Effect of Subgrade Boundary on Seismic Response of the High-Speed Railway Track-Bridge System

Biao Wei[1,3,a], Shuaijie Yuan[2,3,b*], Lizhong Jiang[1,3,c], Yujie Yu[1,3,d]

[1]National Engineering Research Center of High-Speed Railway Construction Technology, Changsha, 410075, China
[2]China Railway Group Limited, Beijing, 100039, China
[3]School of Civil Engineering, Central South University, Changsha, 410075, China

[a]weibiao@csu.edu.cn, [b*]234811027@csu.edu.cn
[c]Izhjiang@csu.edu.cn, [d]yujiecsu@csu.edu.cn

Abstract. As a crucial component of the boundary conditions on both sides of the high-speed railway track-bridge system, the seismic response of the flexible subgrade structure is markedly different from that of the bridge structure. This difference has been increasingly pronounced with the widespread implementation of constant welded rail technology in the construction of high-speed railway bridges. This study delves into the bridge system incorporating the CRTSII ballastless track structure, specifically examining the effect of the longitudinal constraint range of the subgrade structure on the bridge system 's seismic response under various seismic intensities. The findings reveal that the subgrade structure profoundly impacts the bridge system 's longitudinal stiffness, whereas its effect on transverse stiffness is comparatively marginal. It is observed that the impact on the system stabilizes as the subgrade structure extends to 130 meters. Therefore, a 130-meter length of the subgrade structure can be used as a feasible reference value for the range of bridge-subgrade coupling.

Keywords: the High-Speed Railway Track-Bridge System, Longitudinal constraint effect, the Subgrade Structure, Seismic Response.

1 Introduction

The role of subgrade structure is crucial in defining the boundaries on both side of a bridge within the High-Speed Railway Track-Bridge System (HSRTBS)[1]. Additionally, the application of continuous welded rail technology in high-speed railway bridge construction has resulted in a unified track structure extending from the bridge structure to the subgrade structure, effectively creating a cohesive link between them[2]. During seismic events, the seismic response of the track structure on the bridge is more pronounced compared to that on the flexible subgrade. Being the only longitudinally unified structure in the continuous beam bridge of a high-speed railway, the track structure acts as a constraint, limiting the bridge's seismic displacement response to a certain degree. The length of the subgrade structure differentially affects the seismic response

P. Liu et al. (eds.), *Proceedings of the 2024 5th International Conference on Civil, Architecture and Disaster Prevention and Control (CADPC 2024)*, Atlantis Highlights in Engineering 31,
https://doi.org/10.2991/978-94-6463-435-8_24

of the bridge system. In finite element modeling, a limited subgrade longitudinal constraint range might lead to inaccuracies in seismic response calculations, failing to adequately reflect the complexities of the actual project. On the other hand, an extensive longitudinal constraint range in the subgrade enhances the computational precision but also increases the analysis time, which can be challenging for project schedules[3]. Conventional bridge engineering design frequently neglects the longitudinal constraining impact of the subgrade structure on the bridge's seismic behavior, which can result in possible inaccuracies or misjudgments in the design methodology[4].

Accurate seismic analysis of bridge structures necessitates considering the subgrade structure in the railway track-bridge system, as explored by numerous researchers. Hu[5] created a coupling system encompassing a train, track, and subgrade, revealing that the bridge-subgrade transition section experiences peak dynamic stress and displacement. Yan[6] employed a 100-meter finite element model for the subgrade track outside the bridge, aiming to minimize boundary condition impacts. Montenegro[7] modeled track extensions at viaduct ends for accurate transition zone representation. Liu[8] extended the subgrade length to 150 meters as per DS899 and UIC774-3 codes to negate boundary condition influences. Zhang[9] established a simplified model of CRTS II slab ballastless track high-speed railway beam bridge, focusing on longitudinal constraints and track-beam interactions, highlighting that the subgrade's effect on the bridge is only partial. Yu[10] analyzed a bridge model to study the post-earthquake discrepancies in the railway track-bridge system, emphasizing the adjacent subgrade's impact. Wei[11] examine the seismic vulnerability of HSR bridges with track constraints, emphasizing the importance of track-bridge interaction in seismic response analysis. Zhang[12] examined the seismic response difference across spans of high-speed railway bridges, proposing a method to control the difference by enhancing connection stiffness between girders. Jiang[13] found that there is a critical track length in the subgrade track structure when evaluating the influence of subgrade track structure with different lengths on the simply supported beam bridge system of high-speed railway. Prior research indicates a substantial impact of the subgrade structure on a bridge's seismic responses. However, previous simulations of the subgrade structure usually approximate them as single-layer longitudinally continuous systems[14-16], which is insufficient to address the longitudinal constraint effects of multi-layer continuous track systems. While creating an authentic subgrade model enhances the simulation of the subgrade-bridge interaction, introducing such a model into a highly detailed bridge simulation significantly hampers computational efficiency. Moreover, given the symmetry and repeatability of simply supported beam bridges in modeling, many studies focus on multi-span simply supported beam bridges, with fewer considering continuous beam bridges[17]. With the gradual increase of bridge construction span, the proportion of continuous beam bridge in the bridge is getting higher and higher. There are still few studies on the influence of subgrade structure on the seismic response of key components of continuous beam system. Consequently, investigating the impact of subgrade structure on the seismic response of continuous beam bridge systems is of paramount importance.

Based on SAP2000 finite element analysis software, this study takes a 48 m + 80 m + 48 m two-lane continuous beam bridge[18] as the research object, fully considering the longitudinal restraint effect of subgrade structure. This model includes a four-span simply supported beam approach bridge and subgrade structures on both sides of the continuous beam bridge. The upper section of this assembly features a CRTSII ballastless track structure. Figure 1 in the document depicts this as a model of a high-speed railway continuous beam bridge.

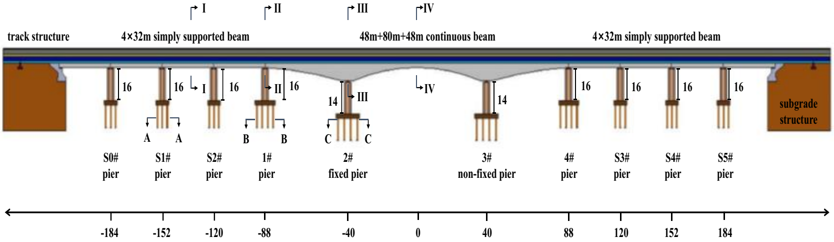


Fig. 1. High-Speed Railway Continuous Beam Bridge Model

2 Finite Element Model

Typically, bridge superstructures exhibit elastic behavior during seismic activities. The HSRTBS components, such as box beams, base plates, track plates, and rails, are represented by frame elements spaced 0.65 meters apart[19]. Critical components like the sliding layer, CA mortar layer, fasteners, shear tooth groove, shear reinforcement, and horizontal block are integral to the internal force transmission in the track structure[20]. Hence, they are modeled using elastic-plastic connection elements. The material properties of each element are detailed in Table 1. In cases where seismic impact on the piers is considered minimal under damping conditions, solid rectangular piers are effectively represented using rectangular beam elements. The intervals for side piers are set at 0.8 meters, and for main piers at 1 meter. Bearings are modeled as spherical rigid bearings, with their dynamic hysteresis curves resembling the stress-strain behavior of ideal elastic-plastic materials. This study also accounts for the pile-soil effect. The interaction between the piles and the soil at the foundation base is simulated using zero-length elements, essentially fully elastic soil-spring connected units with six degrees of freedom. Additionally, the subgrade section also includes friction plates, end spurs and water-hardened support layers. In this study, it is assumed that the bottom constraint of the subgrade structure is fixed, and the influence of the deformation of the foundation and the change of internal force on the subgrade structure can be ignored. In the finite element software, friction plates, end spurs and water-hardened support layers can be simulated using boundary elastic joint unit pairs.

3 Earthquake Input

In the absence of historical seismic data for the bridge, a seismic acceleration response spectrum curve is chosen based on the seismic design standards for highway bridges. The HSRTBS assumes a damping ratio of 0.05, with the bridge's characteristic seismic period established at 0.25 seconds and a dynamic amplification factor of the seismic spectrum at 2.25[21]. To explore the potential restraining effect of subgrade structures on continuous beam bridge systems in both longitudinal and transverse directions, this study utilizes two distinct seismic load combinations. The first comprises longitudinal and vertical ground movements, while the second involves transverse and vertical ground movements. Employing these combinations, the research conducts response spectrum analyses on continuous beam bridge models featuring various lengths of subgrade structures, specifically at 0 meters, 10 meters, 50 meters, 90 meters, and 130 meters. In order to analyze the differences in the seismic response of HSRTBS under normal earthquakes, design earthquakes, and rare earthquakes, the Peak Ground Acceleration (PGA) can be taken as 0.1g, 0.2g, and 0.4g, respectively. The proportional coefficient of the ground motion component is detailed in Table 2.

Table 1. Material properties of critical components

Component	Material	Elastic modulus(N·mm^{-2})	Density(kg·m^{-3})	Poisson ratio
main beam	C50	$2.0\times10^{\wedge5}$	7850	0.3
bridge pier	C30	$3.6\times10^{\wedge5}$	2500	0.2
base plate	C30	$3.3\times10^{\wedge5}$	2500	0.2
track slab	C55	$3.7\times10^{\wedge5}$	2500	0.2
rail	CHN60	$2.1\times10^{\wedge5}$	7830	0.3
friction plate	C30	$1.8\times10^{\wedge5}$	2500	0.2

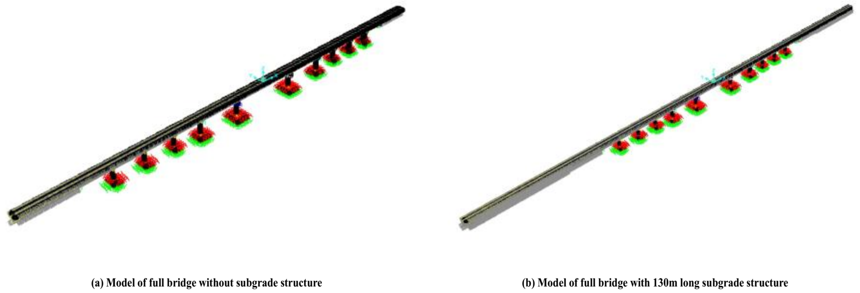
Table 2. Proportion coefficient of ground motion component

Working condition	Name	Longitudinal peak ground acceleration	Transverse peak ground acceleration	Vertical peak ground acceleration
1	Ex+z-0.05g	0.05	——	0.0333
2	Ey+z-0.05g	——	0.05	0.0333
3	Ex+z-0.1g	0.1	——	0.0666
4	Ey+z-0.1g	——	0.1	0.0666
5	Ex+z-0.2g	0.2	——	0.1333
6	Ey+z-0.2g	——	0.2	0.1333
7	Ex+z-0.4g	0.4	——	0.2666
8	Ey+z-0.4g	——	0.4	0.2666
9	Ex+z-0.8g	0.8	——	0.5332
10	Ey+z-0.8g	——	0.8	0.5332

4 The Effect of Subgrade Structure on HSRTBS

4.1 Dynamic Characteristic Analysis

Dynamic characteristic analysis is the basis of bridge seismic performance analysis. As shown in Figure 2, two bridge models without subgrade structure and subgrade structure with a length of 130m are selected for modal analysis. Through the analysis and comparison of vibration mode and natural vibration period, it can be seen that the longitudinal constraint effect of subgrade structure has a certain influence on the order of the first 10 modes of the model. The main beam's primary longitudinal deflection vibration shifts from the first to the seventh modal order. Additionally, this constraining effect drastically shortens the bridge model's longitudinal modal period by 48.12%, although it marginally affects the transverse vibration period. This phenomenon is attributed to the subgrade's longitudinal constraint, which unifies the bridge and subgrade structures, thereby enhancing the bridge's longitudinal coherence and providing extra longitudinal stiffness. Therefore, during the seismic design phase of bridges, it is imperative to thoroughly account for the longitudinal restraining influence exerted by subgrade structures. This approach not only yields more precise data for the seismic design of bridges but also mitigates the financial expenditure associated with the overdesign of bridge seismic robustness.



(a) Model of full bridge without subgrade structure

(b) Model of full bridge with 130m long subgrade structure

Fig. 2. Finite Element Model

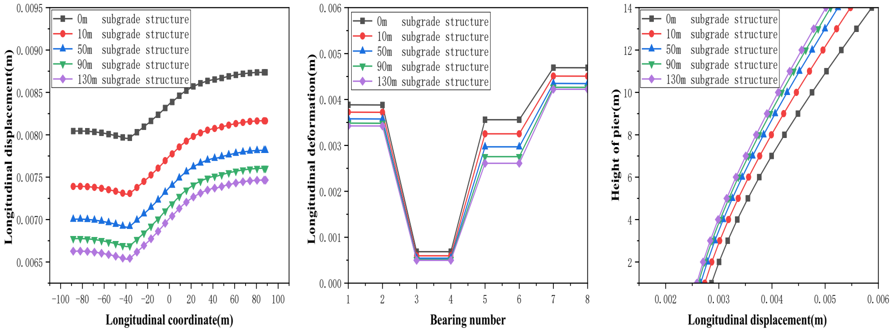
4.2 Bridge structure

This section describes the change of the seismic response of the critical components of the HSRTBS when the length of the subgrade structure is 0m, 10m, 50m, 90m and 130m respectively. Since each finite element model is in an elastic state, its displacement and internal force change proportionally and linearly under different peak ground accelerations. Therefore, this section only lists the response spectrum analysis and comparison results of each finite element model when the peak ground acceleration is 0.1g.

Under the comprehensive effect of longitudinal and vertical seismic motions, the study reveals a notable trend correlating with the increasing length of the subgrade structure. Specifically, there is a consistent decrease in the main beam' longitudinal displacement, the bearings' longitudinal deformation, and the piers' longitudinal displacement. Concurrently, a reduction is observed in the vertical axial force, longitudinal shear force, and transverse bending moment of certain foundation piles. This decreasing trend of seismic effects tends to stabilize when the subgrade structure extends to approximately 130 meters, as demonstrated in Figure 3. In contrast, the study shows that under the influence of lateral and vertical seismic motions, the increase in the length of the subgrade structure does not significantly alter the main beam' lateral displacement, the bearings' lateral deformation, or the bearings' vertical axial force. Moreover, the lateral displacement, lateral shear force, and longitudinal bending moment of the piers, as well as the forces and moments experienced by the pile foundations, exhibit minimal change, clearly depicted in Figure 4. Consequently, when addressing longitudinal seismic motion in bridge seismic design, especially during the finite element modeling of bridge structures, it is crucial to comprehensively incorporate the longitudinal restraining effect of subgrade structures. This consideration ensures the effective and precise determination of the seismic response of critical components within the continuous beam bridge system. Conversely, in the context of seismic design for bridges where transverse seismic motion is the focus, the longitudinal restraint effect exerted by subgrade structures may be disregarded. By excluding the subgrade structure from the finite element model, one can significantly enhance the computational efficiency of the model.

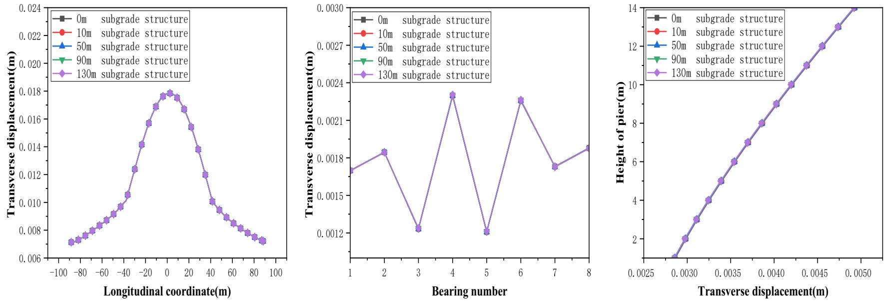
4.3 Track Structure

Amid the combined effects of longitudinal and vertical seismic movements, extending the subgrade structure's length tends to gradually reduce the longitudinal displacement of the base plate, track plate, and track. However, their vertical displacement remains largely unchanged. There is a steady increase in the longitudinal shear force of the shear tooth groove and the CA layer at the juncture between the side pier and approach bridge. This impact begins to subside as the subgrade structure length nears 130 meters, as illustrated in Figure 5. Facing the composite influence of lateral and vertical seismic motions, the extension of the subgrade structure does not significantly alter the lateral and vertical displacements of the base plate. The transverse shear force of the shear tooth groove and CA layer, along with the longitudinal and transverse shear forces of the fasteners, largely remain constant. However, there is an observable gradual decrease in the longitudinal shear force within both the shear tooth groove and the CA layer. This decreasing trend begins to level off as the subgrade structure approaches a length of approximately 130 meters, as depicted in Figure 6. With the prevalent adoption of continuous rail welding technology in the infrastructure of high-speed railway bridge systems, ensuring the track structures' smoothness has gained paramount importance. Integrating the longitudinal restraining effect of the subgrade structure into the design not only aids in accurately assessing track irregularities but also markedly diminishes stress concentration at the beam joints. This approach ensures the preservation of the track system's integrity across both subgrade structures and bridge structures. Additionally, the impact of the subgrade's longitudinal constraint on the track structure diminishes as the length of the subgrade increases. A subgrade track structure measuring 130 meters can serve as a benchmark for optimizing subgrade-bridge interaction. In finite element modeling, this insight allows for the avoidance of simulating an infinitely long track structure by adequately addressing the boundary conditions of the subgrade track structure.



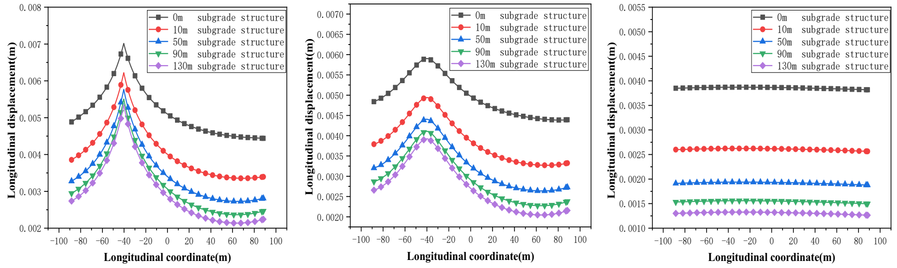
(a)Main beam (b)Bearing (c)Fixed pier

Fig. 3. Seismic response results of main beam, bearing and pier under the combined action of longitudinal and vertical ground motion



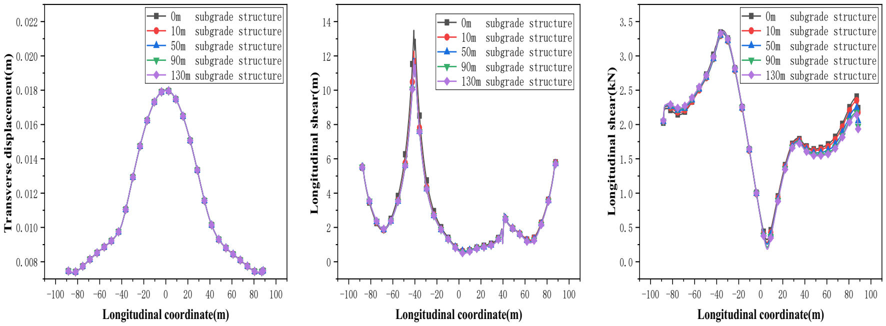
(a)Main beam (b)Bearing (c)Fixed pier

Fig. 4. Seismic response results of main beam, bearing and pier under the combined action of lateral and vertical ground motion



(a)Base plate (b)Track plate (c)Rail

Fig. 5. Seismic response results of main beam, bearing and pier under the combined action of longitudinal and vertical ground motion



(a)Base plate (b)Track plate (c)Rail

Fig. 6. Seismic response results of base plate, CA layer and fastener under the combined action of lateral and vertical ground motion

5 Conclusions

In this study, a model of a continuous beam bridge that incorporates the subgrade structure was developed using the SAP2000 finite element software. Through the analysis of the seismic responses of the continuous beam bridge system under the influence of subgrade structures of varying lengths, the following conclusions can be drawn:

1. The longitudinal restraint effect caused by subgrade structure will significantly reduce the longitudinal vibration period of the bridge structure, and has little effect on the transverse vibration period. This phenomenon can be attributed to the significant impact of subgrade structure on the bridge's longitudinal stiffness., in contrast to its relatively minor influence on the lateral stiffness.
2. Amid the combined effects of longitudinal and vertical seismic movements, the longitudinal restraint effect caused by subgrade structure has more obvious influence on the seismic response of critical components of bridge system. However, Facing the composite influence of lateral and vertical seismic motions, the influence of the longitudinal restraint effect of the subgrade structure on the seismic response of the critical components of the bridge and track structure is almost negligible.
3. As the length of the subgrade structure progressively reaches 130m, the degree of impact levels off. Therefore, according to the object studied in this paper, the subgrade structure with a length of 130 m can be used as a feasible reference value for the bridge-subgrade coupling range.
4. The longitudinal constraint effect of subgrade structure is obviously related to the length of subgrade structure. However, it is not clear whether the change of subgrade structure parameters will affect the longitudinal constraint effect of subgrade structure, which needs further research and determination. Since the track system extends from the bridge structure to the subgrade structure, whether the subgrade structure parameters and their types affect the irregularity of the track structure is the focus of further research.

Acknowledgements

This research work was jointly supported by Science and Technology Research and Development Program Project of China Railway Group Limited (2020-Key-02,2022-major-17), the Natural Science Foundations of Hunan Province (Grant No. 2022JJ10079 and 2022JJ20073), and the Frontier cross research project of Central South University (Grant No.2023QYJC006).

References

1. Lai, Z.P.; Jiang, L.Z. (2022) Analytical evaluation of lateral rail unevenness on high-speed railway bridge after transversal seismic shaking. ENGINEERING STRUCTURES 267, doi: 10.1016/j.engstruct.2022.114614.
2. Zhai, W.M.; Wang, K.Y.; Chen, Z.W.; Zhu, S.Y.; Cai, C.B.; Liu, G. (2020) Full-scale multi-functional test platform for investigating mechanical performance of track-subgrade systems of high-speed railways. RAILWAY ENGINEERING SCIENCE 28, 213-231, doi:10.1007/s40534-020-00221-y.
3. Guo, W.; Hu, Y.; Gou, H.Y.; Du, Q.D.; Fang, W.B.; Jiang, L.Z.; Yu, Z.W. (2020) Simplified seismic model of CRTS II ballastless track structure on high-speed railway bridges in China. ENGINEERING STRUCTURES 211, doi: 10.1016/j.engstruct.2020.110453.
4. Zhou, W.B.; Peng, D.H.; Liu, L.L.; Zhang, Y.T.; Lai, Z.P.; Yu, J.; Jiang, L.Z. (2023) Transverse seismic analysis of high-speed railway bridge in China based on a simplified calculation model. JOURNAL OF CENTRAL SOUTH UNIVERSITY 30, 351-364, doi:10.1007/s11771-023-5226-7.
5. Hu, P.; Zhang, C.S.; Guo, W.; Wang, Y.H. (2020) Dynamic Response of a Bridge-Embankment Transition with Emphasis on the Coupled Train-Track-Subgrade System. APPLIED SCIENCES-BASEL 10, doi:10.3390/app10175982.
6. Yan, B.; Dai, G.L.; Zhang, H.P. (2012) Beam-track interaction of high-speed railway bridge with ballast track. JOURNAL OF CENTRAL SOUTH UNIVERSITY 19, 1447-1453, doi:10.1007/s11771-012-1161-8.
7. Montenegro, P.A.; Calçada, R.; Pouca, N.V.; Tanabe, M. (2016) Running safety assessment of trains moving over bridges subjected to moderate earthquakes. EARTHQUAKE ENGINEERING & STRUCTURAL DYNAMICS 45, 483-504, doi:10.1002/eqe.2673.
8. Liu, W.S.; Dai, G.L.; Yu, Z.W.; Chen, Y.F.; He, X.H. (2018) Interaction between continuous welded rail and long-span steel truss arch bridge of a high-speed railway under seismic action. STRUCTURE AND INFRASTRUCTURE ENGINEERING 14, 1051-1064, doi:10.1080/15732479.2017.1386690.
9. Zhang, Y.T.; Jiang, L.Z.; Zhou, W.B.; Feng, Y.L.; Tan, Z.H.; Chai, X.L. (2020) Study of bridge-subgrade longitudinal constraint range for high-speed railway simply-supported beam bridge with CRTSII ballastless track under earthquake excitation. CONSTRUCTION AND BUILDING MATERIALS 241, doi: 10.1016/j.conbuildmat.2020.118026.
10. Yu, J.; Jiang, L.Z.; Zhou, W.B.; Lu, J.Y.; Zhong, T.X.; Peng, K. (2021) Study on the influence of trains on the seismic response of high-speed railway structure under lateral uncertain earthquakes. BULLETIN OF EARTHQUAKE ENGINEERING 19, 2971-2992, doi: 10.1007/s10518-021-01085-1.
11. Wei, B.; Wang, W.H.; Wang, P.; Yang, T.H.; Jiang, L.Z.; Wang, T. (2022) Seismic Responses of a High-speed Railway (HSR) Bridge and Track Simulation under Longitudinal

Earthquakes. JOURNAL OF EARTHQUAKE ENGINEERING 26, 4449-4470, doi: 10. 1080/13632469.2020.1832937.

12. Zhang, Y.T.; Jiang, L.Z.; Zhou, W.B.; Lai, Z.P.; Liu, X.; Peng, K.; Wang, Z.; Feng, Y.L. (2022) Control of Difference of Seismic Response across Different Spans of high-speed railway multi-spans simply supported bridge. BULLETIN OF EARTHQUAKE ENGINEERING 20, 6919-6941, doi:10.1007/s10518-022-01470-4.
13. Jiang, L.Z.; Feng, Y.L.; Zhou, W.B.; He, B.B. (2019) Vibration characteristic analysis of high-speed railway simply supported beam bridge-track structure system. STEEL AND COMPOSITE STRUCTURES 31, 591-600, doi:10.12989/scs.2019.31.6.591.
14. Zanardo, G.; Hao, H.; Modena, C. (2002) Seismic response of multi-span simply supported bridges to a spatially varying earthquake ground motion. EARTHQUAKE ENGINEERING & STRUCTURAL DYNAMICS 31, 1325-1345, doi:10.1002/eqe.166.
15. Jankowski, R.; Wilde, K.; Fujino, Y. (2000) Reduction of pounding effects in elevated bridges during earthquakes. EARTHQUAKE ENGINEERING & STRUCTURAL DYNAMICS 29, 195-212, doi: 10.1002/(SICI)1096-9845(200002)29:2<195: AID-EQE897> 3.0.CO;2-3.
16. Li, Y.; Conte, J.P. (2016) Effects of seismic isolation on the seismic response of a California high-speed rail prototype bridge with soil-structure and track-structure interactions. EARTHQUAKE ENGINEERING & STRUCTURAL DYNAMICS 45, 2415-2434, doi:10.1002/eqe.2770.
17. Gou, H.Y.; Yang, L.C.; Leng, D.; Bao, Y.; Pu, Q.H. (2018) Effect of bridge lateral deformation on track geometry of high-speed railway. STEEL AND COMPOSITE STRUCTURES 29, 219-229, doi:10.12989/scs.2018.29.2.219.
18. Yang, M.G.; Meng, D.L.; Gao, Q.; Zhu, Y.P.; Hu, S.T. (2019) Experimental study on transverse pounding reduction of a high-speed railway simply-supported girder bridge using rubber bumpers subjected to earthquake excitations. ENGINEERING STRUCTURES 196, doi: 10.1016/j.engstruct.2019.109290.
19. Wei, B.; Li, C.B.; Wang, P.; Jiang, L.Z.; Wang, T. (2020) The seismically induced failure sequence of multiple components of high-speed railway bridges under different earthquake intensities. JOURNAL OF VIBROENGINEERING 22, 1629-1647, doi: 10. 21595/ jve. 2020.21280.
20. Meng, D.L.; Chen, S.Z.; Yang, M.G.; Hu, S.T. (2021) Effects of shear keys and track system on the behavior of simply-supported bridges for high-speed trains subjected to transverse earthquake excitations. ADVANCES IN STRUCTURAL ENGINEERING 24, 2607-2621, doi:10.1177/13694332211007398.
21. Kang, X.; Jiang, L.Z.; Bai, Y.; Caprani, C.C. (2017) Seismic damage evaluation of high-speed railway bridge components under different intensities of earthquake excitations. ENGINEERING STRUCTURES 152, 116-128, doi: 10.1016/j.engstruct.2017.08.057.