

# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	High-Speed Railways in China	1
1.1.1	Development of High-Speed Railways	1
1.1.2	Development of High-Speed Railways in China	3
1.2	Overview of HSR Bridges in China	10
1.2.1	Characteristics of HSR Bridges in China	10
1.2.2	Key Technologies of HSR Bridge Construction in China	14
1.2.3	Common-Span HSR Bridges	17
1.2.4	Long-Span HSR Bridges	20
1.2.5	Application of Train-Bridge Dynamic Analysis to HSR Design in China	20
1.3	Vibration Problems of Railway Bridges	24
1.3.1	Bridge Vibration Induced by Wind Load	25
1.3.2	Bridge Vibration Due to Earthquake Action	28
1.3.3	Bridge Vibration Induced by Collision of Vessels, Vehicles, and Drifters	31
1.3.4	Bridge Vibration Induced by Crowd Load	37
1.3.5	Bridge Vibration Induced by Running Trains	39
1.4	Research History and Status Quo of Train-Bridge Coupling Vibration: An Overview	41
1.4.1	Research on Vibration of Railway Bridges Under Moving Train	41
1.4.2	Study on Dynamic Responses of Train-Bridge System Under Wind Loads	51
1.4.3	Study on Dynamic Responses of Train-Bridge System Subjected to Earthquake Action	55
1.4.4	Study on Dynamic Responses of Train-Bridge System Subjected to Collision Load	58
1.5	Research Contents of Train-Bridge Coupling Vibrations	62

1.6	Dynamic Analysis Methods of Train-Bridge System . . . . .	67
1.6.1	Dynamic Analysis Methods of Train-Bridge Coupling System. . . . .	68
1.6.2	Motion Equation and Solution of Train-Bridge System. . . . .	70
	References. . . . .	73
<b>2</b>	<b>Fundamental Theories and Analytical Methods for Vibrations of Simply-Supported Beams Under Moving Loads. . . . .</b>	<b>85</b>
2.1	Vibrations of Simply-Supported Beam Under Moving Loads . . . . .	85
2.1.1	Analysis Model . . . . .	85
2.1.2	Vibration of Simply-Supported Beam Under a Moving Concentrated Load . . . . .	89
2.1.3	Displacement of Bridge Subjected to a Moving Load Series. . . . .	98
2.1.4	Analytical Solution for Vibration of Simply-Supported Beam Under a Moving Harmonic Load . . . . .	101
2.2	Vibration of Simply-Supported Beam Under Moving Loads with Variable Speed . . . . .	106
2.2.1	Calculation Model . . . . .	106
2.2.2	Case Study . . . . .	110
2.3	Resonance Analysis of a Simply-Supported Beam Subjected to Moving Loads . . . . .	113
2.3.1	Bridge Resonance Induced by a Moving Load Series . . . . .	114
2.3.2	Resonance Analysis of Train Vehicles. . . . .	125
2.4	Vibration Suppression and Cancellation Analysis of Train-Bridge System . . . . .	126
2.4.1	Resonance and Cancellation of Simply-Supported Beam Under Moving Equidistant Load Series. . . . .	127
2.4.2	Resonance and Cancellation of Simply-Supported Beam Under a Series of Train Loads . . . . .	132
2.4.3	Numerical Verification. . . . .	136
	References. . . . .	145
<b>3</b>	<b>Self-excitations of Train-Bridge Coupling Vibration System . . . . .</b>	<b>149</b>
3.1	Track Irregularities . . . . .	149
3.1.1	Definition of Track Irregularities . . . . .	149
3.1.2	Excitation Function of Track Irregularities in the Train-Bridge Vibration System . . . . .	155
3.1.3	Mathematical Description of Random Irregularity Characteristics . . . . .	157
3.1.4	Typical Track PSD . . . . .	164
3.1.5	Control Standards of Track Irregularities. . . . .	172

3.1.6	Numerical Simulation of Track Irregularities . . . . .	174
3.2	Vehicle Hunting Movement . . . . .	179
3.2.1	Mechanism of Vehicle Hunting Movement . . . . .	179
3.2.2	Hunting Movements of Wheel-Set in Free and Actual States . . . . .	180
3.2.3	Description of Wheel Hunting Movement in Train-Bridge System . . . . .	183
3.3	AR Model Simulation of Random Excitations on Train-Bridge System . . . . .	184
3.3.1	Measurement of Random Excitation . . . . .	184
3.3.2	AR Model Simulation of System Excitation . . . . .	185
	References . . . . .	188
<b>4</b>	<b>Vibration Criteria for HSR Bridges and Train Vehicles in China . . . . .</b>	<b>191</b>
4.1	General Introduction . . . . .	192
4.2	Criteria for Train Running Safety . . . . .	195
4.2.1	Derailment Factor . . . . .	195
4.2.2	Offload Factor . . . . .	197
4.2.3	Lateral Wheel/Rail Force . . . . .	198
4.2.4	Overturn Coefficient . . . . .	199
4.2.5	Discussion About Sampling Frequency of Vehicle Safety Indices . . . . .	199
4.3	Criteria for Train Running Stability . . . . .	200
4.3.1	Car-Body Acceleration . . . . .	200
4.3.2	Sperling Comfort Index (Riding Quality Index) . . . . .	203
4.4	Criteria for Bridge Dynamic Performance . . . . .	205
4.4.1	Natural Frequency . . . . .	205
4.4.2	Deformation . . . . .	208
4.4.3	Amplitude . . . . .	212
4.4.4	Acceleration . . . . .	217
4.4.5	Rotation Angle at Beam-Ends . . . . .	219
4.4.6	Distortion Angle of Beam-Deck . . . . .	220
4.4.7	Dynamic Coefficient . . . . .	221
4.5	Conditions Unnecessary to Conduct Train-Bridge Coupling Dynamic Analysis . . . . .	222
	References . . . . .	225
<b>5</b>	<b>Dynamic Analysis of Train-Bridge Coupling System . . . . .</b>	<b>227</b>
5.1	Introduction . . . . .	227
5.2	Train Subsystem . . . . .	228
5.2.1	Fundamental Vibration Patterns of a Vehicle . . . . .	228
5.2.2	Vehicle Element Model . . . . .	231
5.3	Bridge Subsystem . . . . .	233
5.4	Wheel-Rail Interaction . . . . .	235

5.4.1	Wheel-Rail Contact Geometry . . . . .	236
5.4.2	Normal Hertz Contact Theory . . . . .	240
5.4.3	Vertical Wheel-Rail Correspondence Assumption . . . . .	241
5.4.4	The Kalker's Linear Creep Theory and the Shen's Correction . . . . .	243
5.4.5	The Simplified Kalker Linear Creep Theory . . . . .	247
5.4.6	Hunting Assumption . . . . .	248
5.4.7	Comparison of Various Wheel-Rail Relationship Models . . . . .	250
5.5	Establishment of Train-Bridge System Motion Equations . . . . .	251
5.5.1	Motion Equation of Vehicle Element . . . . .	251
5.5.2	Motion Equation of Train-Bridge Coupling System . . . . .	259
5.6	Solution Methods for Train-Bridge Coupling System . . . . .	260
5.6.1	The Direct Coupling Iteration Method . . . . .	260
5.6.2	The In-Time-Step Iteration Method . . . . .	264
5.6.3	The Intersystem Iteration Method . . . . .	265
5.7	A Case Study . . . . .	268
5.7.1	Introduction to the Bridge . . . . .	268
5.7.2	Field Experiment . . . . .	269
5.7.3	Calculation Parameters of the Bridge . . . . .	273
5.7.4	Calculation Parameters of Vehicle . . . . .	275
5.7.5	Dynamic Responses of Bridge and Experimental Verification . . . . .	275
5.7.6	Dynamic Responses of Vehicle . . . . .	281
5.7.7	Discussion on Iteration Convergence . . . . .	285
5.7.8	Vertical Resonance Analysis of Bridge Subsystem . . . . .	286
	References . . . . .	288
<b>6</b>	<b>Dynamic Analysis of Train-Bridge System Subjected to Crosswinds . . . . .</b>	<b>291</b>
6.1	Numerical Simulation of Wind Loads . . . . .	291
6.1.1	Spectral Representation Method . . . . .	292
6.1.2	Linear Filtering Method . . . . .	297
6.1.3	Wavelet Simulation . . . . .	300
6.1.4	Wind Field Simulation Based on Observed Records . . . . .	302
6.2	Effect of Wind Barriers on Wind Flow Field Around Bridge . . . . .	304
6.2.1	Types of Wind Barriers . . . . .	305
6.2.2	Aerodynamic Optimization of Wind Barriers Based on CFD Theory . . . . .	306
6.2.3	Aerodynamic Performance of Train-Bridge System Under Crosswinds and Windproof Effect of Wind Barriers . . . . .	322

6.3	Dynamic Model of Train-Bridge System Subjected to Crosswinds . . . . .	326
6.3.1	Wind Forces on Vehicle-Bridge System . . . . .	327
6.3.2	Motion Equations of Coupled Train-Bridge System Subjected to Crosswinds . . . . .	332
6.4	Dynamic Analysis of a Train and Long-Span Bridge System Under Crosswinds. . . . .	333
6.4.1	Engineering Background . . . . .	333
6.4.2	Wind and Structural Health Monitoring System (WASHMS) on the Bridge . . . . .	335
6.4.3	Case Identification of Train Loads. . . . .	336
6.4.4	Numerical Simulation and Analysis. . . . .	337
6.5	Dynamic Analysis of Wind-Train-Bridge System Considering Aerodynamic Effects of Wind Barriers . . . . .	341
6.5.1	Engineering Background . . . . .	341
6.5.2	Input Data . . . . .	342
6.5.3	Bridge Responses . . . . .	345
6.5.4	Vehicle Responses. . . . .	346
	References. . . . .	347
<b>7</b>	<b>Dynamic Analysis of Train-Bridge System Subjected to Earthquake Action . . . . .</b>	<b>351</b>
7.1	Introduction . . . . .	351
7.2	Numerical Simulation of Seismic Ground Motion . . . . .	352
7.2.1	Spatial Variation of Seismic Ground Motion. . . . .	352
7.2.2	Simulation of Seismic Ground Motion Considering Spatial Variation . . . . .	354
7.2.3	Consistency Treatment of Earthquake Record . . . . .	366
7.3	Dynamic Analysis of Structures Subjected to Seismic Ground Motion . . . . .	371
7.3.1	Single-Degree-of-Freedom Model (SDOF Model). . . . .	372
7.3.2	Multi-Degree-of-Freedom Model (MDOF Model). . . . .	373
7.4	Dynamic Analysis Model of Train-Bridge System Subjected to Earthquake Action . . . . .	380
7.4.1	Simplified Analysis Model . . . . .	380
7.4.2	Vibration Analysis of WSM Units Running on a Simply-Supported Beam Subjected to Multi-support Seismic Excitations. . . . .	382
7.4.3	MDOF Train-Bridge Coupling Model. . . . .	391
7.5	Running Safety of Train on Bridge During Earthquakes. . . . .	395
7.5.1	Evaluation Indices for Running Safety of Train During Earthquakes. . . . .	395
7.5.2	Procedures of Train Running Safety Evaluation During Earthquakes. . . . .	397

- 7.6 Case Study . . . . . 398
  - 7.6.1 Calculation Parameters . . . . . 398
  - 7.6.2 Calculation Results and Discussion . . . . . 400
  - 7.6.3 Main Conclusions . . . . . 407
- References. . . . . 408
- 8 Dynamic Analysis of Train-Bridge System Subjected to Collision Loads . . . . . 411**
  - 8.1 Collision Loads. . . . . 411
    - 8.1.1 Collision by Vessels . . . . . 412
    - 8.1.2 Collision by Road Vehicles. . . . . 420
    - 8.1.3 Collision by Drifting-Floe . . . . . 426
    - 8.1.4 Characteristics of Bridge Collision Loads . . . . . 431
  - 8.2 Dynamic Analysis Model of Train-Bridge System Subjected to Collision Loads . . . . . 432
  - 8.3 Dynamic Analysis of Train-Bridge System Subjected to Collision Loads . . . . . 436
    - 8.3.1 Bridge Description and Calculation Parameters. . . . . 436
    - 8.3.2 Dynamic Responses of the Bridge. . . . . 441
    - 8.3.3 Dynamic Responses of the Train. . . . . 448
  - 8.4 Influence of Collision Effect on Running Safety of High-Speed Train. . . . . 450
    - 8.4.1 Influence of Train Speed . . . . . 451
    - 8.4.2 Influence of Collision Load Intensity. . . . . 451
    - 8.4.3 Influence of Train Types . . . . . 453
    - 8.4.4 Influence of Impulse Form and Duration of Collision Loads. . . . . 457
  - 8.5 A Framework for Running Safety Assessment of High-Speed Train on Bridge Subjected to Collision Loads . . . . . 459
    - 8.5.1 Analysis Method . . . . . 459
    - 8.5.2 Threshold Curves for Running Safety of ICE3 Train on the Bridge Subjected to Ice-I Collision Load . . . . . 460
    - 8.5.3 Comparison of Running Safety Thresholds for Different Collision Loads. . . . . 463
    - 8.5.4 Comparison of Running Safety Thresholds for Different Trains . . . . . 464
  - 8.6 Conclusions . . . . . 466
  - References. . . . . 467
- 9 Dynamic Analysis of Train-Bridge System Under Differential Settlement and Scouring Effect of Foundations. . . . . 471**
  - 9.1 Differential Settlement of Bridge Foundations . . . . . 471
  - 9.2 Prediction of Cumulative Settlement of Bridge Foundation Under Cyclic Train Loading . . . . . 474
    - 9.2.1 Determination of Stress State in the Subsoil . . . . . 475

9.2.2	Calculation of Cumulative Pore Pressure. . . . .	477
9.2.3	Calculation of Additional Settlement of Bridge Foundation Under Train Loads . . . . .	478
9.2.4	Case Study . . . . .	479
9.3	Numerical Analysis of Differential Settlement of a Bridge Foundation Caused by Adjacent Foundation Construction . . . . .	487
9.3.1	Engineering Background . . . . .	487
9.3.2	Finite Element Modeling . . . . .	488
9.3.3	Division of Construction Stages . . . . .	491
9.3.4	Displacements of Existing Piles After the Construction of New Group-Piles. . . . .	492
9.3.5	Displacements of Existing Pile Foundation After the Pit Excavation of New Platform. . . . .	494
9.3.6	Displacements of Existing Pile Foundation After the Concrete Cast of New Platform . . . . .	495
9.3.7	Displacements of Existing Pier and Platform When the New Bridge Pier Is Loaded by Superstructure Loads . . . . .	495
9.4	Influence of Differential Settlement of Bridge Foundation on Dynamic Responses of Train-Bridge System. . . . .	497
9.4.1	Simulation of Additional Track Unevenness Induced by Differential Settlement of Bridge Foundation . . . . .	498
9.4.2	Dynamic Response Analysis of the Train . . . . .	500
9.4.3	Dynamic Response Analysis of the Bridge . . . . .	506
9.5	Influence of Pier Foundation Scouring on Running Safety of High-Speed Trains . . . . .	508
9.5.1	Outline of Pier Foundation Scouring. . . . .	508
9.5.2	Scouring Mechanism . . . . .	510
9.5.3	Calculation of Scouring Depth . . . . .	511
9.5.4	Effect of Scouring on Equivalent Stiffness of Group-Piles. . . . .	513
9.5.5	Dynamic Analysis Method for Train-Bridge System Considering Foundation Scouring Effect . . . . .	520
9.5.6	Effect of foundation scouring on equivalent stiffness of group-piles . . . . .	522
9.5.7	Effect of foundation scouring on dynamic responses of train-bridge system . . . . .	526
	References. . . . .	534
10	<b>Dynamic Analysis of Train-Bridge System Under Beam Deformation Induced by Concrete Creep and Temperature Effect . . . . .</b>	<b>537</b>
10.1	Introduction . . . . .	537
10.2	Influence of PC Beam Creep Camber on Dynamic Responses of Train-Bridge System. . . . .	538

- 10.2.1 Creep Camber of PC Beams . . . . . 538
- 10.2.2 Experimental Investigation on PC Beam Creep  
Camber and Additional Track Unevenness . . . . . 542
- 10.2.3 Analysis of Additional Track Unevenness  
Induced by PC Beam Creep Camber. . . . . 545
- 10.2.4 Simulation of Additional Track Unevenness  
Caused by Beam Creep Camber . . . . . 553
- 10.2.5 Influence of Beam Creep on Dynamic Responses  
of Train-Bridge System . . . . . 556
- 10.3 Influence of Temperature Deformation on Dynamic  
Responses of Train-Bridge System . . . . . 566
  - 10.3.1 Temperature Deformations of Bridge. . . . . 566
  - 10.3.2 Numerical Simulation for Sidewise Bending  
of Beam. . . . . 568
  - 10.3.3 Temperature Warping Deformation of Track Slab  
and Its Effect on Dynamic Responses  
of Train-Track System. . . . . 569
- References. . . . . 578