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Theory and Applications

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Preface

In recent years, the high-speed railway (HSR) has got remarkable development in China. By the end of 2016, the total length of HSR lines had been 22,000 km. In addition, there are more than tens of HSR lines being constructed. According to the "Thirteenth Five-year Plan" of China, the total length of HSR lines will reach 30,000 km by 2020, and it will be further extended to 38,000 km by 2025.

The high-speed railway has the characteristics of high speed and high traffic density of trains; thus, the problem of train-bridge coupling vibrations is very prominent. On the one hand, the high-speed train will produce a dynamic impact on the bridge structure, causing it to vibrate, which directly affects the working status and the service life of the bridge. On the other hand, the vibration of the bridge will in turn affect the running safety and stability of the on-bridge train. This makes the vibration behaviors of train-bridge system become one of the fundamental problems that need to be solved in the bridge design. It is an actual requirement for engineers to carry out comprehensive studies on the dynamic interaction of the coupled train-bridge system. This includes the dynamic analysis and assessment on the dynamic properties of the bridge structure, as well as the running safety and stability of the high-speed train. Therefore, great efforts have been continuously made to study the dynamic interaction between high-speed train and bridge. After years of development, the coupling vibration of train-bridge system has become a specialized research field.

In China, researchers have established a number of analysis models, performed systematic study on the dynamic responses of train-bridge interaction system, and achieved remarkable results for the actual engineering projects, making important contribution to the dynamic design of HSR bridges.

This book is the fruitful result of the research projects sponsored by the National Key Basic Research Program ("973" Program, 2013CB036203), the National High-technology Research and Development Program (863 Program, 2011AA11A103-3-2-1), the Natural National Science Foundations (Grant No. 51078029, 511780255, 51208027, 51208028, 51308034, 51308035, U1434205, U1434210, and 51678032), the Research Fund for Doctoral Program of Higher Education (20130009110036), and the Supporting Program for New-century Excellent Talents in Universities (NCET-10-0219) of China, the Science and Technology Research Plans of China Railway Corporation (2013G001-A-1, 2013G001-B, 2013G004-C, 2015G002-A and 2015G006-M), and the Flanders (Belgium)-China Bilateral Project (Grant No. BIL 07/07).

In Chap. 1, starting with a general overview of HSR developments in China and abroad, the key technologies of HSR bridge construction in China are introduced, the research history and status quo of train-bridge coupling vibration are reviewed, the dynamics problems of HSR bridges are summarized, and the research contents and analysis methods for coupling vibrations of train-bridge system in HSR are expounded.

In Chap. 2, some fundamental theories and methods for vibration analysis of simply-supported beams under moving loads are presented. The analytical solutions of beam vibrations induced by a moving concentrated load, a moving harmonic load, and a moving wheel-spring-mass load with varying speed are deduced, and the vibration characteristics of them are investigated in several case studies. As one of the important phenomena related to the train-bridge coupling vibration, the mechanisms of vibration resonance, suppression, and cancellation happened in the moving-load and beam system are analyzed.

In Chap. 3, the self-excitations of train-bridge coupling vibration system are introduced. The characteristics and control standards of track irregularities, and the mechanism and description of vehicle hunting movement are summarized. The AR (auto-regressive) model simulation method of random excitations on the train-bridge system is studied.

In Chap. 4, the vibration criteria for HSR bridges and train vehicles in China are summarized, including a series of codes, standards and specifications related to the dynamic coupling analysis and test of train-bridge system, the control criteria for running safety of high-speed train due to bridge and train vibrations, the riding comfort of passengers on running train vehicles, and the structural safety serviceability of bridge due to vibrations. The conditions unnecessary to conduct coupling dynamic analysis of train-bridge system are also introduced.

Chapter 5 recapitulates the dynamic analysis models for train-bridge coupling system and the solution methods. The motion equations for the train-bridge coupling vibration system are derived. The solution methods for motion equations of train-bridge system, such as the direct coupling method, the in-time-step iteration method, and the intersystem iteration method, are studied. By taking a Pioneer EMU running through a multi-span simply-supported PC box-beam bridge on the Qinhuangdao-Shenyang HSR line as an illustrating example, the dynamic responses of train-bridge system are analyzed and the convergence in equation solution procedure is investigated.

Chapter 6 studies the vibration of coupled train-bridge system subjected to crosswinds. The influences of wind barriers on the wind velocity field around bridge structure and the aerodynamic behaviors of train vehicles are investigated. A spatial dynamic analysis model of train-bridge system subjected to crosswinds is established. The dynamic responses of the Tsing Ma Suspension Bridge in Hong

Kong are calculated, and some results are compared with the measured data, from which the threshold curve of train speed and wind velocity for ensuring the running safety of the train on the bridge is proposed. Considering the aerodynamic effect of wind barriers on a simply-supported PC girder bridge, the dynamic responses of the wind-train-bridge system are calculated, and the windbreak effect of different wind barriers is evaluated.

Chapter 7 deals with the vibration of train-bridge system subjected to earthquake action. The spectral theory-based simulation method for seismic ground motion considering spatial variation and the method for obtaining consistent earthquake record are summarized. The dynamic analysis models of a single wheel-spring-mass unit (series) passing through a simply-supported beam as well as the train-bridge system subjected to earthquakes are established. The dynamic responses of an ICE3 train passing through a steel trussed-arch bridge subjected to earthquakes are calculated, and the influences of the seismic characteristics and the input manners on the dynamic responses of train-bridge system are investigated. The running safety criteria and evaluation process of train vehicles on bridge subjected to earthquakes are proposed.

Chapter 8 is devoted to the vibration of train-bridge system subjected to collision loads. The characteristics of various collision loads on bridge are summarized. A dynamic analysis model is established for a coupled high-speed train and bridge system subjected to collision loads. An HSR double-track continuous bridge with (32+48+32) m PC box-girders is considered as an illustrative case study. The dynamic responses of the bridge and the running safety indices of the train on the bridge under three types of collision loads are analyzed. The results show that the large responses of the bridge induced by collision may strongly threaten the running safety of the train. An assessment procedure is proposed for the running safety of high-speed trains on bridges subjected to collision loads, and related threshold curves for train speed versus collision intensity are proposed.

Chapter 9 deals with the vibration of train-bridge system under differential settlement and scouring effect of foundations. The influence factors of differential settlement and the mechanism of scouring effect of pier foundations are summarized. A prediction method for cumulative settlement of bridge foundations caused by cyclic train loading is proposed, and the settlement of existing bridge foundations induced by the nearby bridge construction is calculated. The influence of differential settlement of bridge foundations on dynamic responses of train-bridge system is studied, and the train speed-settlement threshold curves for running safety and riding comfort of train are proposed. The stiffness of a single pile and the equivalent stiffness of group piles are studied, and the scouring effect on the stiffness of bridge foundations and the dynamic responses of the train-bridge system is investigated.

Chapter 10 deals with the vibration of train-bridge system under beam deformation induced by concrete creep and temperature effect. The numerical simulation method for PC beam creep camber is introduced. The vibration responses of train-bridge system excited by creep camber deformation are analyzed, and the safety threshold curves of creep camber under different train speeds are proposed, to ensure the running safety and stability of train vehicles. By numerical simulation and field measurement, the characteristics of bridge sidewise-bending and track slab-warping deformation under non-uniform temperature field are studied, and their influences on the dynamic response and running safety of the train-bridge system are investigated.

This book will not only provide theoretical formulations and various solutions for coupling vibrations of train-bridge system, but also describe the ways to extend the life of existing bridge structures and present a guide to the rational design of new bridges. It can also be referenced for solving vehicle–structure dynamic interaction problems in the design and the research of various types of highways, railways, and other transport structures.

This book is chiefly authored by H. Xia, N. Zhang, and W.W. Guo, with Chapter 1 written by H. Xia, N. Zhang, W.W. Guo, and Y.M. Cao; Chapter 2 by H. Xia, H.L. Li, K.P. Wang, and S.Q. Wang; Chapter 3 by W.W. Guo; Chapter 4 by N. Zhang; Chapter 5 by N. Zhang and X. Wu; Chapter 6 by W.W. Guo and T. Zhang; Chapter 7 by X.T. Du; Chapter 8 by C.Y. Xia; Chapter 9 by Y.M. Cao and K.P. Wang; and Chapter 10 by J.W. Zhan and K.P. Wang. In addition, the work by Y. Tian, K.B. Li, J.J. Yang, H. Qiao, M. Xu, S. Zhou, Y.J. Wang, Q. Sun, G.H. Ge, G.L. Xiao, and other graduate students also contributed to the related chapters.

In writing this book, we drew much on the knowledge and experience acquired from collaboration with many colleagues in China and abroad. We wish to express our deep appreciation to them. We also acknowledge the information and inspiration derived from the references listed at the end of the chapters.

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Contents

Chapter 1
Introduction

Since its occurrence, railway has been the focus of the world transportation. Entering the twenty-first century, railway construction has been speeded up in China to improve the passenger and freight transports. Especially, the development of high-speed railway has made remarkable achievements. As an infrastructure, bridges play a very important role in high-speed railway. With continuous raise of train speed, the bridge vibrations and their influences on running safety and stability of trains have drawn more attention. This chapter summarizes the key dynamics problems of high-speed railway bridges, reviews the research background and current status of train-bridge coupling vibration, and expounds the corresponding research contents and analysis method for coupling vibrations of train-bridge system in high-speed railway.

1.1 High-Speed Railways in China

1.1.1 Development of High-Speed Railways

The railway traffic has got great development with its safety, punctuality, and high efficiency since it appeared in England in 1825. With the progress of society and the development of science and technology, the demand for railway transport capacity is increasing, as well as for the train speed. According to UIC (Union Internationale des Chemins de Fer) in 1996, "new tracks specially constructed for high speeds, allowing a maximum running speed of at least 250 km/h, or existing tracks specially upgraded for high speeds, allowing a maximum running speed of at least 200 km/h" are defined as high-speed railway (HSR).

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Fig. 1.1 Shinkansen train passing by Mountain Fuji (wikipedia 2006)

The idea of high-speed train was firstly proposed and started to try by Germany in the late nineteenth century. On October 23, 1903, the S&H-equipped railcar achieved a speed of 206.7 km/h, demonstrating the feasibility of electric high-speed railway. However, regularly scheduled electric high-speed railway travel was still more than many years away. In 1964, the first high-speed railway in the world was built in Japan, namely the Tokaido Shinkansen line connecting Tokyo and Osaka (Fig. 1.1). The Shinkansen train speed was 200 km/h and gradually speeded up to 270 $\sim$ 300 km/h and used to have a record of 443 km/h in an experiment (1996, 955 Series 300X). On April 21, 2015, the new type "L0" maglev train with seven carriages achieved the world record of train speed of 603 km/h in a test (Fig. 1.2). In 1981, the articulated high-speed train TGV (Train à Grande Vitesse) was put into service on the Paris-Lyon HSR in France, and on April 3, 2007, it created the world record of 574.8 km/h for wheeled trains (Fig. 1.3). In 1971, Germany started the construction of Hanover-Wüzburg HSR and completed it in 1991, with the operation train speed of 280 km/h (Fig. 1.4).

Up to now, high-speed railways have been constructed in many countries, such as China, Spain, Japan, Germany, France, Sweden, Italy, Korea, Belgium, Netherlands, Switzerland, and Turkey and are planned or scheduled to construct in

Fig. 1.2 "L0" maglev train in Japan (world.huanqiu 2013)

Fig. 1.3 World record of train speed by TGV (060s 2016)

Fig. 1.4 ICE high-speed train in Germany (eurail 2016)

the USA, UK, Russia, India, Indonesia, Thailand, Vietnam, South Africa, Nigeria, and other countries. By November 1, 2013, except China, the total operation mileage of high-speed railways in the world reached 11,605 km; moreover, there were 4,883 km under construction and 12,570 km in plan, according to the statistics of UIC.

The development of high-speed railway can be divided into three stages. In the initial stage, Japan, France, and Germany started and constructed their HSR lines. In the second stage, the technology for HSR was improved and got matured in Japan and several European countries and then extended to some other countries. In the third stage, high-speed railways are constructed and planned in more countries worldwide.

1.1.2 Development of High-Speed Railways in China

Since 1990s, China's railway has accelerated its modernization process. During 1997–2007, six round large-scale speed-up campaigns were conducted, raising the highest speed of passenger trains from 120 km/h to 200 km/h on more than

6,000 km rail lines. Meanwhile, theoretical and experimental researches on high-speed trains and HSR infrastructures were started.

The Qin-Shen (Qinghuangdao-Shenyang) HSR, started to construct in August 1999, was the first high-speed railway in China, with total length of 404 km and design train speed of 200 km/h (reserved to 250 km/h). In December 2002, the China made "Pioneer" EMU and "China Star" high-speed train achieved the highest test speed of 292 km/h and 321.5 km/h on this line, respectively. The Qin-Shen HSR was opened to service on October 12, 2013, being the pioneer of high-speed railways in China.

The Suining-Chongqing Railway was constructed from 2003 to 2006, with total length of 155 km and design train speed of 200 km/h. In May 2005, a test speed of 234 km/h was achieved by the "Changbai Mountain" EMU in the test section of this line.

The Guangzhou-Shenzhen Railway built in 2007 was the first four-track railway in China, with two tracks for 200 km/h high-speed trains and two for common passenger trains and freight trains, which realized the passenger\freight separation transport, being the first intercity rail transit in China.

On January 7, 2004, the first "National Medium-and-long Term Railway Development Program" was approved by the China State Council and began to implement. According to the program, by 2020, the overall railway operation mileage would reach 100,000 km; the passenger\freight separation transport would be realized on the main lines; the percentages of double-track and electrified lines should be increased to 50%; the technical standards for main railway facilities should reach or approach to advanced international level, to meet the requirement of national economy and social development on railway transport capacity. In the program, one of the important plans was to speed up the construction of high-speed railways. As shown in Fig. 1.5, the HSR network composed of "Four-vertical and Four-parallel" trunk lines and three Regional FRT (fast rail transit) systems was scheduled, to build more than 12,000 km high-speed railways.

The HSR network was planned as follows:

(1) The Four Vertical HSR Trunk Lines

- Beijing-Shanghai HSR. Total length 1,318 km, passing through three municipalities (Beijing, Tianjin, and Shanghai) and four provinces (Hebei, Shandong, Anhui, and Jiangsu), connecting two important economic zones (the Circum-Bohai Sea and the Yangzi River Delta).
- Beijing-Wuhan-Guangzhou-Shenzhen HSR. Total length 2,260 km, connecting the northern, central, and southern zones of China.
- Beijing-Shenyang-Harbin HSR. Total length 1,700 km, connecting the Northeast China to the inside Shanhaiguan zones.
- Hangzhou-Ningbo-Fuzhou-Shenzhen HSR. Total length 1,600 km, connecting the Yangzi River Delta, Pearl River Delta, and southeast coastal zones of China.

Fig. 1.5 Planned HSR network in China by 2020

(2) The Four Parallel HSR Trunk Lines

- Xuzhou-Zhengzhou-Lanzhou-Urumqi HSR. Total length 3,177 km, connecting the northwest and eastern zones of China.
- Hangzhou-Nanchang-Changsha HSR. Total length 880 km, connecting the central and eastern zones of China.
- Qingdao-Shijiazhuang-Taiyuan HSR. Total length 770 km, connecting the northern and eastern zones of China.
- Nanjing-Wuhan-Chongqing-Chengdu HSR. Total length 1,600 km, connecting the southwest and eastern zones of China.

(3) The Three Regional FRT Systems

The three regional FRT systems include the Yangtze River Delta, the Pearl River Delta, and the Circum-Bohai Zone (Beijing, Tianjin, and Hebei Province), respectively, covering the major cities in their regions.

- The Yangzi River Delta FRT System. With Shanghai, Nanjing, and Hangzhou as the centers, forming a Z-shaped traffic framework to connect nearby main cities.

- The Pearl River Delta FRT System. With the 105 km Guangzhou-Shenzhen and the 143 km Guangzhou-Zhuhai intercity lines as a main axis, forming an A-shaped traffic framework and connecting nine large and medium cities to build up the one-hour economic circle around this area including Hong Kong and Marco.
- The Circum-Bohai FRT System. With Beijing and Tianjin as the centers, and the 115 km Beijing-Tianjin intercity HSR as a main axis, forming an outward radiation traffic framework to the surrounding cities.

On November 27, 2008, according to the national development strategy and the demand for a resource-saving and environment-friendly society, the National Development and Reform Commission adjusted and optimized the scale and layout arrangement of the planned railway network issued in the “National Medium-and-long Term Railway Development Program” in 2004, increasing the development target of total railway mileage by 2020 from 100,000 km to over 120,000 km. According to the updated program, the target mileage of high-speed railway was adjusted from 12,000 km to 16,000 km. The Ningbo-Shenzhen HSR was extended northward to Shanghai, and the Hangzhou-Changsha HSR was extended westward to Kunming. To further expand the HSR network, several new HSR lines, such as Lanzhou-Urumqi, Bengbu-Hefei, Nanjing-Hangzhou, Nanchang-Jiujiang, Liuzhou-Nanning, Mianyang-Chengdu-Leshan, Harbin-Qiqihar, Harbin-Mudanjiang, Changchun-Jilin, Shenyang-Dandong, and Jinzhou-Yingkou, were scheduled to construct. Meanwhile, more regional FRT systems would be constructed for economically developed and densely populated areas, such as in Chengdu-Chongqing region, Changsha-Zhuzhou-Xiangtan region, Central China cities, Wuhan city circle, Guanzhong city group, and East coast economic zone, covering the major cities and towns within their respective regions.

During “The Eleventh Five-year Plan for National Economic and Social Development” period (2006–2010) of China, the significant investment was put into HSR construction, which not only promoted the development of HSR technologies, but also increased the construction scale and operation mileage of China’s HSR to the leading position in the world. The main target of railway development in “The Eleventh Five-year Plan” was to construct 17,000 km new railway lines, including HSR lines of 7,000 km, to double-track reform existing lines of 8,000 km, and to electrify existing lines of 15,000 km.

On June 24, 2008, the China CRH3 EMU achieved a maximum speed of 394.3 km/h in the operation tests on Beijing-Tianjin Intercity HSR. On September 28, 2010, the CRH380A EMU broke the record with a maximum speed of 416.6 km/h in the operation test on Shanghai-Hangzhou Intercity HSR. On December 3, 2010, the new generation high-speed EMU renewed the record and created a speed of 486.1 km/h in the Bengbu-Zaozhuang test section located on Beijing-Shanghai HSR, which is the worldwide highest train speed on operation railway. In China, the train speed used to be 350 km/h (the highest operational train speed in the world) on Beijing-Tianjin, Wuhan-Guangzhou, Shanghai-Nanjing, and

Shanghai-Hangzhou HSR lines. Moreover, the designed operation train speed on Beijing-Shanghai HSR was up to 380 km/h.

"The Twelfth Five-year Plan" started in 2011 proposed to further speed up HSR construction. The objective was to build a rapid railway network with total length of 45,000 km, including 16,000 km HSR lines. Meanwhile, the construction standard and initial operation train speed of high-speed railways were further clarified.

In recent years, the construction of high-speed railways in China was further accelerated. A number of HSR lines have been put into operation, such as Dalian-Harbin Line (921 km), Hangzhou-Changsha Line (927 km), Lanzhou-Urumqi Line (1,776 km), Guiyang-Guangzhou Line (857 km), Nanning-Guangzhou Line (577 km), Chengdu-Chongqing Line (308 km), and Hefei-Fuzhou Line (808 km). With the opening and operation of the Shanghai-Kunming HSR line in the end of 2016, the total operation mileage of Chinese HSR reached 22,000 km, ranking first in the world. At present, the HSR operation mileage in China has far exceeded the total mileage of other countries in the world. China owns the world's most extensive HSR network with the fastest-growing, most comprehensive technology, strongest integration capability, longest operation mileage, highest operation speed, and largest construction scale.

According to the "National Medium-and-long Term Railway Development Program" and the current construction progress, by 2020, the total HSR operation mileage in China is predicted up to 25,000 km. Together with other new and existing railways, a 50,000 km rapid railway network will be completed, connecting all the provincial capitals and big cities with more than half million population, covering over 90% of the whole Chinese population. In general, the railway transport capacity will be able to meet the requirements of national economy and social development. The one-hour regional traffic networks will be established around the provincial capitals. The traveling time from Beijing to most of the provincial capitals will be less than 8 h.

According to the 2016-updated version of the "National Medium-and-long Term Railway Development Program," during the "Thirteenth Five-year Plan" period, China will continue to extend its HSR lines. The target of the program is to form an HSR framework with "eight vertical and eight horizontal channels," as shown in Fig. 1.6, and by 2025, the total mileage of China's HSR lines will reach 38,000 km.

The main contents of the HSR framework with "eight vertical and eight horizontal channels" are as follows:

(1) **The eight vertical channels**

V1: The East Coastal Channel. This channel starts from Dalian to Zhanjiang, via Shenyang, Qinhuangdao, Tianjin, Weifang, Qingdao (Yantai), Lianyungang, Yancheng, Nantong, Shanghai, Hangzhou, Ningbo, Fuzhou, Xiamen and Shenzhen, which connects the east coastal areas of China, through cities in the Eastern-Southern Liaoning Peninsula, the Beijing-Tianjin-Hebei area, the Shandong Peninsula, the east coastal areas, the Yangtze River Delta, the Pearl River Delta, and the Beibu Gulf coast.

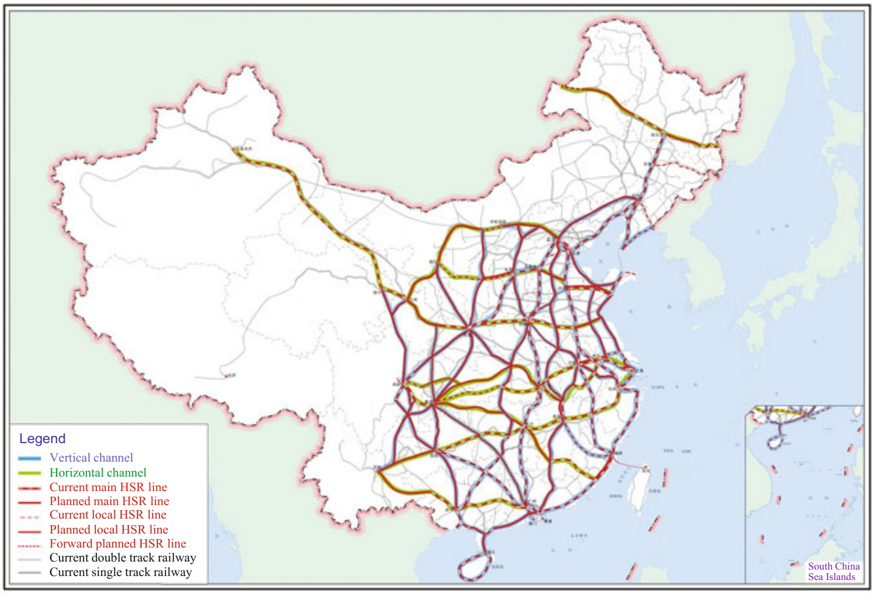

Fig. 1.6 HSR framework with "eight vertical and eight horizontal channels"

V2: The Beijing-Shanghai Channel. This channel starts from Beijing to Shanghai, and extends to Hangzhou, via Tianjin, Jinan and Nanjing, which connects the north and east areas of China, through cities in the Beijing-Tianjin-Hebei area, Shandong, Anhui and Jiangsu provinces, and the Yangtze River Delta.

V3: The Beijing-Shenzhen (Hong Kong) Channel. This channel starts from Beijing to Shenzhen, and extends to Hong Kong (Kowloon), via Hengshui, Heze, Shangqiu, Fuyang, Hefei, Jiujiang, Nanchang and Ganzhou, with a Branch Channel from Hefei to Fuzhou, via Nanchang. This channel connects the north, central, east and south areas of China, through cities in the Beijing-Tianjin-Hebei area, the middle reaches of Yangtze River, the west coast of Taiwan Strait, and the Pearl River Delta.

V4: The Harbin-Beijing-Hong Kong Channel. This channel starts from Harbin to Hong Kong, via Changchun, Shenyang, Beijing, Shijiazhuang, Zhengzhou, Wuhan, Changsha, Guangzhou and Shenzhen, including the Guangzhou-Zhuhai-Macao HSR. It connects the northeast, north, central and south areas, and the Hong Kong and Macao regions of China, through cities in Heilongjiang, Jilin and Liaoning provinces, the Beijing-Tianjin-Hebei area, the central plains, the middle reaches of Yangtze River, and the Pearl River Delta.

V5: The Hohhot-Nanning Channel. This channel starts from Hohhot to Nanning, via Datong, Taiyuan, Zhengzhou, Xiangyang, Changde, Yiyang, Shaoyang, Yongzhou and Guilin, which connects the north, central and south areas of China, through cities in the Hohhot-Baotou-Erdos area, the Central Shanxi area, the central plains, the middle reaches of Yangtze River, and the Beibu Gulf coast.

V6: The Beijing-Kunming Channel. This channel starts from Beijing to Kunming, via Shijiazhuang, Taiyuan, Xi'an and Chengdu, which connects the north, northwest and southwest areas of China, through the cities in Beijing-Tianjin-Hebei area, the Central and South Shanxi area, the Central Shaanxi plain, the Chengdu-Chongqing area, and the Central Yunnan area.

V7: The Baotou-Hainan Channel. This channel starts from Baotou to Sanya, via Yan'an, Xi'an, Chongqing, Guiyang, Nanning, Zhanjiang and Haikou, including the Yinchuan-Xi'an HSR and the Hainan island-loop HSR. It connects the northwest, southwest and south areas of China, through the cities in the Hohhot-Baotou-Erdos area, the Ningxia Along-Yellow River areas, the Central Shaanxi plain, the Chengdu-Chongqing area, the Central Guizhou area, and the Beibu Gulf coast.

V8: The Lanzhou (Xining)-Guangzhou Channel. This channel starts from Lanzhou (Xining) to Guangzhou, via Chengdu, Chongqing and Guiyang, which connects the northwest, southwest and south areas of China, through the cities in the Lanzhou-Xi'an area, the Chengdu-Chongqing area, the Central Guizhou area, and the Pearl River Delta.

(2) **The eight horizontal channels**

H1: The Suifenhe-Manzhouli Channel. This channel starts from Suifenhe to Manzhouli, via Mudanjiang, Harbin, Qiqihar and Hailar, which connects the Eastern Heilongjiang area and the Eastern Inner Mongolia area.

H2: The Beijing-Lanzhou Channel. This channel starts from Beijing to Lanzhou, via Hohhot-Yinchuan, which connects the north and northwest areas of China, through cities in Beijing-Hebei area, the Hohhot-Baotou-Erdos area, the Ningxia Along-Yellow River areas, and the Southern Gansu area.

H3: The Qingdao-Yinchuan Channel. This channel starts from Qingdao to Yinchuan, via Jinan, Shijiazhuang, Taiyuan and Zhongwei, which connects the east, north and northwest areas of China, through cities in Shandong Peninsula, Beijing, Hebei, Shanxi, Shaanxi and Ningxia provinces.

H4: The Continental-bridge Channel. This channel starts from Lianyungang to Urumqi, via Xuzhou, Zhengzhou, Xi'an, Lanzhou and Xining, which connects the east, central and northwest areas of China, through cities in east coastal area, the Central Plains, the Central Shaanxi Plain, and the Lanzhou-Tianshan Mountain corridor.

H5: The Along-Yangtze River Channel. This channel starts from Shanghai to Chengdu, via Nanjing, Hefei, Wuhan and Chongqing, including the Nanjing-Anqing-Jiujiang-Wuhan-Yichang-Chongqing HSR and the Wanzhou-Dazhou-Suining-Chengdu HSR, which connects the east, central and southwest areas of China, through cities in the Yangtze River Delta, the middle reaches of Yangtze River, and the Chengdu-Chongqing area.

H6: The Shanghai-Kunming Channel. This channel starts from Shanghai to Kunming, via Hangzhou, Nanchang, Changsha and Guiyang, which connects the east, central and southwest areas of China, through cities in the Yangtze River Delta, the middle reaches of Yangtze River, and the Guiyang-Kunming area.

H7: The Xiamen-Chongqing Channel. This channel starts from Xiamen to Chongqing, via Longyan, Ganzhou, Changsha, Changde, Zhangjiajie and Qianjiang, which connects the west coast of Taiwan Strait, and the central and southwest areas of China, through cities in the west coast of Taiwan Strait, the middle reaches of Yangtze River, and the Chengdu-Chongqing area.

H8: The Guangzhou-Kunming Channel. This is the Guangzhou-Nanning-Kunming HSR, which connects the south and southwest areas of China, through cities in the Pearl River Delta, the Beibu Gulf, and the Central Yunnan area.

In Taiwan Province, the high-speed railway was proposed in 1980s and started to construct in 1998, adopting the Japanese Shinkansen technology. The HSR line in Taiwan passes through the west coast of the island, connecting the two cities of Taipei and Kaohsiung, with the total length of 345 km. The line was opened to service on January 5, 2007, with the maximum train speed of 300 km/h.

1.2 Overview of HSR Bridges in China

1.2.1 Characteristics of HSR Bridges in China

The high-speed railway bridges in China have the following characteristics:

(1) Large proportion of elevated bridges

To meet the requirements on strict horizontal and vertical alignment parameters and the high track smoothness and stability, and for easier implementation of fully isolated operation pattern, the HSR lines usually adopt larger proportion of bridges than common railway. Especially in densely populated regions or unfavorable geological conditions, elevated bridges are used to cross the existing roads, reduce urban block segmentation, save land resource, and avoid uneven settlement of high embankment. Summarized in Tables 1.1 and 1.2 are the HSR bridges in China and abroad.

As shown in the tables, the highest proportion of HSR bridges abroad occurs in Japan, in which the percentages of bridge length on the Joetsu Shinkansen Line and Tohoku Shinkansen Line are 61.5% and 58.1%, respectively. In China, the average percentage of HSR bridges is 58.74%, in which, the percentage of bridge length on the Beijing-Shanghai HSR is 80.7%, on the Beijing-Tianjin intercity HSR is 87.7%, on the Shanghai-Hangzhou intercity HSR is 89%, and on the Guangzhou-Zhuhai intercity HSR is as high as 94.2%. By contrast, the average percentage of bridge length in common railways in China is only 4%.

(2) Mainly adopting small and medium spans

In China, HSR mainly adopts small-and-medium common-span bridges. It is not only because of the strict limits on stiffness and deformation, but also due to their advantages in standardized design, industrialized production, mechanized erection, high quality and fast construction speed that the bridge span should not be too large,

Table 1.1 Overview of HSR bridges abroad

Country	HSR lines	Line length (km)	Bridge length (km)	Percentage of bridge length (%)
Germany	Cologne-Frankfurt	177	4.8	2.7
	Hanoverian-Wurzburg	327	41	12.5
	Mannheim-Stuttgart	99	6	6.1
France	LGV Paris-Lyon	417	25	6
	LGV Atlantique	282	36	12.8
	LGV Nord-Europe	330	72	21.8
	LGV Rhône-Alpes	121	39	32.2
Japan	Tokaido Shinkansen	515	173	33.6
	Sanyō Shinkansen	554	211	38.1
	Jōetsu Shinkansen	270	166	61.5
	Tōhoku Shinkansen	493	344	58.1
	Hokuriku Shinkansen	117	39	33.3
Spain	Madrid-Sevilla	471	15	3.2
	Madrid-Barcelona	621	75.8	12.2
Italy	Rome-Florence	254	32	12.6
	Rome-Naples	204	39	19.1
	Florence-Milan	260.4	23.1	8.9
Korea	Seoul-Busan	412	111.8	27.1

generally less than 100 m. Through years of research, the series of simply-supported double-track box-beams with common spans of 32, 24, and 20 m are proposed, which can be ballasted or ballastless. According to the statistics, in the built HSR bridges, the total amount of standardized 32 m simply-supported PC box-beams is more than 300,000 spans, and the extended length is over 10,000 km, occupying 98% of the total bridge length.

In addition to the extensive application of prefabricated simply-supported PC box-beams, continuous beams, continuous rigid frames, arches, and composite beams are also adopted to cross valleys, rivers, railways, and roadways, in which the double-track PC box-section is prior to use.

(3) High rigidity and good integrity

To ensure the running safety and riding comfort of high-speed trains, HSR bridges should have sufficient stiffness and integrity in both vertical and lateral directions, to avoid too large deflection and amplitude. Besides, deformations induced by concrete creep and uneven temperature difference should be restricted, to ensure good smoothness of the track. Therefore, the design of HSR bridges is mainly controlled by stiffness rather than by strength. Although the live load for a HSR bridge is smaller than that for common railway, both the height and the weight of a HSR beam are larger than those of a common railway beam.

Table 1.2 Overview of HSR bridges in China

HSR line	Line length (km)	Bridge length (km)	Percentage of bridge length (%)
Beijing-Shanghai	1314	1060.9	80.7
Shanghai-Chengdu	1223	586	47.9
Shanghai-Kunming	2261	1207	53.4
Beijing-Wuhan	1121.7	858.7	76.5
Wuhan-Guangzhou	968.2	465.244	48.1
Nanning-Guangzhou	577.1	180.7	31.2
Hangzhou-Shenzhen	1508	565	37.5
Shijiazhuang-Taiyuan	189.93	39.2	20.6
Hefei-Nanjing	187.1	31.2	16.7
Zhengzhou-Xi'an	486.9	283.5	58.0
Beijing-Harbin	1713	1269	74.1
Harbin-Dalian	903.9	663.3	73.3
Beijing-Kowloon	2193	1384	63.1
Qingdao-Taiyuan	679	329	48.4
Xuzhou-Lanzhou	1360	822	60.5
Hainan Eastern Loop	308.11	102.95	33.4
Beijing-Tianjin	115.2	101.0	87.7
Shanghai-Nanjing	301	215.8	71.7
Guangzhou-Zhuhai	142.3	134.1	94.2
Shanghai-Hangzhou	160	142.4	89.0
Changchun-Jilin	96.26	30.3	31.5
Nanchang-Jiujiang	91.58	31.96	34.9
Taipei-Kaohsiung	345	257	74.5

(4) Extensive use of ballastless slab tracks

According to the operation experiences in China and abroad, both ballasted and ballastless tracks can meet the requirement of high-speed railway on high smoothness, reliability, and stability, but they have different characteristics. Bridges with ballastless track can reduce the secondary dead load, increase the natural frequency, and improve the dynamic behavior of train-bridge system. Therefore, the ballastless track is commonly used in HSR bridges in China. However, as a new type of track structure, the ballastless track brings new requirements on how to control the deformation, foundation settlement, and longitudinal force transmission in the bridge track system, which is one of focuses in the design of HSR bridges.

(5) High longitudinal stiffness of pier foundation

In China, most HSR lines adopt CWR (continuous welded rail). Under conditions of temperature variation, train braking, and span deflection, the bridge will produce longitudinal displacement, which induces additional stresses in the rails on the bridge. In turn, the additional stress of rails may cause instability of CWR track on the bridge, thus affecting the running safety of trains. Therefore, the high longitudinal stiffness is required for pier foundation of HSR bridges, to minimize the additional rail stresses and the related displacement between beam and track.

(6) High structural durability and convenient maintenance

High-speed railway is an extremely important transportation facility, and any interruption of it will cause huge economic losses and social influences. Therefore, less maintenance or maintenance-free should be one of the targets for the HSR bridge construction, which requires that the structural durability should be ensured by reasonable design of structure and construction details and strict quality process control in construction. According to the design code for high-speed railways in China, as the main bearing structure, a bridge should have 100 years of durability under the predetermined actions and maintenance conditions. On the other hand, it is very difficult to maintain a HSR bridge due to the busy operation, high train speed, and limited maintenance windows of high-speed railway; therefore, the bridge structure should have efficient access for routine inspection and maintenance.

(7) Nice looking appearance and good coordination with environment

As the important modern transportation facility, in addition to safety and economy, the architecture esthetics of bridges should be taken into account in HSR design, by emphasizing the coordination of bridge structures with the natural and cultural environment, as well as the structural appearance and colors. Moreover, special attentions should be paid to ecological environment protection, by reducing train-induced noises, and avoiding pollution and damage to the ecological environment during construction and service of the bridge. Figures 1.7, 1.8, 1.9, and 1.10 give several typical HSR bridges in China.

It is seen that these bridges are designed with coordinated dimensions and fluent appearance, well-matched superstructure and substructure, open and wide clearance, and harmony with surroundings, forming a magnificent landscape.

Fig. 1.7 Nanjing Dashengguan Yangzi River Bridge