	[46]
Li et al.	Typical highway simply supported box girder bridges in China	Short piers are more sensitive to variations in shear key strength	[73]
Pi et al.	Shoujiang Bridge	For short piers, the design strength of shear keys should not be excessive.	[74]
Ma et al.	High-intensity seismic zone typical highway 5 span continuous girder bridge	The strength of shear keys should be maintained within a reasonable range; otherwise, it may increase the probability of pier damage	[75]

With the advancement of artificial intelligence Nettis et al. systematically investigated the seismic performance of seismically isolated bridges subjected to pre-existing differential ground displacements, such as those induced by landslides. The research quantitatively assessed the impact of various displacement scenarios on the residual deformation capacity of elastomeric bearings. Notably, it provided the first systematic validation of the significant increase in bridge fragility and risk under multi-hazard coupling effects [76]. Di Mucci et al. proposed an integrated computer vision and probabilistic analysis framework for assessing corrosion in reinforced concrete (RC) bridge piers and introduced BriCANet, a neural network capable of automatically identifying corrosion levels from images. A fiber model incorporating non-uniform corrosion was developed to quantify the degradation in seismic performance. Furthermore, an incremental seismic risk indicator ($\Delta\lambda_c$) was proposed to evaluate corrosion-induced risk elevation. Case results demonstrated that severe corrosion could increase the seismic risk of piers by up to 598%, highlighting the framework's potential for advancing fragility analysis of corroded RC piers under seismic conditions [77]. Zheng et al. proposed a near-fault pulse-type bridge response and fragility analysis method based on a Long Short-Term Memory (LSTM) network. This approach captures the nonlinear mapping between pier bending moments, pier bottom curvatures, and pier top displacements, enabling rapid prediction of structural response indicators under long-duration and multi-output conditions. Their method significantly reduces prediction time (1 s versus 66 h), providing robust theoretical support for post-disaster bridge assessment [78].

2.3. Seismic Resistance and Strengthening of Girder Bridges

In response to potential seismic damage to the substructure of bridges, the mainstream methods are installing rubber cushioning layers or steel restrainers can reduce impact loads transmitted to shear keys and piers [54,79,80]. Alternatively, structural reinforcement—such as strengthening connections between girders and bearings, enlarging pier cross-sections, or increasing reinforcement—may enhance resilience [81]. However, robust girder–bearing connections (i.e., strong connections) may induce plastic deformation in piers during strong earthquakes. Without sufficient reverse acceleration, piers cannot revert to equilibrium [82]. Furthermore, pier reinforcement compromises aesthetics, elevates costs, and alters dynamic characteristics [83].

Therefore, for distinct bridge systems, seismic fortification measures should be tailored by considering both the seismic capacity and inherent vulnerabilities of each bridge type. For example, in girder bridges, particularly continuous girder bridges, the arrangement of fixed piers and variations in pier heights lead to significant disparities in the horizontal lateral resistance stiffness among individual piers. During seismic events, this stiff imbalance can result in a severely uneven distribution of seismic forces, thereby exacerbating stress concentrations. To mitigate this risk, the installation of a Voltage Limiting Device (VLD) is often recommended to harmonize the horizontal force distribution among piers, thereby enhancing uniformity in internal force allocation. In 2009, Li et al. proposed a damping tenon specifically tailored for girder bridges. Based on the concept of functional separation of supports, this device transfers the horizontal forces from the girder to the damping tenon, which absorbs energy and mitigates impact through plastic deformation, thus protecting the pier structures effectively [21,84,85]. Subsequent research has further advanced the development and application of damping tenons, leading to variants such as tenon-shaped anti-falling devices, which have been widely implemented in simply supported railway bridges located in high-seismic-intensity zones [86–89]. In addition to damping tenons, other structural and material-based seismic measures have garnered significant attention. These include: (1) structural measures such as adding concrete cap beams [90], increasing the span between bearings, installing compression-tension bearings [91], and implementing pier–girder rigid connections to improve overall stability [92]; seismic isolation and energy dissipation techniques, for instance, using friction pendulum bearings or lead-rubber bearings to prolong the structural period or dissipate seismic energy [93–96]; (2) advanced material reinforcements like Ultra-High Performance Concrete (UHPC) and Carbon Fiber-Reinforced Polymer (CFRP), which are employed to strengthen girders or piers, enhancing their seismic performance and damage tolerance.

Recently, seismic resilience assessment of girder bridges in high-intensity zones has become a focal point of research. By integrating systematic vulnerability analysis, functional loss quantification, and recovery modeling, scholars have established resilience evaluation frameworks that account for multi-component damage and repair processes. These frameworks provide a theoretical basis for optimizing the seismic performance of bridges throughout their life cycle [97–99].

2.4. Summary

Research on the horizontal seismic response of bridges has established a mature system—with theoretical, experimental, and numerical advancements yielding substantial achievements. Building on these, many countries have formulated specific design requirements for lateral restraint blocks, and the academic community has proposed corresponding mitigation strategies for secondary pier damage induced by transverse collisions. However, observations from near-field earthquakes over the past two decades reveal that the impact of vertical seismic components on piers can no longer be overlooked, presenting new challenges to seismic resilience research for bridge piers.

3. Impact of Vertical Seismic Excitation on Bridge Piers

Based on historical far-field seismic records, the peak acceleration of vertical ground motions is significantly lower than that of horizontal ground motions [100,101]. In structural design, vertical issues are predominantly attributed to static loads (e.g., self-weight and vehicle load), while the impact of vertical seismic forces is often overlooked. Consequently, bridge dynamics research has primarily focused on the transverse direction, with limited studies addressing vertical responses. However, over the past three decades, near-field earthquakes such as the 1987 Imperial Valley, 1989 Loma Prieta, 1995 Kobe, and 2008 Wenchuan earthquakes have recorded intense vertical ground motions, with amplitudes even exceeding horizontal counterparts by multiples [102–105]. This anomalous amplification of vertical ground motions has garnered widespread attention among researchers.

3.1. Vertical Responses of Bridge Structures

High-amplitude seismic excitations may induce vertical separation in girder bridge structures, characterized by disengagement between girders and cap beams or between girders and piers. The phenomenon of structural uplift attributed to vertical ground motions was initially documented during the 1899 Assam earthquake in India, where stones were observed being ejected into the air. Survivors of the Tangshan earthquake similarly reported witnessing debris propelled over distances exceeding 4 m [106]. During the Loma Prieta earthquake, recorded vertical ground accelerations attained 1.0 g, while observed damage pattern (the bridge piers penetrated the deck) in Struve Slough highway bridge piers indicated violent impact forces arising between superstructures and bearings under vertical seismic actions (Figure 7). A similar instance occurred during the 1995 Great Hanshin Earthquake in Japan, where the bridge bearings of the Nishinomiya bridge suffered severe damage due to immense vertical impact forces [107].



Figure 7. Vertical earthquake-induced phenomena at Struve Slough bridge in the Loma Prieta earthquake: (a) Collapse of bridge at Struve Slough [108]; (b) Detail of punching failure [109].

Based on analysis of structural dynamic responses recorded during three earthquakes, Papazoglou et al. demonstrated that vertical seismic forces may alter shear and bending behaviors in piers, potentially causing structural damage [110]. Bozorgnia et al. further indicated that high-amplitude vertical ground motions may induce uplift of ground objects [102,111]. Tanimura et al. identified the separation and subsequent pounding of bridge superstructures as the primary cause of damage to the Nielsen Bridge during the Kobe earthquake [112]. Xu et al. quantitatively verified the potential for multiple separation-collapse cycles between piers and girders through theoretical calculations neglecting bearing effects, providing critical theoretical validation for vertical separation phenomena [113]. Additionally, An et al. demonstrated that under coupled vertical-longitudinal ground motions, the loss of bearing constraints and altered natural frequencies after girder-pier sep-

ation significantly amplify longitudinal displacements in piers, exacerbating structural deterioration [14,114].

3.2. Vertical Responses on Bridge Piers

Vertical seismic excitations also adversely affect bridge piers [6,115], with primary damage mechanisms including: Vertical pounding-induced eccentric collisions [110,116] (Figure 8a; axial crushing of piers [31,112] (Figure 8b); unseating failures resulting from degraded girder–bearing contact [111,117] (Figure 8c); and upper pier and girder damage triggered by vertical seismic pounding [31,112] (Figure 8d). These damage patterns were extensively documented during the Northridge, Christchurch, Chi-Chi, and Loma Prieta earthquake. Such failures are attributed to amplified displacements and intensified pounding caused by the degradation of structural constraints between girders and piers under vertical excitations.



Figure 8. Seismic damage of bridge piers due to vertical seismic excitation (a) Vertical pounding-induced eccentric collisions [118]; (b) axial crushing of piers [119]; (c) unseating failures resulting from degraded girder–bearing contact [120]; (d) upper pier and girder damage triggered by vertical seismic pounding [118].

Despite mounting evidence indicating that proximity vertical excitations impose detrimental effects on structures, research on this phenomenon remains notably insufficient compared to horizontal seismic actions. Papazoglou and Elnashai pioneered systematic evidence on the significant destructive effects of strong vertical ground motions on building and bridge structures. Their core conclusion demonstrates that resonance phenomena occur when structural vertical vibration periods approach the predominant periods of ground motions, substantially amplifying dynamic responses (e.g., axial force fluctuations), thereby degrading component load-bearing capacity and ultimately triggering shear failure [110]. Subsequently, Warn et al. investigated the effects of vertical ground motions on bridge isolation systems through shake-table testing, likewise concluding that vertical deformations of isolation systems should not be neglected in seismic design [121]. In 2011, Kim and Holub tested two bridge pier specimens under horizontal (ICT) and horizontal–vertical seismic actions (ICC), demonstrating that vertical ground motions amplify axial force variations in the specimens. Accounting for vertical seismic contributions, substantial axial force fluctuations increased lateral stiffness and triggered up to 200% helical strain in the specimens. Consequently, these findings indicate that neglecting vertical seismic excitations leads to unconservative seismic safety assessments of structures [116]. Lee and Mosalam (2014) investigated the seismic response of bridge structures under bidirectional coupled excitations through shake-table

testing; the experimental results demonstrated that vertical excitation increases tensile stress in bridge piers, thereby reducing their shear capacity [122].

Theoretically, Xu et al. investigated vertical pounding phenomena between the deck and piers of a two-span continuous girder bridge under harmonic seismic excitation, employing transient wave eigenfunction theory without considering bearing effects (Figure 9a). This approach effectively elucidated the underlying mechanisms of such interactions [113,123]. Building upon this foundation, Yang et al. analyzed vertical separation-collision phenomena in two-span continuous bridges considering bearing participation effects (Figure 9b). The results demonstrated that when seismic amplitudes fall within a specific range and excitation frequencies approach any of the bridge's first three natural frequencies, the structure undergoes repeated vertical separation and collision events. Furthermore, under strong near-field vertical seismic excitation, axial compressive stress in piers exhibits high-amplitude fluctuations and may even transition to axial tensile stress. This phenomenon aligns with the abnormal damage characteristics of piers described earlier, necessitating consideration in seismic bridge design [12,13].

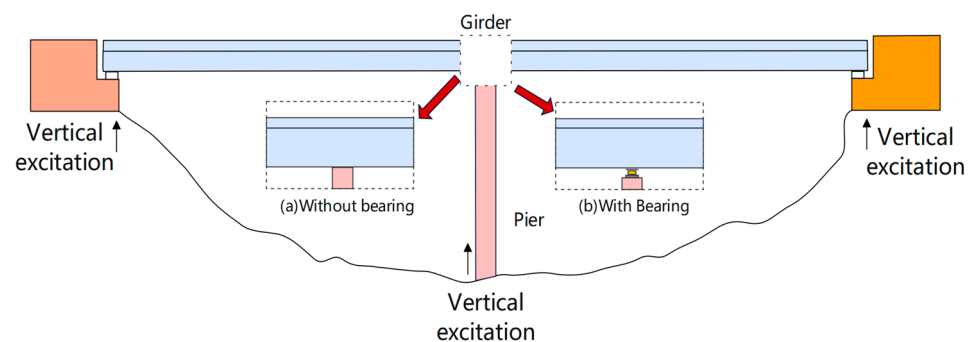


Figure 9. Vertical seismic response models of bridge structures: (a) without Bearings; (b) with Bearings.

3.3. Summary

This section reviews the dynamic responses of bridge structures under vertical seismic excitation, with a focus on summarizing existing research findings on pier damage induced by vertical collisions, stress redistribution, and changes in displacement responses—all triggered by vertical seismic components (Figure 10). Currently, the role of vertical seismic excitation has garnered widespread attention from the academic community. Building on the conclusions from the previous section regarding lateral seismic excitation, the coupled effects of vertical and lateral seismic actions have emerged as a prominent research focus.

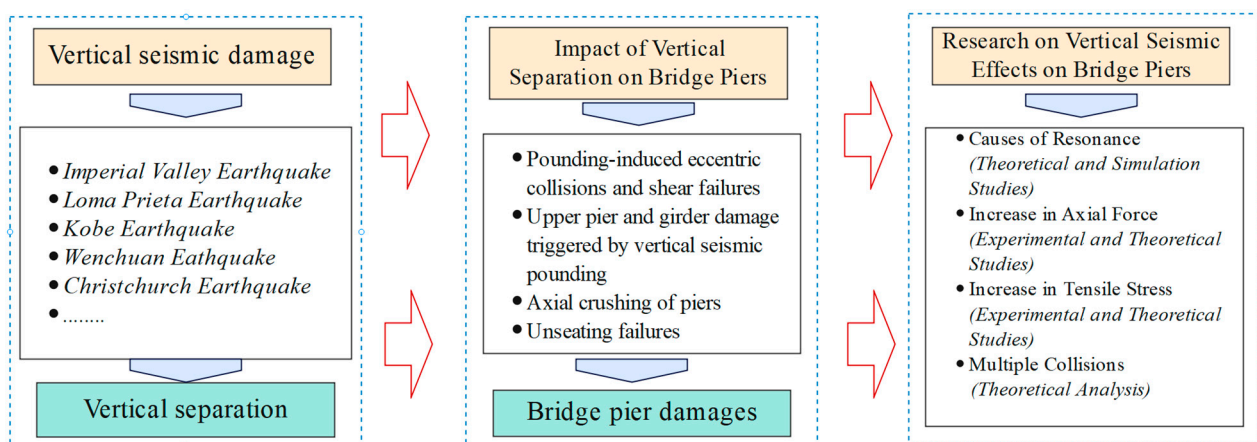


Figure 10. Framework of Section 3.

4. Impact of Horizontal and Vertical Seismic Excitations on Bridge Piers

As mentioned above, the connection state between the girder and bearings, along with the internal stress distribution within piers, undergoes significant changes under vertical seismic excitation. Consequently, the dynamic response and internal force distribution of bridge structures under lateral excitation may exhibit notable variations. Given the current limited research on bridge dynamic responses under bidirectional seismic excitation, this section systematically reviews existing findings from two aspects: the characteristics of near field ground motion and the impact of bidirectional seismic actions on piers.

4.1. The Characteristics of near Field Ground Motions

The most critical parameter characterizing near-field ground motions is the vertical-to-horizontal acceleration ratio (V/H). Based on previous far-field ground motion records, the peak vertical acceleration is significantly lower than its horizontal counterpart [7]. Simultaneously, in structural design, the substantial safety margin in the vertical direction justifies the common assumption that the vertical seismic component is taken as two-thirds of the horizontal component. Consequently, many seismic codes in earthquake-prone countries stipulate the vertical ground motion acceleration at 2/3 or 65% of its horizontal counterpart [111,124–126]. Nevertheless, Analysis of near-field ground acceleration data collected over the past three decades has revealed potential limitations in its rigor [102,125,127–130]. Bozorgnia et al. analyzed 41 alluvial site records from the 1994 Northridge earthquake, 4, 131 free-field ground motion records from 1999, and 443 near-field acceleration records. The results revealed that their primary characteristics align with those observed in the 1989 Loma Prieta and California earthquakes. The V/H primarily depends on source depth and vibration period, with minimal correlation to magnitude or source mechanism. For short periods, particularly on soft soil sites, the V/H ratio significantly exceeds the conventionally assumed value of 2/3, whereas it falls below 2/3 for long periods. These features are universally consistent across the datasets. Consequently, a simplified model for vertical seismic response spectra was developed [102,111,128]. Watabe and Silva's team yielded resemble conclusions by analyzing seismic data [131,132].

Furthermore, the FEMA P-750 (2011) specifications, based on Bozorgnia et al.'s research, explicitly propose a vertical design response spectrum scheme as follows:

$$V/H = \begin{cases} 0.3C_v S_{ps} & 0 < T < 0.025s \\ 0.8C_v S_{ps} & 0.05 < T < 0.15s \\ 0.8C_v S_{ps} (0.15/T)^{0.75} & 0.15 \leq T < 2s \end{cases} \quad (3)$$

where C_v is the site coefficient for velocity; and S_{ps} can be donated as mapped spectral acceleration parameter [133].

Eurocode (EC8) specifies the vertical seismic response spectrum based on site classification and source magnitude. The calculation formula is as follows:

$$S_v(T) = \begin{cases} \alpha_{vg} \cdot [1 + T/T_B \cdot (3 \cdot \eta - 1)] & 0 \leq T \leq T_B \\ \alpha_{vg} \cdot 3 \cdot \eta & T_B \leq T \leq T_C \\ \alpha_{vg} \cdot 3 \cdot \eta [T_C/T] & T_C \leq T \leq T_D \\ \alpha_{vg} \cdot 3 \cdot \eta [T_C T_D / T^2] & T_C \leq T \leq 4 \end{cases} \quad (4)$$

where α_{vg} represents the reference value of the vertical seismic influence coefficient, which is associated with factors such as site category and design earthquake grouping; η is the damping adjustment factor. T_B , T_C and T_D are the characteristic periods of the response spectrum [101].

Based on 228 vertical seismic records from 254 borehole data stations in the western United States, sites were classified according to Chinese seismic codes by Geng et al. The influences of focal depth, site conditions, and structural natural periods were systematically investigated, culminating in an improved model for vertical seismic response spectra. The calculation model is shown in Equation (5) [134]:

$$V/H = \begin{cases} 1 & T < 0.1s \\ 1 - 2.5(T - 0.1) & 0.1s \leq T < 0.3s \\ 0.5 & 0.3s \leq T \end{cases} \quad (\text{Soil}) \quad (5)$$

The increasing availability of near-field seismic data has significantly advanced research on the characteristics of vertical ground motion. Researchers have collected localized site conditions and seismic records to determine regional vertical-to-horizontal spectral ratio (V/H) features, thereby facilitating the development of localized models for seismic evaluation and hazard analysis [103,129,130,135–137].

4.2. Impact of Bidirectional Seismic Excitations on Piers

Compared to the extensive research on horizontal seismic effects, studies on the dynamic response of bridges under multi-directional seismic excitation have long received insufficient attention, resulting in a relatively weak foundational knowledge in this area. Historically, over the past several decades, limited findings were predominantly derived from costly shake table tests or field observations. Recent advances in computational power and the maturation of finite element simulation technologies have led to a gradual increase in numerical simulation studies incorporating bidirectional and even tri-directional seismic inputs. This progress has enabled deeper exploration of the complex response characteristics of bridges subjected to multi-directional excitation. In 1998, Jankowski et al. modeled the girders and piers as three-dimensional elastic beam elements, simulating bearing contacts through spring-damper elements to investigate the influence of bearing vertical stiffness on lateral shear key collisions. The results indicate that vertical stiffness predominantly governs variations in collision forces, with the spatial effects of seismic excitation being non-negligible [138]; Shrestha et al. further emphasized that bridge collisions under tri-directional seismic excitation may manifest in vertical, longitudinal, and horizontal modes, while multi-mode coupling significantly amplifies impact forces [139]. However, Bi et al. simulated the tri-directional seismic collision responses between bridge decks and abutments (piers) using a three-dimensional finite element model, revealing that the collision effect in the vertical direction is negligible due to the high stiffness of abutments, while collisions between adjacent girders in the lateral direction remain significant. This conclusion contrasts with Jankowski's findings regarding the influence of vertical stiffness on collision forces [140]. Jiao et al. conducted shaking table tests on a two-span multi-span curved bridge with a small radius, revealing that vertical pulses (with $PGA_v/PGA_h > 1.2$) further amplified the lateral collision forces by an additional 25%. This phenomenon primarily stems from vertical acceleration pulses exacerbating girder uplift and subsequent pounding impacts during deck dropping [141]. Chen et al. systematically simulated the dynamic responses of deck-abutment collisions in both vertical and longitudinal directions using two-dimensional and three-dimensional models incorporating soil-structure interaction (SSI). The results demonstrated that under bidirectional seismic inputs, the coupling of fluid-structure interaction (FSI) with SSI induced torsional responses in the bridge deck, causing the fluctuation amplitude of vertical collision forces to reach twice that observed under unidirectional excitation [142]. Sun et al. investigated the seismic response of reinforced concrete double-layer bridge bent piers under near-fault vertical ground motion through numerical modeling. The results demonstrated that, compared to the response under unidirectional horizontal excitation alone, the combined action of horizontal and vertical

ground motions led to a significant increase in multiple key response indicators, such as the maximum inter-story drift ratio and residual drift ratio at both the top and bottom of the piers, accompanied by more severe damage patterns [143]. Wu et al. demonstrated that bidirectional horizontal cyclic loading exacerbates damage accumulation, reduces ductility, and triggers reinforcement buckling in reinforced concrete circular bridge piers, highlighting significant seismic performance degradation under multidirectional demands [144]. As research progresses, accumulating evidence indicates that bidirectional seismic excitation in near-fault regions inflicts significantly greater damage on bridge piers—and indeed on the entire bridge structure—compared to unidirectional excitation. Consequently, seismic assessments that consider only lateral impact or unidirectional seismic action may substantially underestimate the actual extent of pier damage during real earthquake events [145–148].

Compared to finite element and experimental studies, theoretical research remains relatively scarce. Yang and Yin pioneered the analysis of vertical separation and pounding behavior in two-span continuous bridges based on the continuous dynamic method, revealing potential pier failure mechanisms induced by such interactions [117]. An et al. established a multi-span simply supported bridge model to theoretically analyze the influence of girder–bearing separation and pounding on piers under an integrated cap-free system, considering varying V/H seismic force ratios. The results indicate that piers initially undergo flexural failure when axial force is low; as the axial force at the pier base increases, the failure mode gradually shifts to shear failure. When vertical pounding forces between the girder and pier are significant, even minor longitudinal deformation can trigger compressive failure in the pier. For non-superhigh piers, the nonlinear dynamic deformation and increased contact forces induced by vertical girder–pier separation have a negligible impact on instability failure [14,114,149]. Chen et al. derived the seismic dynamic response equations for multi-span girder bridges incorporating cap beams and shear keys based on continuum dynamics theory and analyzed the amplification effect of vertical excitation-induced girder–bearing separation on the horizontal collision response of bridge shear keys under near-field earthquakes through theoretical modeling and numerical simulations (Figure 11). The research reveals that vertical separation significantly intensifies horizontal collision forces via two mechanisms: altering structural natural characteristics (e.g., increasing frequency differences between girders and piers) and resonance coupling. When vertical seismic action is considered, the maximum collision force of shear keys is 37.5% higher than traditional design estimates that neglect vertical excitation. It provided a more precise theoretical framework for the seismic design of shear keys; however, the resultant impact on pier mechanical behavior and failure mechanisms remains insufficiently investigated [19,107,150].

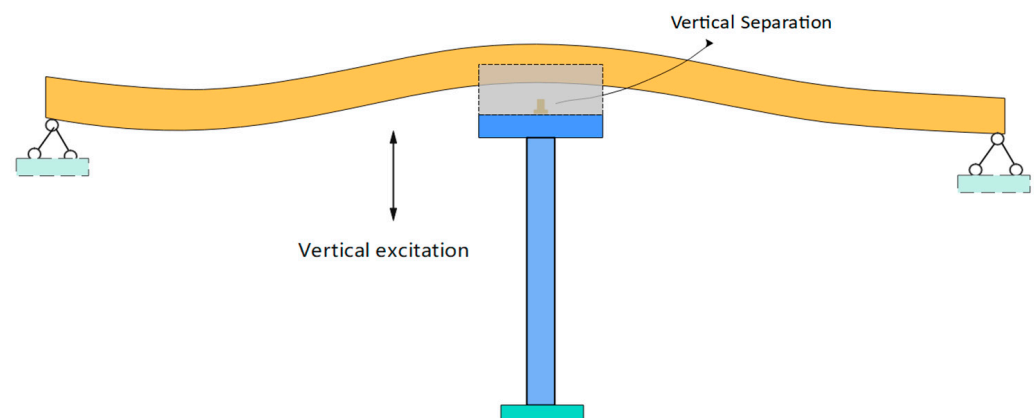


Figure 11. Vertical separation calculation model of two-span girder bridge.

4.3. Summary

This section summarizes the dynamic response characteristics of girder bridges under horizontal and vertical seismic excitations. Starting from the intrinsic characteristics of vertical seismic excitations, it consolidates the current research consensus on the V/H ratio, and building on this foundation, explores the research methodologies and analytical models for bridge structures subjected to bidirectional seismic ground motions. The specific framework is illustrated in Figure 12. An increasing number of research findings have revealed that the potential risk that conventional unidirectional seismic analysis may severely underestimate the actual seismic response of bridge structures. However, current research on this topic remains insufficiently in-depth, and many detailed scenarios have not been fully considered.

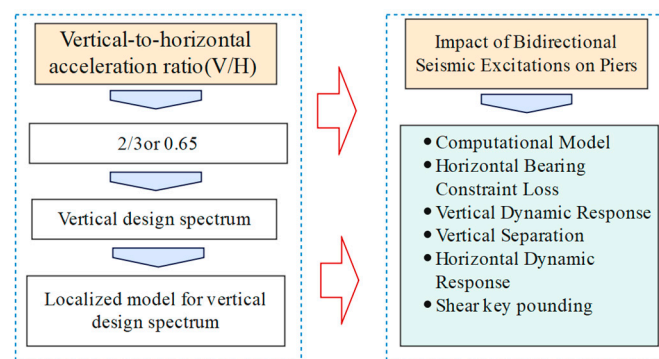


Figure 12. Framework of Section 4.

5. Seismic Performance of Bridge Piers

As critical substructure components bearing the load of bridges, the selection and application of pier types have long received significant attention. Based on structural configuration, mainstream bridge piers are primarily categorized into the following four types: gravity piers, which rely on their self-weight for stability and are commonly used in large- and medium-span bridges under heavy load conditions; hollow piers, where the solid cross-section is partially excavated to substantially reduce self-weight and save materials, making them suitable for sites with limited foundation bearing capacity; flexible piers, characterized by slender forms and relatively low stiffness, often employed as intermediate supports in multi-span bridges to optimize the overall structural mechanical behavior; thin walled piers, characterized by their relatively thin wall thickness, are extensively employed in long-span and high-pier bridges; and column piers, which have become the most widely adopted type in highway bridges due to their lightweight structure, ease of construction, and economic efficiency [151].

This section focused on two core topics of all types of piers to systematically review relevant research advances: the failure modes of piers under seismic action and targeted seismic mitigation strategies and design philosophies.

5.1. Failure Modes of Bridge Piers

Existing research has identified several primary failure modes in bridge piers under seismic excitations: compressive failure, shear failure, flexural failure, and instability failure [152], and extensive research has been conducted by scholars on these failure mechanisms. In 2008, Ghannoum established a relational model between flexural and shear failure at pier ends through stepwise linear regression analysis of a column test database, revealing that axial load, hoop spacing, and shear stress are critical factors influencing flexural capacity at the onset of shear failure in columns [153]. Based on the

investigation of 1,337 simply supported bridges damaged in the Wenchuan earthquake, Zhuang et al. (2009) [5] summarized that column piers exhibiting crushing and shear failure were critically influenced by the hoop reinforcement ratio. Their field analysis emphasized that adequate transverse hoops are essential for ensuring pier load-bearing capacity and must be prioritized in high-intensity seismic zones. Kunnath et al. investigated the seismic response of highway interchanges single and multi-column piers and found that vertical seismic action significantly increased axial forces in columns and bending moments in beams. Consequently, the flexural performance of these structural components requires particular attention in actual earthquake scenarios [154]. Kim et al. conducted experiments on reinforced concrete (RC) frames with varying geometric parameters under vertical excitation, observing that axial forces could surge by approximately 240% when vertical seismic actions were considered [116,155]. This finding indirectly corroborates Kunnath's perspective on the amplification effects of vertical ground motions. Based on these experimental results, the Korean "Standard for Seismic Design of Buildings (KDS 41 17 00:2019)" introduced a new provision requiring that the axial compression ratio of columns in near-fault regions ($PGA \geq 0.3 \text{ g}$) be verified against a vertical acceleration peak of $0.7 \times SDS$ [156]. Sun et al. investigated the mechanical behavior of thin-walled rectangular hollow reinforced concrete (RC) tall piers through quasi-static tests. The experiments revealed that due to the shear lag effect, concrete spalling and longitudinal reinforcement buckling predominantly occurred at the flange corners, leading to a flexural-shear failure mode [157]. Subsequently, researchers conducted an in-depth computational analysis of the bending and shear deformations of RC piers from initial loading to failure by employing the Modified Compression Field Theory (MCFT) and fiber beam-column element models. Novel on the relationship between these deformations, a novel criterion for distinguishing shear, flexural-shear, and flexural failure modes in piers was proposed [158]. Lu et al. analyzed the effect of longitudinal reinforcement on the capacity of gravity piers that fail in flexure, with damage concentrated in the plastic hinge zone at the base. They found that increasing the reinforcement ratio significantly improves the pier's load-bearing capacity and displacement ductility [159]. Liu et al. systematically characterized the failure-mode transition of thin-walled tall piers from flexural-shear response to brittle shear by conducted hybrid tests and proposed a criterion for predicting this shift [160].

5.2. Seismic Mitigation Measures for Bridge Piers and Their Design Philosophies

Current research on bridge pier seismic resistance has shifted from the traditional "disaster resistance" approach to a "resilient seismic design" philosophy. Within this framework, the flexibility indicator has become a critical factor. Contemporary academic investigations are primarily concentrated in three key areas: energy dissipation design strategies, structural systems, and material innovations.

Historically, most seismic design codes, such as the early American AASHTO 1983 specification [161] and China's Highway Engineering Seismic Design Code (JTJ 004-89) [162], were primarily based on strength-based design principles, utilizing structural response spectra or equivalent static methods. However, observations from the 1971 San Fernando earthquake revealed that structural collapse was predominantly caused by cyclic deformation under repeated seismic loading rather than insufficient strength. This paradigm shift triggered a fundamental reassessment of design philosophies. Consequently, Park and Paulay proposed the ductility-based seismic design theory and methodology, which has since gained widespread adoption [163]. Currently, modern seismic codes—including American's AASHTO [59], Japan's JRA Specification [64], Europe's EC8 [101], and China's JTG/T 2231-01-2020 [164]—have comprehensively incorporated these principles.

Driven by advancements in seismic response simulation and materials science, bridge pier design philosophy has witnessed transformative breakthroughs. Brando et al. (New Zealand), analyzing bridge damage patterns from the 2011 Canterbury and Kaikōura earthquakes, underscored the imperative shift toward recoverable seismic design in bridge structures [165]. Mahin further posited that future research on pier seismicity should prioritize self-centering capabilities, repairability, and minimize public/environmental impacts [166]. Concurrently, Li et al. advocated integrating three critical metric detectability, replaceability, and maintainability—into performance-based seismic design frameworks for bridges [167].

The evolution of innovative seismic design philosophies has positioned novel pier structural systems as a key area of investigation within bridge engineering research. Among these, precast segmental piers represent a prominent research direction in seismic engineering, offering significant advantages over conventional cast-in-place piers: they substantially reduce construction time, minimize disruptions to traffic and the environment, and enable the implementation of rocking piers to meet recoverability design objectives. In a seminal study, M.J. Ameli et al. conducted scaled experiments comparing Accelerated Bridge Construction (ABC) piers—fabricated using two distinct grouted sleeve splice configurations—with traditional monolithic reinforced concrete piers. The results demonstrated that ABC piers exhibit superior ductility performance at the base connections while maintaining adequate strength across both splice types [168]. Guerrini et al. conducted shake table tests and finite element (FE) simulations on dual-column self-centering concrete-filled steel tube (CFST) bridge piers, demonstrating their superior seismic performance compared to conventional reinforced concrete (RC) piers. The results revealed that the self-centering CFST piers exhibit significant self-recentering characteristics and low-damage behavior under seismic loading, offering enhanced resilience and reduced residual displacements [169]. Guo et al. proposed two types of base rocking isolation bridge pier models incorporating high-damping rubber pad blocks and linear springs, respectively. Through vibration experiments and numerical simulations, these models demonstrated favorable seismic performance in terms of structural stability and energy dissipation capabilities [170,171]. Yang et al. further categorized accelerated bridge construction (ABC) piers into three distinct types based on connection configurations: non-emulative piers (Figure 13a), emulative piers (Figure 13b), and hybrid-connected piers (Figure 13c). Through finite element simulations, they conducted a parametric investigation to compare the influence of joint interface locations between precast segments on the seismic performance of these piers [172]. Building upon Liang et al.'s analysis of non-emulative piers [173,174]. Additionally, steel tube piers and hollow reinforced concrete (RC) piers have also been extensively investigated, with preliminary frameworks established for their seismic performance [175–177].

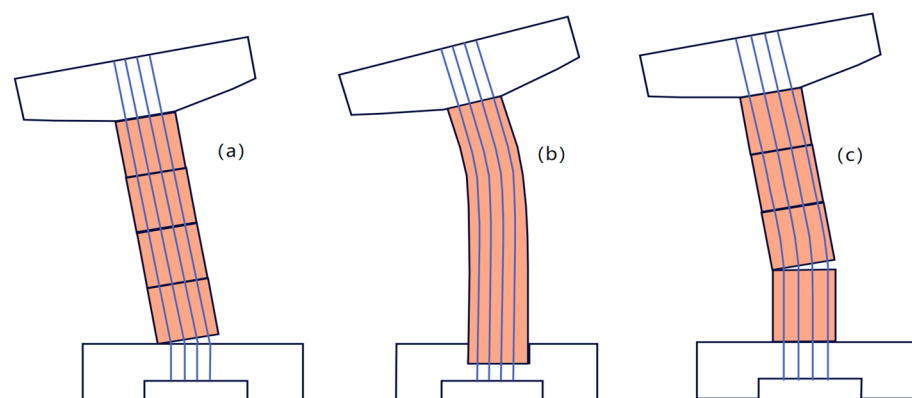


Figure 13. Schematic diagram of joint locations in precast concrete bridge piers (a) non-emulative piers; (b) emulative pier; (c) hybrid-connected pier (redrawn based on [172]).

The continuous advancement of novel materials has motivated researchers to explore their application in bridge piers for enhanced seismic performance. Ultra-High-Performance Concrete (UHPC), a cementitious composite material engineered based on the principle of maximum packing density, effectively enhances structural stiffness, ductility, and durability. Its exceptional properties make it a material of significant research value in bridge engineering, particularly for improving structural resilience under seismic loads. Zhang et al. conducted flexural tests on RC bridge piers strengthened with UHPC under high-temperature steam curing. The results demonstrated a substantial improvement in the mechanical properties of the retrofitted structures, particularly in terms of structural stiffness and load-bearing capacity [178]. Xu et al. conducted quasi-static tests to investigate the effects of two connection methods—grouted sleeve connections and UHPC connections—between bridge piers and bearing platforms on seismic performance. Experimental results demonstrated that both connection methods met seismic requirements, though they exhibited distinct failure modes. Precast piers with grouted sleeve connections failed via rebar fracture, while those with UHPC connections failed through crushing of the ordinary core concrete above the connection zone. Notably, excessive UHPC usage may pose environmental implications due to its high cement content and resource intensity [179]. Pu et al. conducted static load and failure tests on bridge pier structures reinforced with High Toughness Resin Concrete Steel Mesh (HTRCS). The experimental results demonstrated that the HTRCS strengthening method achieves comparable reinforcement effectiveness at lower construction costs, reduced project duration, and minimal traffic disruption compared to conventional techniques [180]. Xu et al. conducted a comprehensive Life Cycle Assessment (LCA) of reinforced concrete bridge piers to investigate the environmental impact of integrating traditional concrete (CC) and UHPC in seismic design. The study demonstrated that utilizing higher-grade UHPC does not enhance seismic resistance but instead increases the global warming potential (GWP). In contrast, employing resin concrete as the base material significantly reduces hardening time while delivering higher tensile strength [181]. Additionally, carbon fiber-reinforced polymer (CFRP) [182–185] composites, shape memory alloys (SMAs) [186,187] and Engineered cementitious composite (ECC) materials [188,189] have been extensively studied for enhancing the seismic performance of bridge piers due to their superior self-centering capabilities, corrosion resistance, and fatigue durability. In parallel with the deepening of material research, significant theoretical advances have been made in understanding the creep behavior of internal granular phases within structural components [190,191] and in exploring innovative domains such as seismic metamaterials [192]. These theoretical developments provide critical support for performance optimization and design of earthquake-resistant structural elements.

5.3. Summary

This section systematically reviews research on the seismic failure modes of the main structural forms of girder bridge piers and summarizes the research progress of mainstream pier seismic isolation and energy dissipation methods from three aspects: materials, structure, and conceptual design. However, despite the rapid advancement of bridge seismic resistance research in experimental and simulation domains, its fundamental theoretical research still exhibits notable deficiencies.

6. Research Prospects

6.1. Shortcomings of Existing Research

Existing research has established a relatively comprehensive understanding of the lateral dynamic response and impact mechanisms (including adjacent girders, and girders versus abutments/shear keys) in highway bridges. It is widely recognized that horizontal collisions with shear keys significantly amplify the inertial forces on bridge piers and

exacerbate their damage. In the domain of vertical excitation, studies confirm that girder bridges are susceptible to girder “uplift phenomena” under near-field vertical earthquakes due to the vulnerability of their bearings, thereby altering the horizontal dynamic response and internal force distribution of piers. The application of advanced materials (e.g., UHPC, FRP) and innovative design concepts (e.g., ductility, recoverability) has markedly elevated the seismic safety thresholds of bridge piers. However, current research exhibits the following limitations:

- Current research on seismic performance of bridge piers primarily focuses on horizontal ground motion response analyses, which inadequately represent actual earthquake scenarios. A representative case is the brittle shear failure of piers induced by high-frequency cyclic axial forces during the 1994 Northridge earthquake. This failure mechanism likely results from the combined dynamic effects of high-amplitude vertical and horizontal seismic excitations. The influence of vertical excitation on the horizontal internal forces and dynamic response of bridge piers urgently requires systematic investigation.
- Current research endeavors concerning vertical seismic effects predominantly focus on validating separation phenomena and conducting preliminary exploration into failure mechanisms, while giving scant consideration to the secondary hazards stemming from vertical separation. As previously discussed, the girder–bearing separation phenomenon in girder bridges significantly intensifies the impact forces and exacerbates both horizontal and vertical load requirements on piers, thereby substantially elevating collapse risks (Figure 14). This critical issue has, thus far, failed to garner adequate attention. Notably, girder bridges have emerged as the dominant selection for small-to-medium span highway bridges, attributable to their structural simplicity, rapid construction process, and high degree of standardization. Nevertheless, these inherent structural attributes also render them particularly vulnerable to seismic-related challenges, necessitating urgent and focused research efforts.
- Current bridge design paradigm has undergone a significant transformation, embracing the principles of “ductility” and “recoverability”, which substantially improves seismic performance. However, a considerable proportion of these performance indicators remain established based on unidirectional seismic and pounding response analyses. Consequently, such design standards run the risk of potentially underestimating the magnitude of structural damage under actual earthquake scenarios.

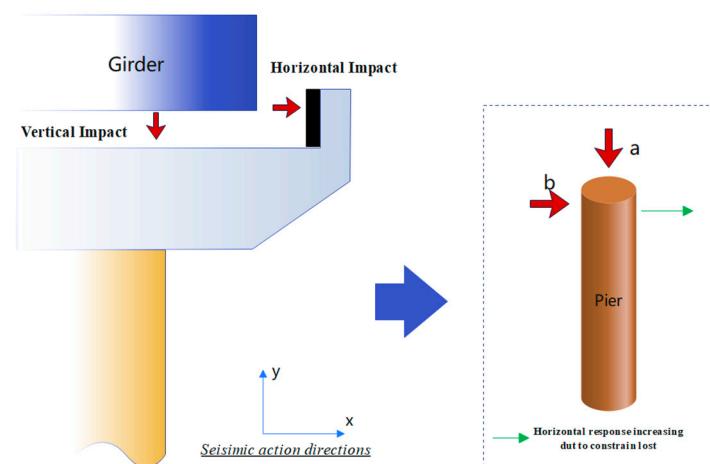


Figure 14. Extreme pounding effects on bridge pier subject to bi-directional earthquakes (a) Vertical collision; (b) Horizontal collision.

6.2. Advances and Future Directions in Bridge Piers

Seismic response analysis of bridge structures has emerged as a prominent research focus in recent years. Extensive studies employing finite element simulation methods have investigated earthquake impacts on bridges.

Nevertheless, theoretical research outcomes remain comparatively scarce relative to numerical simulations. Given the critical role of theoretical approaches in seismic bridge design, this field demands heightened attention and deeper investigation. This paper proposes an innovative risk assessment perspective for pier damage based on the ‘vertical separation–collision–horizontal pounding–pier response’ mechanism (Figure 15), aiming to advance the study of pier failure under near-field seismic excitations.

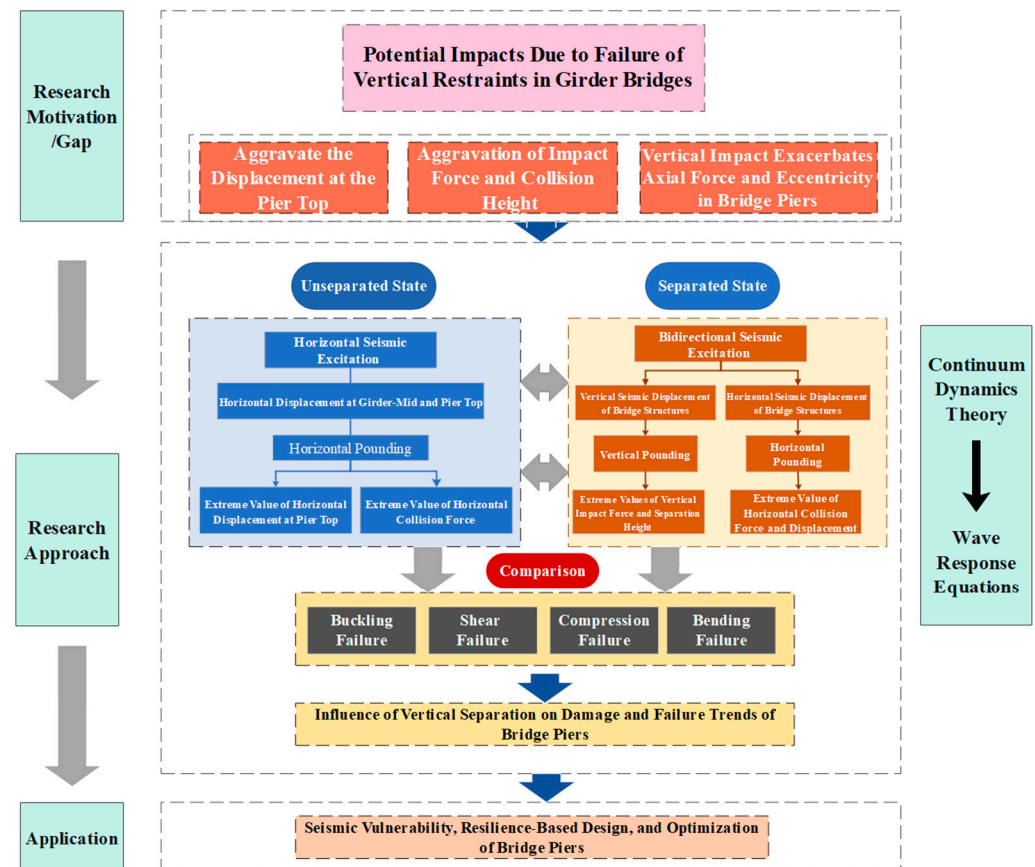


Figure 15. Research process and procedures.

7. Conclusions

This paper presents a comprehensive review of the research achievements pertaining to pier seismic performance over the past three decades, with the principal findings summarized as follows:

- Under horizontal seismic excitation, bridge structures demonstrate intricate collision phenomena, encompassing girder-to-girder impacts and girder-to-shear-key pounding. Notable advancements in the characterization of shear key failure modes when subjected to impact loads, thereby confirming their pivotal function in mitigating unseating failures through effective girder restraint. However, excessively rigid shear keys may inadvertently exacerbate damage to pier and cap beam, while simultaneously failing to prevent the unseating design conundrum starkly illustrated by catastrophic shear key failures observed during the 2008 Wenchuan earthquake. Consequently, the optimization of shear key constraint forces to achieve an equilibrium

between unseating prevention and substructure protection remains a pivotal challenge in seismic design.

- Existing research endeavors have unveiled a spectrum of impacts induced by vertical earthquakes, which primarily encompass the following aspects: (1) eccentric collisions and shear failures; (2) upper pier damage triggered by pounding; (3) pier crushing; (4) unseating failures due to weakened girder–bearing contact; (5) bridge collapse scenarios. These seismic damages primarily originate from the displacement amplification and intensified collisions exacerbated by diminished contact between girders and piers under vertical excitation. Studies provide mechanistic elucidation for these phenomena, thereby deepening the comprehension of bridge responses under vertical earthquakes and furnishing scientific foundations for seismic design and assessment.
- In investigating the effects of coupled horizontal–vertical seismic actions on structures, the V/H serves as a critical parameter. Current research consensus confirms that the V/H ratio exhibits strong correlations with multiple factors, including site conditions, excitation periods, and focal depths. Consequently, adopting a fixed V/H ratio (e.g., 2/3 or 65%) may inadequately represent actual seismic scenarios, revealing methodological limitations in current approaches. Advances in seismic monitoring technologies and expanded datasets have enabled the development of dynamic V/H ratio prediction models, which significantly improve the accuracy of structural response simulations under multi-directional seismic actions. Both theoretical and experimental analyses demonstrate that bridge piers subjected to coupled horizontal–vertical excitations may experience significantly more severe damage compared to unidirectional seismic inputs. This coupling effect manifests through increased displacement demands and amplified curvature ductility requirements, exacerbating structural damage during actual earthquakes. To improve the safety and reliability of bridge structures under seismic events, it is imperative to deepen investigations into coupled horizontal–vertical seismic influences and systematically incorporate dynamic V/H ratio variations and coupling effects into design frameworks.
- The seismic performance of bridge piers has advanced substantially in recent decades, with significant progress achieved through innovations in design concepts, materials, and structural systems. From a philosophical perspective, the field has transitioned from traditional strength-based failure criteria toward designs that prioritize ductile failure performance, establishing a more robust foundation for pier engineering. Future development trends will emphasize recoverability and self-centering capabilities. Precast segmental piers represent an emerging paradigm in this context, while innovative configurations such as rocking piers constitute a critical focus for seismic research. Concurrently, the application of advanced materials offers transformative potential for enhancing bridge seismic resilience. Notably, UHPC and FRP composites contribute not only to improved seismic resistance but also enhanced durability, safety, and cost-effectiveness. These materials endow piers with superior toughness and reliability under extreme seismic events, fundamentally redefining structural response mechanisms.
- Current theoretical frameworks for seismic response analysis remain limited, with particularly inadequate research on dynamic collision forces and contact evolution mechanisms. Crucially, bidirectional coupled seismic excitation significantly induces girder uplift phenomena, amplifying transverse pounding forces at shear keys and generating more severe damage effects on piers compared to uniaxial static collisions. Notably, a critical research gap persists regarding the seismic damage mechanisms of bridge piers under this specific phenomenon, with no systematic investigations reported in existing literature. While continuum dynamics contact method-

ologies show promise for simulating these evolutionary processes, both the underlying theoretical foundations and subsequent seismic-resistant design systems require substantial refinement.

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References

1. Amir Mazaheri, D. Seismic design methodology of bridges: Point of present reflections. In Proceedings of the 10th European Conference on Earthquake Engineering, Vienna, Austria, 28 August–2 September 1994.
2. Iwasaki, J.P.; Clough, R. *Literature Survey-Seismic Effect on Highway Bridges*; College of Engineering, University of California: Oakland, CA, USA, 1972.
3. Kawashima, K.; Unjoh, S. Impact of Hanshin/Awaji earthquake on seismic design and seismic strengthening of highway bridge. *Doboku Gakkai Ronbunshu* **1997**, *556*, 211–240. [[CrossRef](#)]
4. Wang, K.H.; Sun, Y.H.; Wei, H.; Jiang, Z.Y. Comments on seismic strengthening for Structural Engineering in China after Wenchuan Earthquake. *J. Highw. Transp. Res. Dev.* **2008**, *11*, 54–59.
5. Zhuang, W.L.; Liu, Z.Y.; Jiang, J.S. Earthquake-induced damage analysis of highway bridges in Wenchuan earthquake and countermeasures. *Chin. J. Rock Mech. Eng.* **2009**, *7*, 1377–1387.
6. Papazoglou, A.J.; Elnashai, A.S. Analytical and field evidence of the damaging effect of vertical earthquake ground motion. *Earthq. Eng. Struct. Dyn.* **1996**, *10*, 1109–1137. [[CrossRef](#)]
7. Yang, J.; Lee, C.M. Characteristics of vertical and horizontal ground motions recorded during the Niigata-ken Chuetsu, Japanese Earthquake of 23 October. *Eng. Geol.* **2007**, *94*, 50–64. [[CrossRef](#)]
8. Lew, M.; Bonneville, D. New building code requirements for the seismic design of tall buildings near active faults. *Struct. Des. Tall Build.* **1997**, *4*, 279–297. [[CrossRef](#)]
9. Somerville, P.K. *Engineering Characteristics of Near-Fault Ground*, in SMIP97; Department of Conservation: Los Angeles, CA, USA, 1997; pp. 9–28.
10. Fan, L.C.; Wang, J.J. Design code for earthquake-resistance of bridge: Current situation and trend. *Earthq. Eng. Eng. Vib.* **2001**, *2*, 70–77.
11. Loh, C.-H.; Liao, W.-I.; Chai, J.-F. Effect of near-fault earthquake on bridges: Lessons learned from Chi-Chi earthquake. *J. Earthq. Eng. Eng. Vib.* **2002**, *1*, 86–93. [[CrossRef](#)]
12. Yang, H.B.; Yin, X.C. Theoretical investigation of bridge seismic responses with pounding under near-fault vertical ground motions. *Adv. Struct. Eng.* **2014**, *4*, 453–468. [[CrossRef](#)]
13. Yang, H.B.; Yin, X.C.; Xu, R. Effect of bridge bearings on vertical pounding in bridges under near-fault vertical earthquakes. *Eng. Mech.* **2014**, *31*, 183–189.
14. An, W.J.; Zhou, P.; Wang, P.; Zheng, Z.; Yang, H. Analysis of dynamic interaction and response in multi-span girder bridges subjected to near-fault earthquakes. *Structures* **2023**, *58*, 105622. [[CrossRef](#)]

15. Wang, C.F.; Chen, X.C. The effect of vertical seismic motion on the seismic response of bridge structures. *J. Vib. Shock* **2007**, *26*, 31–35. [\[CrossRef\]](#)
16. Li, H.F.; Luo, Y.F.; Chen, L.C.; Meng, Z. Effect of axial force fluctuation on seismic behavior of steel box column. *J. Southwest Jiaotong Univ.* **2014**, *49*, 425–431.
17. Zhao, W.F.; Tian, S.W.; Zhao, J. Shear resistant performance of RC columns subjected to vertical near-fault velocity pulse-like earthquake actions. *J. Chongqing Univ.* **2013**, *6*, 103–111.
18. Xin, L.F.; Li, X.Z.; Fu, P.Y.; Mu, D. Seismic behavior of precast segmental column bridges under near-fault forward-directivity ground motions. *Earthq. Eng. Eng. Vib.* **2022**, *2*, 559–571.
19. Chen, S.T.; Fadzli, M.N.; An, W.J.; Fu, H. A theoretical calculation method of seismic shear key pounding based on continuum model. *MethodsX* **2023**, *2023*, 102370. [\[CrossRef\]](#)
20. Bi, K.H.H. Modelling of shear keys in bridge structures under seismic loads. *Soil Dyn. Earthq. Eng.* **2015**, *74*, 56–68. [\[CrossRef\]](#)
21. Wang, X.W.; Ye, A.G.; Wu, X.P.; Zhou, X.P.; Song, K.H.; Li, J.; Lou, L.; Wei, X.N.; Peng, J. Seismic resilience assessment method for girder bridges: Expert opinion-based post-earthquake functionality recovery models of bridge components. *China Civ. Eng. J.* **2025**, *58*, 65–76.
22. Wang, M.Q. *Performance Based Design Method of Bridge Seismic Resistance*; Chongqing Jiaotong University: Chongqing, China, 2021.
23. Wang, Y.X.; Sun, Z.G.; Men, J.J.; Chen, X.Y. Research on seismic behavior of RC double-deck viaduct under near-fault vertical ground motions. *Eng. Mech.* **2024**, *42*, 1–11.
24. Megally, S.H.; Filva, P.; Seible, F. *Seismic Response of Sacrificial Shear Keys in Bridge Abutments*; University of California: San Diego, CA, USA, 2001.
25. Liu, P. *Research on Dynamic Pounding Between Grider and Transverse Shear Key of Bridge Under Earthquake*; Southwest Jiaotong University: Chengdu, China, 2010.
26. Norton, J.A.; King, A.B.; Bull, D.K.; Chapman, H.E.; McVerry, G.H.; Larkin, T.J.; Spring, K.C. Northridge earthquake reconnaissance report. *Bull. N. Z. Soc. Earthq* **1994**, *27*, 235–344. [\[CrossRef\]](#)
27. Shamsabadi, A. *Three-Dimensional Nonlinear Seismic Soil-Foundation-Structure Interaction Analysis of Skewed Bridge*; University of Southern California: Los Angeles, CA, USA, 2007.
28. Wang, D.S.; Guo, X.; Sun, Z.G.; Meng, Q.L.; Yu, D.H.; Li, X.L. Damage to highway bridges during Wenchuan Earthquake. *J. Earthq. Eng. Vib.* **2009**, *3*, 84–94.
29. Jonsson, M.H.; Bessason, B.; Hafliðason, E. Earthquake response of a base-isolated bridge subjected to strong near-fault ground motion. *Soil Dyn. Earthq. Eng.* **2010**, *36*, 447–455. [\[CrossRef\]](#)
30. Schanack, F.; Valdebenito, G. Seismic damage to bridge during the 27 February 2010 magnitude 8.8 Chile earthquake. *Earthq. Spectra* **2012**, *1*, 301–315. [\[CrossRef\]](#)
31. Bi, K.; Hong, H.; Chow, N. Required separation distance between decks and at abutments of bridge crossing a canyon site to avoid seismic pounding. *Earthq. Eng. Struct Dyn.* **2010**, *39*, 303–323. [\[CrossRef\]](#)
32. Xu, H.Z.; Liu, Z.; Zhang, Y.K. Study on horizontal displacement characteristics of plate rubber bearing. *Sci. Technol. Eng.* **2023**, *7*, 3038–3043.
33. I-5/Hwy 14 Interchange. *Northridge Earthquake*; NISEE-PPER; University of California: Berkeley, CA, USA, 1994.
34. Wyllie, L.A. *Cracked Bridge Shear Block After 1985 Chile Earthquake*; NISEE-PEER; University of California: Berkeley, CA, USA, 1985.
35. Bozorgzadeh, A.; Megally, S.H.; Restrepo, J.I. Capacity evaluation of exterior sacrificial shear keys of bridge abutments. *J. Pf Bridge Eng.* **2006**, *5*, 555–565.
36. Xu, L.Q.; Li, J.Z. Experiment on seismic performance and its improvement of reinforced concrete retainers. *China J. Highw. Transp.* **2014**, *9*, 41–48.
37. Zheng, W.S.; Tang, G.W. Quasi-static test research on seismic block of bridges. *Technol. Highw. Transp.* **2013**, *4*, 54–58.
38. Xu, J.L. *Research on Resilient Concrete Continuous Bridges Under Earthquake and Over-Height Trunk Collision*; Tsinghua University: Beijing, China, 2016.
39. Wang, C.; Xu, W.B.; Hu, W.B.; Hu, Z.Q.; Hou, P.; Guang, G.Z.; Cui, F.K. Research on the seismic vulnerability of prefabricated bridge reinforced concrete lateral limit blocks. *Transp. World* **2024**, *20*, 16–18. [\[CrossRef\]](#)
40. Liu, P. Improved algorithm of contact element model for earthquake-induced pounding between structures. *J. Chongqing Univ.* **2012**, *35*, 135–142.
41. Xu, L.Q.; Li, J.Z. Seismic strength prediction of reinforced concrete retainers based on rigid body rotation model. *Eng. Mech.* **2014**, *10*, 143–150.
42. Xu, L.Q.; Li, J.Z. Dual-level design method of sacrificial seismic retainers. *China Highw. Transp.* **2015**, *10*, 59–66.
43. Kottari, A. *Horizontal Load Resisting Mechanisms of External Shear Keys in Bridge Abutments*; University of California: San Diego, CA, USA, 2016.
44. Han, Q.; Zhou, Y.; Ou, Y.; Du, X. Seismic behavior of reinforced concrete sacrificial exterior shear keys of highway bridges. *Eng. Struct.* **2017**, *139*, 59–70. [\[CrossRef\]](#)

45. Han, Q.; Hu, M.H.; Wen, J.N. Seismic capacity evaluation of interior shear keys for highway bridges. *J. Earthq. Eng.* **2018**, *24*, 972–987. [[CrossRef](#)]
46. Meng, D.L.; Yang, M.G.; Fei, F. Shake-table tests on the influence of the pounding on transverse seismic responses of high-speed railway Simply supported bridges. *Eng. Mech.* **2019**, *8*, 161–170.
47. Fan, L.C.; Nie, L.Y.; Li, J.Z. Dynamic characteristic analysis of laminated rubber bearing sliding under earthquake. *China J. Highw. Transp.* **2003**, *4*, 30–35.
48. Wang, K.H.; Hui, Y.X.; Wu, G. Study on seismic performance of seismic earthquake double-layer stopper. *Earthq. Eng. Eng. Dyn.* **2014**, 505–510. [[CrossRef](#)]
49. Xiang, N.L.; Li, J.Z. Effect of different types of retainers on transverse seismic performance of small and mid-span girder bridges. *Eng. Mech.* **2016**, *3*, 188–195.
50. Bhuiyan, A.R.; Alam, M.S. Seismic performance assessment of highway bridges equipped with super-elastic shape memory alloy-based laminated rubber isolation bearing. *Eng. Struct.* **2013**, *2*, 396–407. [[CrossRef](#)]
51. Wu, W.P.; He, J.; Li, L.; Li, H. Experimental study on the post-tensioned unbonded prestressing UHPC prefabricated retaining blocks for highway bridges. *Bull. Earthq. Eng.* **2023**, *21*, 6477–6498. [[CrossRef](#)]
52. Kelly, J.M.; Skinner, R.I.; Heine, A.J. Mechanisms of Energy Absorption in Special Devices for Use in Earthquake Resistant Structures. *Bull. New Zealand Natl. Soc. Earthq. Eng.* **1972**, *5*, 63–88.
53. Ciampi, V. Use of energy dissipating devices, based on yielding of steel, for earthquake protection of structures. In Proceedings of the International Meeting on Earthquake Protection of Buildings, Ancona, Italy, 22 April 1991; pp. 41–58.
54. Vasseghi, A. Energy dissipating shear key for precast concrete girder bridges. *Sci. Iran.* **2011**, *3*, 296–303. [[CrossRef](#)]
55. Tang, Z.H. *Experimental Study and Calculation Method on Bridge Seismic Stoppers*; Chongqing Jiaotong University: Chongqing, China, 2015.
56. Zhu, C.; Fan, B.B. Methods to calculate key mechanical parameters of H-beam stopper. *World Earthq. Eng.* **2019**, *3*, 186–197.
57. Wei, B.; Wan, K.; Wang, W.; Hu, Z.; Jiang, L.; Li, S. Seismic isolation effect of a new type of friction pendulum bearing in high-speed railway girder bridge. *Structures* **2023**, *51*, 776–790. [[CrossRef](#)]
58. South Carolina Department of Transportation. *Seismic Design Specification for Highway Bridges, In Version 2.0*; South Carolina Department of Transportation: Columbia, SC, USA, 2008. Available online: <http://hdl.handle.net/10827/30251> (accessed on 23 November 2025).
59. *Guide Specifications for LRFD Seismic Bridge Design*, 2nd ed.; American Association of State Highway and Transportation Officials: Washington, DC, USA, 2014.
60. *Seismic Design Criteria*; California Department of Transportation: Saramento, CA, USA, 2013.
61. FHWA-RD-94-052; Federal Highway Administration. *Seismic Retrofitting Manual for Highway Bridges*. Turner Fairbank Highway Research Center: McLean, VA, USA, 1995.
62. ACI 318-14; Building Code Requirements for Structural Concrete. American Concrete Institute: Farmington Hills, MI, USA, 2014.
63. ASCE-7; Minimum Design Loads and Associated Criteria for Buildings and Other Structures. American Society of Civil Engineers Press: Reston, VA, USA, 2022.
64. Hanshin Expressway Company. *Seismic and Retrofit of Bridges-From Post-Disaster Emergency Repair to Seismic Maintenance and Reinforcement*; China Architecture and Building Press: Beijing, China, 2013; ISBN 978-7-1121-4891-2.
65. New Zealand Transport Agency. *Bridge Manual*; NZTA: Wellington, New Zealand, 1994.
66. JTG/TB02-01-2008; Guidelines for Seismic Design of Highway Bridges. China Communication Press: Beijing, China, 2008.
67. GB50111-2006; Code for Seismic Design of Railway Engineering (Version 2009). China Planning Press: Beijing, China, 2009.
68. Priestley, M.J.N.; Seible, F.; Calvi, G.M. *Seismic Design and Retrofit of Bridges*; John Wiley & Sons Inc.: Hoboken, NJ, USA, 1996. [[CrossRef](#)]
69. Nielson, B.G.; DesRoches, R. Seismic performance assessment of simply supported and continuous multi-span concrete girder highway bridges. *J. Bridge Eng.* **2007**, *5*, 611–620. [[CrossRef](#)]
70. Wang, K.H. *Bridge Seismic Research*, 1st ed.; China railway publishing house: Shanghai, China, 2012; pp. 269–279.
71. Wang, K.H.; Wei, H.; Li, X. Philosophies on Seismic Design of Highway Bridges of Small or Medium Spans. *China Civ. Eng. J.* **2012**, *9*, 115–121.
72. Xu, L.Q.; Li, J.Z. Effects of retainer on simplified seismic analytical methods for regular continuous girder bridge. *World Earthq. Eng.* **2013**, *2*, 124–131.
73. Li, J.Z.; Xiang, N.L.; Tang, H. Shake-table tests and numerical simulation of an innovative isolation system for highway bridges. *Soil Dyn. Earthq. Eng.* **2020**, *86*, 55–70. [[CrossRef](#)]
74. Pi, S.M.; Xu, L.Q.; Sun, R.W. Research on bearing-shear key-pier interaction of simply-supported girder bridges under earthquake excitation. *World Earthq. Eng.* **2020**, *1*, 137–145.
75. Ma, Y.T.; Wang, J.M.; Wu, D.C. Study on the effect of transvers retainers on seismic vulnerability of typical highway continuous beam bridge in high seismic region. *Earthq. Resist. Eng. Retrofit.* **2022**, *5*, 67–75.

76. Nettis, A.; Di Mucci, V.M.; Ruggieri, S.; Uva, G. Seismic fragility and risk assessment of isolated bridges subjected to pre-existing ground displacements. *Soil Dyn. Earthq. Eng.* **2025**, *194*, 109335. [\[CrossRef\]](#)
77. Di Mucci, V.M.; Cardellicchio, A.; Ruggieri, S.; Nettis, A.; Reno, V.; Uva, G. Computer vision-based seismic assessment of RC simply supported bridges characterized by corroded circular piers. *Bull. Earthq. Eng.* **2025**. [\[CrossRef\]](#)
78. Zheng, S.X.; Lei, C.H.; Jia, H.Y.; Zheng, Y.P.; Liu, L.W.; Zhao, C.H. LSTM-based method for fast prediction of seismic response and vulnerability of Near-fault bridges. *China J. Highw. Transp.* **2025**, *38*, 18–30.
79. Pan, P.; Yan, H.; Wang, T. Development of steel dampers for bridges to allow large displacement through a vertical free mechanism. *Earthq. Eng. Eng. Vibration* **2014**, *3*, 375–388. [\[CrossRef\]](#)
80. Selna, L.G.; Malvar, L.J.; Zelinski, R.J. Bridge retrofit testing: Hinge cable restrainers. *J. Struct. Eng.* **1989**, *4*, 920–934. [\[CrossRef\]](#)
81. *JTG 5410-2020; Specifications for Design of Highway Maintenance Engineering*. Jiaoke Transport Consultants Co., Ltd.: Beijing, China, 2020.
82. Wu, W.P.; Li, L.F.; Hu, Z.L. Effects of the bearing arrangement on seismic performance of continuous girder bridges under near-fault ground motions. *Earthq. Eng. Eng. Vib.* **2015**, *4*, 155–163.
83. Liu, B.D.; Liu, H.F. Dynamic characteristic analysis and performance evaluation of the existing piers. *J. Highw. Transp. Res. Dev.* **2006**, *6*, 95–97.
84. Meng, X.; Gao, R.; Li, C.G. Theoretical and experimental study of hysteric behavior of shock absorbers. *Bridge Constr.* **2015**, *3*, 20–25.
85. Li, C.G.; Gao, R. Study on the shock absorbing technique of high-speed railway bridges. *Railw. Constr. Technol.* **2009**, *2*, 24–29.
86. Zhou, Y.Q.; Li, C.G. Simplified calculation method for steel bar damper and steel bar restrainer applied to high-speed railway simply supported beam bridge. *Railw. Stand. Des.* **2019**, *5*, 65–70.
87. Zhou, Y.Q.; Wen, Q.; Kang, W. Research on the effect of steel bar damper and steel bar restrainer applied to railway simply supported bridge. *Railw. Stand. Des.* **2020**, *S1*, 79–84.
88. Meng, X.; Gao, R.; Li, C.G. Design and seismic mitigation performance study of shock absorber for railway simply-supported beam bridge. *Bridge Constr.* **2014**, *3*, 81–86.
89. Ma, Y.B.; Li, Y.; Zhang, Y.L.; Huang, Y.B. Analysis of the seismic isolation and energy dissipation effects of the damping tenons in high-speed railway simply supported beam bridges. *Railw. Stand. Des.* **2025**, *5*. [\[CrossRef\]](#)
90. He, Z.Y.; Wang, Y. Safety assessment and reinforcement design of a single column pier curved girder bridge. *J. China Foreign Highw.* **2018**, *3*, 124–130.
91. Zhou, J.M.; Wu, W.P.; Wang, C.J. Study on anti-overturning reinforcement structure and design method of single pillar pier based on strut-and-tie. *J. Highw. Transp. Res. Dev.* **2021**, *8*, 110–115.
92. Chen, C.C.; Huang, J.Z.; Yu, Y.G. Robustness design of bridge collapse resistance. *J. Chongqing Jiaotong Univ. (Nat. Sci.)* **2014**, *1*, 1–7.
93. Xiong, Z.H.; Liu, X.Y.; Li, J.Q.; Liu, C. Seismic resilience evaluation of steel-concrete composite girder bridge in cold regions with high seismic intensity. *Prog. Steel Struct.* **2023**, *9*, 65–85.
94. Zhang, J.R.; Wei, K.; Qin, J.X. Resilience and economic loss assessment of highway bridges in deep reservoir under near-fault ground motion. *J. Bridges Eng.* **2021**, *3*, 04021007. [\[CrossRef\]](#)
95. Xu, J.G.; Cai, Z.K.; Feng, D.C. Life-cycle seismic performance assessment of aging RC considering multi-failure modes of bridge columns. *Eng. Structures* **2021**, *244*, 112818.
96. Huang, C.G.; Huang, S.R. Seismic resilience assessment of aging bridges with different failure modes. *Structures* **2021**, *33*, 36823690. [\[CrossRef\]](#)
97. Yang, G.J.; Ye, S.; Li, X.M. Time-dependent seismic resilience analysis of RC bridge piers considering chloride induced erosion. *J. Huazhong Univ. Sci. Technol. (Nat. Sci. Ed.)* **2023**, *8*, 60–66.
98. Li, X.M.; Ye, S.; Yang, G.J. Improved evaluation method for seismic resilience of continuous beam bridges based on system vulnerability. *Eng. J. Wuhan Univ.* **2024**, *12*, 1716–1724.
99. Qian, J.; Zheng, Y.; Dong, Y. Sustainability and resilience of steel-shape memory alloy reinforced concrete bridge under compound earthquakes and functional deterioration within entire life cycle. *Eng. Struct.* **2022**, *271*, 114937. [\[CrossRef\]](#)
100. Boore, D.M.; Joyner, W.B.; Oliver, A.A., III; Page, R.A. Peak acceleration, velocity, and displacement from strong-motion records. *Bull. Seismol. Soc. Am.* **1980**, *70*, 305–321. [\[CrossRef\]](#)
101. *EN 1998-1:2004 Eurocode 8; Design of Structures for Earthquake Resistance*. European Committee for Standardization: Brussels, Belgium, 2004.
102. Bozorgnia, Y.; Niazi, M.; Campbell, K.W. Characteristics of free-field vertical ground motion during the Northridge earthquake. *Earthq. Spectra* **1995**, *4*, 515–526. [\[CrossRef\]](#)
103. Wang, G.Q.; Zhou, X.Y.; Zhang, P.Z. Characteristics of amplitude and duration for near fault strong ground motion from the 1999 Chi-Chi, Taiwan earthquake. *Soil Dyna Earthq. Eng.* **2002**, *1*, 73–96. [\[CrossRef\]](#)
104. Fukushima, Y.; Irikura, K.; Uetake, T. Characteristics of observed peak amplitude for Stronge ground motion from the 1995 Hygoken Nanbu (Kobe) earthquake. *Bull. Seismol. Soc. Am.* **2000**, *90*, 545–565. [\[CrossRef\]](#)

105. Wang, D.; Xie, L. Attenuation of peak ground accelerations from the great Wenchuan earthquake. *Earthq. Eng. Vib.* **2009**, *2*, 179–188. [[CrossRef](#)]
106. Han, W.F.; Song, C.; Liang, Q.G. Strong ground motion at meizoseismal area & safety of important engineering projects at potential earthquake region. *J. Eng. Geol.* **2004**, *4*, 346–353.
107. Chen, S.T.; An, W.J.; Fu, H.; Fadzli, M.N. The effect of bridge girder-bearing separation on shear key pounding under vertical earthquake action—A state-of-the-art review. *Structures* **2023**, *2023*, 2445–2460.
108. Boulanger, R.W. *Collapse of Bridge at Struve Slough*; NISEE-PEER; University of California: Berkeley, CA, USA, 1989.
109. Boulanger, R.W. *Detail of Punching Failure*; NISEE-PEER; University of California: Berkeley, CA, USA, 1989.
110. Yang, H. Research on Multiple Pounding Responses and Characteristics of Bridges Under Near-Fault Vertical Ground Motions. Doctoral Dissertation, Nanjing University of Science & Technology, Nanjing, China, 2014.
111. Bozorgnia, Y.; Campbell, K.W. *Vertical Ground Motion: Characteristics, Modeling, and Applications in Seismic Design*; University of California: Berkeley, CA, USA, 2004.
112. Tanimura, S.; Heya, H.; Umeda, T.; Mimura, K.; Yoshikawa, O. 3-Dimensional Analysis of Dynamic Behavior of Bearing of Nielsen Bridge. *JSME Int. J.* **2002**, *2*, 190–198. [[CrossRef](#)]
113. Xu, R.; Yin, X.C. Transient wave response analysis of a bridge under vertical earthquakes. *J. Vib. Shock.* **2012**, *1*, 49–55.
114. An, W.J.; Zhou, L.; Kang, M.; Yang, H.; Mo, L. Failure mode analysis of bridge pier due to eccentric impact based on separation of pier and beam. *Sustainability* **2023**, *15*, 1435. [[CrossRef](#)]
115. Saadehghaziri, M.A.; Foutch, D.A. Dynamic behavior of RC highway bridge under the combined effect of vertical and horizontal earthquake motions. *Earthq. Eng. Struct. Dyn.* **1991**, *20*, 535–549.
116. Kim, S.J.; Holub, C.J.; Elnashai, A.S. Experimental investigation of the behavior of RC bridge piers subjected to horizontal and vertical earthquake motion. *Eng. Struct.* **2011**, *7*, 2221–2235. [[CrossRef](#)]
117. Wang, C.J.; Shih, M.H. Performance study of a bridge involving sliding decks and pounded abutment during a violent earthquake. *Eng. Struct.* **2010**, *32*, 1100–1112.
118. Boulanger, R.W. *Struve Slough Bridge*; NISEE-PEER; University of California: Berkeley, CA, USA, 1989.
119. Aschheim, M.A. *Mission-Gothic Bridge*; NISEE-PEER; University of California: Berkeley, CA, USA, 1994.
120. *Nakatsuno Bridge Pier*; University of California: Berkeley, CA, USA, 1948.
121. Sun, G.J.; Li, H.J.; Wang, T. Vertical earthquake response analysis of girder bridges considering influence of piers and supports. *Eng. Mech.* **2012**, *10*, 232–239.
122. Lee, H.; Mosalam, M.K. Seismic evaluation of the shear behavior in reinforced concrete bridge columns including effect of vertical accelerations. *Earthq. Eng. Eng. Vib.* **2014**, *3*, 317–337.
123. Xu, R.; Yin, X.C. Calculations of multiple pounding forces between girder and pier bridges under vertical earthquakes. *Eng. Mech.* **2010**, *10*, 124–130.
124. *International Conference of Building Officials, Uniform Building Code (UBC-97)*; International Code Council: Whittier, CA, USA, 1997.
125. Zhou, Z.H. Study on characteristics of vertical ground motion. *Earthq. Eng. Eng. Vib.* **2003**, *3*, 25–28.
126. *GB 50011-2010; Code for Seismic Design of Buildings (2016 Revision)*. China Architecture & Building Press: Beijing, China, 2016.
127. Niazi, M.; Bozorgnia, Y.; Campbell, K.W. Behavior of near-source peak vertical and horizontal ground motions over SMART-1 array, Taiwan. *Earthq. Eng. Struct. Dyn.* **1992**, *21*, 37–50. [[CrossRef](#)]
128. Bozorgnia, Y.; Niazi, M. Distance scaling of vertical and horizontal response spectra of the Loma Prieta earthquake. *Earthq. Eng. Struct. Dyn.* **1993**, *8*, 695–707. [[CrossRef](#)]
129. Ambraseys, N.N.; Douglas, J. Near-field horizontal and vertical earthquake ground motions. *Soil Dyn. Earthq. Eng.* **2003**, *1*, 1–18. [[CrossRef](#)]
130. Sreejaya, K.P.; Bhargavi, P.; Raghukanth, S.T.G. Hazard consistent vertical design spectra for active regions of India. *Soil Dyn. Earthq. Eng.* **2022**, *161*, 107395. [[CrossRef](#)]
131. Watabe, M.; Tohdo, M.; Chiba, O.; Fukuzawa, R. Peak accelerations and response spectra of vertical strong motions from near-field records in USA. In *Proceedings of the 8th Japan Earthquake Engineering Symposium*, Tokyo, Japan, 12–14 December 1990; Volume 1, pp. 301–306.
132. Silva, W. Characteristics of vertical strong ground motions for applications to engineering design. In *FHWA/NCEER Workshop on the National Representation of Seismic Ground Motion for New and Existing Highway Facilities*; National Center for Earthquake Engineering Research: New York, NY, USA, 1997.
133. *FEMA P-750; NEHRP Recommended Seismic Provisions for New Buildings and Other Structures*. FEMA: Washington, DC, USA, 2009.
134. Gen, S.W.; Tao, X.X. The ratios of vertical to horizontal acceleration response spectra. *Earthq. Eng. Eng. Vib.* **2004**, *5*, 33–38.
135. Yilar, E.; Baise, L.G.; Ebel, J.E. Using H/V measurements to determine depth to bedrock and Vs30 in Boston, Massachusetts. *Eng. Geol.* **2017**, *217*, 12–22. [[CrossRef](#)]
136. Mazloom, S.; Assi, R. Estimate of V/H spectral acceleration ratios for firm soil sites in Eastern Canada. *Soil Dyn. Earthq. Eng.* **2022**, *159*, 107350. [[CrossRef](#)]

137. Chieppa, D.; Hobiger, M.; Nagashima, F.; Kawase, H.; Fäh, D. Identification of subsurface structures using H/V curves from earthquake recordings: Application to seismic stations in Switzerland. *Pure Appl. Geophys.* **2023**, *180*, 755–787. [\[CrossRef\]](#)
138. Jankowski, R.; Wilde, K.; Fujino, Y. Pounding of superstructure segments in isolated elevated bridge during earthquakes. *Earthq. Eng. Struct. Dyn.* **1998**, *5*, 487–501. [\[CrossRef\]](#)
139. Shrestha, B.; Hao, H.; Bi, K. *Numerical and Experimental Study of Pounding Damages in Adjacent Bridge Structures Subjected to Spatially Varying Ground Motion and Its Mitigation Method*; Curtin University: Bentley, Australia, 2016.
140. Bi, K.M.; Hao, H.; Chouw, N.W. 3D FEM analysis of pounding response of bridge structures at canyon site to spatially varying ground motions. *Adv. Struct. Eng.* **2012**, *4*, 619–640. [\[CrossRef\]](#)
141. Jiao, C.Y.; Liu, W.B.; Gui, X.S.; Long, P.H.; Wu, Y.F. Shaking table tests of the seismic pounding effect on a small radius curved bridge under near fault ground motions. *Eng. Mech.* **2020**, *8*, 189–201.
142. Chen, S.L.; Wu, R.; Zhang, J.; Gu, Y. Topography and soil-structure interaction effects on the seismic response of three-dimensional canyon-crossing bridge. *Chin. J. Theor. Appl. Mech.* **2021**, *6*, 1781–1794.
143. Sun, Z.G.; Wang, Y.X.; Wang, D.S. Analysis on seismic behavior of double-deck bridge bents under near fault vertical earthquake ground motions. *J. Basic Eng.* **2022**, *6*, 1494–1504.
144. Wu, B.Y.; Chen, B.; Sun, G.; Li, H. Effect of bidirectional haricots cyclic loading on seismic behavior of reinforced concrete circular highway bridge pier. *Structures* **2025**, *79*, 109593. [\[CrossRef\]](#)
145. Fan, J.S.; Wang, Y.X.; Wang, D.S. Seismic performance investigation of composite rigid frame bridge under bi-directional seismic excitations. *J. Vib. Shock* **2014**, *13*, 135–141.
146. Xu, C.X.; Deng, J.T.; Zhu, H.B. Bidirectional seismic fragility analysis of double-deck viaduct frame piers based on stripe-cloud method. *Structures* **2024**, *70*, 107597. [\[CrossRef\]](#)
147. Xu, C.X.; Wu, S.Y.; Zhu, H.B.; Yang, Z. Seismic fragility analysis of double-deck viaduct frame piers under multi-dimensional seismic actions. *Eng. Mech.* **2025**, *42*. [\[CrossRef\]](#)
148. Bazaez, A.S.; Heresi, P.; Astroza, R. Effect of bidirectional hysteretic dampers on the seismic performance of skewed multi-span highway bridges. *Buildings* **2024**, *6*, 1778. [\[CrossRef\]](#)
149. An, W.J.; Song, G.Q.; Chen, S.T. Near-fault seismic response analysis of bridges considering girder impact and pier size. *Mathematics* **2021**, *9*, 704. [\[CrossRef\]](#)
150. Chen, S.T.; An, W.J.; Fu, H.; Fadzli, M.N. Effect of girder-bearing separation on horizontal collision of shear keys under seismic excitations. *Struct. Infrastruct. Eng.* **2025**. [\[CrossRef\]](#)
151. Fan, L.C.; Gu, A.B. *Bridge Engineering*; China Communications Press: Beijing, China, 2017.
152. Editorial Department of China Journal of Highway and Transport. Review on China's bridge engineering research: 2021. *China J. Highw. Transp.* **2021**, *2*, 1–97.
153. Ghannoum, W.M.; Moehle, J.P. Shear failure model for flexure-shear critical reinforced concrete columns. In Proceedings of the 14th World Conference on Earthquake Engineering, Beijing, China, 12–17 October 2008.
154. Kunnath, S.K.; Erduran, E. Effect of near-fault vertical ground motions on seismic response of highway overcrossings. *J. Bridge Eng.* **2008**, *13*, 282–290. [\[CrossRef\]](#)
155. Kim, S.; Kim, S.J.; Chang, C. Analytical assessment of the effect of vertical ground motion on RC frames designed for gravity loads with various geometric configurations. *Struct. Eng. Mech.* **2018**, *5*, 493–504. [\[CrossRef\]](#)
156. KDS 41 17 00; Korean Design Standard: Seismic Design Criteria for Buildings. K.A.F.T. Standards Editors: Seoul, Republic of Korea, 2019.
157. Sun, Z.G.; Guo, X.; Wang, D.S.; Sun, D.Y. Analysis on ductile deformability of hollow reinforced concrete bridge piers. *J. China Railw. Soc.* **2012**, *1*, 91–96.
158. Sun, Z.G.; Li, H.N.; Wang, D.S. Discrimination criteria for flexural-shear failure of RC bridge piers and improved seismic analysis model. *China J. Highw. Transp.* **2015**, *6*, 42–50.
159. Lu, J.H.; Chen, X.C.; Ding, M.B. Influence of longitudinal reinforcement ratio change in plastic hinge area on seismic performance of gravity bridge piers. *J. Railw. Sci. Eng.* **2020**, *9*, 2288–2295.
160. Liu, Y.; Mei, Z.; Wu, B.; Bursi, O.S.; Dai, K.-S.; Li, B.; Lu, Y. Seismic behaviour and failure-mode-prediction method of a reinforced-concrete rigid-frame bridge with thin-walled tall piers: Investigation by model-updating hybrid test. *Eng. Struct.* **2020**, *208*, 110302. [\[CrossRef\]](#)
161. *AASHTO Guide Specifications for LRFD Seismic Bridge Design*; American Association of State Highway and Transportation Officials: Washington, DC, USA, 1983.
162. Ministry of Communications of the People's Republic of China. *Specifications of Earthquake Resistant Design for Highway Engineering*; China Communication Press: Beijing, China, 1989.
163. Park, R.; Paulay, T. *Reinforced Concrete Structures*; John Wiley & Sons: Hoboken, NJ, USA, 1975.
164. *JTG/T 2231-01-2020*; Specifications for Seismic Design of Highway Bridges. People's Communications Publishing House: Beijing, China, 2020.

165. Brando, M.; Lin, S.L.; Giovinazzi, S.; Palermo, A. Observed and predicted bridge damage following the recent Canterbury earthquakes: Toward the calibration and refinement of damage and loss estimation tools. In Proceedings of the 6th International Conference on Bridge Maintenance, Stresa, Italy, 8–12 July 2012; pp. 103–110.
166. Mahin, S. Resilience by design: A structural engineering perspective. In Proceedings of the 16th World Conference on Earthquake Engineering (16WCEE), Santiago, Chile, 9–13 January 2017.
167. Li, J.Z.; Guan, Z.G. Research progress on bridge seismic design: Target from seismic alleviation to post-earthquake structural resilience. *China J. Highw. Transp.* **2017**, *12*, 1–9.
168. Ameli, M.; Parks, J.E.; Brown, D.N.; Pantelides, C.P. Seismic evaluation of grouted splice sleeve connections for reinforced precast concrete column-to-cap beam joints in accelerated bridge construction. *PCI J.* **2015**, *2*, 80–102. [[CrossRef](#)]
169. Geurrini, G.; Restrepo, J.I.; Massari, M.; Vervelidis, A. Seismic behavior of posttensioned self-centering precast concrete dual-shell steel columns. *J. Struct. Eng.* **2015**, *4*, 04014115.
170. Guo, Z.; Chen, X.C.; Ding, M.B. Experimental study and analysis on the seismic performance of new base rocking isolation bridge piers. *J. Vib. Shock* **2020**, *4*, 69–74.
171. Guo, Z.; Chen, Y.; He, K. Shaking table test and numerical simulation study on base rocking isolation bridge piers. *J. Build. Struct.* **2020**, *6*, 38–48.
172. Yang, C.; Okumus, P. Impact of connections on the seismic performance of precast concrete bridge piers. In *The 17th World Conference on Earthquake Engineering*; International Association for Earthquake Engineering: Sendai, Japan, 2021.
173. Liu, Y.Q.; Liang, F.; Au, F.T.K. Precast segmental bridge columns with resettable sliding joints: An inspiration from ancient Chinese pagodas. *Structures* **2021**, *33*, 615–626. [[CrossRef](#)]
174. Liu, Y.Q.; Liang, F.; Au, F.T.K. Experimental study of durable low-friction concrete contacts for precast segmental columns with resettable sliding joints. *Constr. Build. Mater.* **2022**, *318*, 126192. [[CrossRef](#)]
175. Rahmzadeh, A.; Alam, M.S.; Tremblay, R.; King, P. Experimental and finite element studies on the cyclic response of post-tensioned rocking steel bridge piers. In Proceedings of the 17th World Conference on Earthquake Engineering, Sendai, Japan, 27 September–2 October 2021; International Association for Earthquake Engineering: Sendai, Japan, 2021.
176. Shen, Y.L.; Zhao, Z.H.; Wei, B. Experimental evaluation of reinforced concrete hollow piers based on shaking table test. *World Earthq. Eng.* **2021**, *1*, 93–102.
177. Sun, H.; Xu, Q.; Ding, F.; Wang, L.; Lyu, F.; Sadat, S.I. Research on seismic performance of thin-walled stirrup-confined rectangular concrete filled steel tube piers. *J. Railw. Sci. Eng.* **2024**, *176*, 108310.
178. Zhang, Y.; Zhu, Y.P.; Yeseta, M. Flexural behaviors and capacity prediction on damaged reinforcement concrete bridge deck strengthened by Ultra-High-Performance Concrete (UHPC) layer. *Constr. Building Mater.* **2019**, *215*, 347–359. [[CrossRef](#)]
179. Xu, W.J.; Shao, X.D.; Ma, B. Technical and experimental studies of precast bridge piers with the UHPC connection. *China Civ. Eng. J.* **2022**, *12*, 105–116+127.
180. Pu, Q.; Yang, Y.; Lin, Q.; Yang, D. Experimental Study on RC Eccentric Compressive Column Strengthened by HTRCS. *J. Southwest Jiaotong Univ.* **2018**, *3*, 177–184.
181. Xu, T.F.; Chen, Y.; Li, Q. Life cycle sustainability assessment of high-performance concrete bridge piers with resin-based composite connections. *J. Clean. Prod.* **2023**, *13*, 135542.
182. Fu, H.; Zhao, H.; Pan, Z. Behaviour of corroded circular steel tube strengthened with external FRP tube grouting under eccentric loading: Numerical study. *Structures* **2023**, *56*, 104810. [[CrossRef](#)]
183. Fu, H.; Guo, K.; Wu, Z. Experimental investigation of a novel CFRP-Steel composite tube-confined seawater-sea sand concrete intermediate long column. *Int. J. Integr. Eng.* **2024**, *5*, 466–475. [[CrossRef](#)]
184. Fu, H.; Tian, J.; Chen, S.T. Axial compressive performance of CFRP-steel composite tube confined seawater sea-sand concrete intermediate slender columns. *Constr. Build. Mater.* **2024**, *441*, 137399. [[CrossRef](#)]
185. Fu, H.; Tian, J.; Chin, C.L. Axial compression behavior of GFRP-steel composite tube confined seawater sea-sand concrete intermediate long columns. *Eng. Struct.* **2025**, *333*, 120157.
186. Tazarv, M.; Saiidi, M.S. Low-damage precast columns for accelerated bridge construction in high seismic zones. *J. Bridge Eng.* **2015**, *21*, 3. [[CrossRef](#)]
187. Cao, S.; Ozbulut, O.E.; Shi, F.; Deng, J. Experimental and Numerical Investigations on Hysteretic Response of a Multi-level SMA/lead Rubber Bearing Seismic Isolation System. *Smart Mater. Struct.* **2022**, *31*, 035024. [[CrossRef](#)]
188. Tian, J.; Zhang, S.; Wu, X.; Zheng, Y.; Yu, W.; Wang, W.-W.; Yuan, J.; Fu, H.; Pang, S.; Zuo, Y. Study on the comprehensive performances of self-sensing ECC under coupling effect of temperature and load: Microscopic characterization, self-sensing performance, damage self-sensing theoretical model. *Constr Build Mater.* **2025**, *499*, 144088. [[CrossRef](#)]
189. Wu, X.; He, J.; Tian, J.; Zheng, Y.; Fu, H.; Yuan, J.; Lu, S.; Huang, W. Degradation behaviors and damage model of the interface between ECC and concrete under sulfate wet-dry cycling. *Constr Build Mater.* **2025**, *476*, 141283.
190. Tong, L.; Fu, L.; Wu, B. Packing fraction effect on dynamic creep deformation of granular materials. *Acta Geotech.* **2025**, *20*, 2135–2144. [[CrossRef](#)]

191. Tong, L.; Fu, L.; Wu, B.; Xu, C.J.; Lim, W.C.; Ding, H.B. Particle Shape Effect on Creep and Fluidity of Granular Packing. *J. Eng. Mech.* **2025**, *151*, 04025067. [[CrossRef](#)]
192. Ding, H.; Yu, Y.; Xu, C.; Pu, X.; Guo, W.; Tong, L. Analytical Modeling for Nonlinear Seismic Metasurfaces of Saturated Porous Media. *Int. J. Mech. Sci.* **2025**, *303*, 110666. [[CrossRef](#)]

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