Ground Vibrations from High-Speed Railways

Ground Vibrations from High-Speed Railways

Prediction and mitigation

Edited by
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Preface

Over the last two decades, high-speed railways have continued to be developed in many countries in Europe, Asia and North America. The main advantages of high-speed railways are low air pollution per passenger and, of course, very high operational speeds that cannot be achieved by any other means of surface transport. Because of this, high-speed railways have become a viable alternative to air transport for travelling short and medium distances, such as within Europe. Speeds close to or greater than 300 km/h are now typical for high-speed railways, and train speeds still continue to grow. For example, for the new proposed high-speed railway network HS2, which is planned to be built in the UK by the 2030s, operational speeds are to be increased even further, up to 400 km/h.

It has been known for a long time that increased train speeds are usually associated with increased levels of railway noise and vibration. This is especially true in the case of railway-induced ground vibrations that can propagate to nearby buildings and cause annoyance to local residents both directly and via associated air-borne noise. When train speeds become large enough (i.e. larger than certain velocities of elastic waves propagating in the supporting ground or in more complex systems involving tracks, ground and embankments), some specific vibration generation mechanisms can occur, in addition to those already existing for relatively low (conventional) train speeds. Such specific mechanisms may cause substantial increases in the levels of vibrations both in rail track systems and in the supporting ground. In particular, a very large increase in generated ground vibrations may occur if train speeds exceed the velocity of Rayleigh surface waves in the supporting ground, which is possible for relatively soft grounds. If this happens, a 'ground vibration boom' takes place, similar to a 'sonic boom' from supersonic aircraft. In addition to increased levels of generated ground vibrations, the effects of track critical velocities on rail deflections may result in train derailment – a matter of concern for high-speed railway operators. All these complex problems involving elastic wave propagation in track and ground systems, interaction of these coupled systems with moving trains as well as the final impact of generated elastic waves on nearby buildings should be studied in detail in order to be able to understand and control the associated dynamic phenomena. These studies should also include development of possible mitigation measures to reduce generated ground vibrations and their impact on the environment. This can be done in three ways: (a) by reducing the vibration at source by applying knowledge of track dynamics under the impact of moving trains; (b) by screening and dispersing generated ground vibrations (mainly Rayleigh surface waves) on their propagation from tracks to buildings; and (c) suppressing vibrations in building by applying special vibration-damping systems.

Although a variety of problems associated with ground vibrations from high-speed railways have been addressed in numerous journal papers and conference proceedings, there is still a lack of general reference books that could help the reader study these problems from different points of view and find answers to numerous theoretical and practical questions. The only existing book in this area, *Noise and Vibration from High-speed Trains* (edited by V. V. Krylov), was published in 2001 by Thomas Telford Publishing

(now ICE Publishing). Since then, many new interesting and important investigations have been carried out in the field of railway-induced ground vibrations. In particular, substantial progress has been made in the study of critical velocities in realistic track–ground systems and their effects on generated ground vibrations. New theoretical and numerical approaches, including 2.5-dimensional (2.5D) approaches and hybrid methods, have been developed for prediction and possible mitigation of ground vibrations from underground and surface railways. The effects of layered soils and different types of embankments on generated ground vibrations have been thoroughly investigated both theoretically and experimentally. Therefore, there is a clear need for a new book to inform about the progress in this area. The present book addresses this need, reflecting recent developments in research into ground vibrations from high-speed railways.

Unlike the above-mentioned book *Noise and Vibration from High-Speed Trains* that covered both noise and vibration issues, the present book concentrates on ground vibrations only. The reason for this is the growing importance of vibration problems, both in tracks and ground, with the continuing increase of train speeds. The large rise in the number of journal publications on ground vibrations generated by high-speed trains indicates that there is a growing demand for guidance on this topic. This book aims to present in one volume the views of leading international experts in ground vibrations from high-speed trains on the current status of the problem of the generation and propagation of ground vibrations from high-speed trains and to discuss possible ways of reducing their environmental impact.

This book consists of 12 chapters, which can be read independently. Chapter 1 concentrates on fundamental problems of the dynamic behaviour of track–ground systems under the impact of high-speed trains. The authors consider numerical modelling of different types of tracks and soils as well as different train types. Chapter 2 starts by studying soil–structure interaction, echoing Chapter 1. The author then continues with a description of generated ground vibrations for different types of layered soil and train speeds. The obtained theoretical predictions are compared with the original measurements. The chapter finishes with a description of the proposed mitigation of train-induced ground vibrations due to vehicle–track interaction. Chapter 3 describes recently developed computational tools capable of predicting ground vibrations from surface and underground railways. The authors present several numerical models, and illustrate their operation with a number of practical examples. Chapter 4 presents semi-analytical approaches to the theory of track–ground interaction, echoing the developments described in Chapters 1 and 2 and paying special attention to critical velocities and instabilities of moving systems (trains). The author considers different types of elastic and viscoelastic foundations modelling the supporting ground as well as different types of moving loads considered as oscillating systems. The authors of Chapter 5 describe their studies of ground vibrations from high-speed non-ballasted railways. The investigations include numerical modelling and field experiments. Chapter 6 reports the results of numerical predictions of vibrations of high-speed railways using time-domain approaches. The author considers multibody system simulation involving

railway vehicle–track dynamics. The chapter finishes by consideration of the supercritical phenomenon and of the effect of the track earthwork profile. Chapter 7 presents the 2.5D approach to modelling ground vibrations from high-speed railways. The author considers both the 2.5D finite-element and boundary element methods, which are then applied to different practical problems, including calculation of the ground vibration power spectrum for a given wheel–rail roughness power spectral density. The authors of Chapter 8 describe hybrid prediction methods for vibrations from high-speed railways. Reflecting the three main stages of generation, propagation and reception of railway-generated ground vibrations, the hybrid model implementation considers the source term, the propagation term and the receiver term, respectively. Different practical scenarios are then considered. Chapter 9 describes some benchmark solutions for vibrations generated by moving sources in tunnels, echoing Chapter 3. Field expansions and the application of boundary conditions are discussed, followed by numerical considerations. Chapter 10 describes the scoping assessment of ground and building vibrations generated by railway traffic. The authors consider track–soil forces, the track–soil transfer function, the free-field response and the building response. The author of Chapter 11 describes the finite-element method approach to train-induced vibrations of pile-supported embankments. Such embankments can be used for the mitigation of ground vibrations generated by high-speed trains. Vibration analysis of a pile-supported embankment is considered in detail, including the effect of critical speed. Finally, Chapter 12 presents the new proposed method of mitigation of railway-induced ground vibrations using the attenuation of Rayleigh surface waves propagating over areas of artificially created stochastically rough surfaces adjacent to railways.

This book describes mainly the results of recent academic research, and it is pitched largely at an advanced level. It is assumed that the ideal reader will have a university background in engineering, physics or applied mathematics. However, some of the chapters describe results of recent experimental investigations, and they are expected to be understood by a more general audience. The intended readership of the book is rather wide – scientists and engineers working on the prediction and remediation of railway-induced ground vibration, consultants dealing with environmental impact of railways, designers of new railway lines and so on. The book will be also useful for university students and railway enthusiasts.

Victor V Krylov

About the editor

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Victor Krylov was educated at Moscow M. V. Lomonosov State University Russia, obtaining his PhD in physics and mathematics (with specialisation in acoustics) in 1981 and a DSc in the same disciplines in 1989. He joined the staff of Moscow M. V. Lomonosov State University as a research scientist in 1980, and was later promoted to senior research scientist. During this time he visited the University of Edinburgh in 1990–1991 as an SERC Visiting Fellow. In 1993 he moved to Nottingham Trent University, UK, as Professor of Acoustics, and in 2001 he joined Loughborough University, as Professor of Acoustics and Vibration. His main contributions are in the fields of physical acoustics, surface acoustic waves, localised elastic waves in complex structures, laser ultrasonics, acoustic emission, railway- and road-generated ground vibrations, low-frequency noise and vibration, structure-borne vehicle interior noise, and damping of structural vibrations using the acoustic black hole effect. He has published more than 300 journal and conference papers. He has also authored, co-authored and edited five books, including *Noise and Vibration from High-Speed Trains* (Thomas Telford, 2001), for which he was the editor. In 2000 he was awarded the Rayleigh Medal from the UK Institute of Acoustics. He serves on the editorial boards of the journals *Applied Acoustics* and *Journal of Sound and Vibration*.

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Institution. He has been the principal investigator on many research grants, including funding from the Engineering and Physical Sciences Research Council, the EU, the Technology Strategy Board and industry. He invented a unique patented railway track reinforcement system (XiTRACK) that has been used across the UK and overseas. This technique received the Highly Commended Award in the Innovation of the Year category at the National Rail Awards 2005, the Institution of Civil Engineers Webb Prize 2008, the Network Rail Partnering Award 2014 and the Railway Industry Association Product Innovation of the Year 2015. He has given invited workshops and keynote addresses at major international conferences across the world on railway track geo-dynamics at high-speed, transitions and track reinforcement. He is a consultant to the railway industry, particularly on high-speed ground dynamics and track reinforcement. He advises for the HS2 railway project on track geo-dynamics, and his work is cited in HS2's Earthworks Specification Design Document. He also serves on the Network Rail Track Stiffness Working Group and the High Speed Rail Industry Leaders Group.

Jianjin Yang MSc

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Jianjin Yang is a doctoral candidate (since 2015) at the Train and Track Research Institute of Southwest Jiaotong University, supervised by Professor Wanming Zhai. He received his master's degree, majoring in railway vehicle engineering, at Lanzhou Jiaotong University in 2015. His current research focuses on train-track interaction as well as the prediction and control of environmental vibration induced by railway transportation.

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Zonghao Yuan graduated from the Southwest Jiaotong University of China in 2011 with a bachelor's degree in Civil Engineering, and completed his doctorate in geotechnical engineering at Zhejiang University in 2016. He visited Chalmers University of Technology for 1 year (2015–2016), and is presently a research fellow at Zhejiang University of Technology, focusing on the development of numerical and analytical models for predicting vibrations from underground railways.

Wanming Zhai PhD

Professor of Railway Engineering, Southwest Jiaotong University, Chengdu, China

Wanming Zhai became a full professor and the director of the Train and Track Research Institute at Southwest Jiaotong University, Chengdu, China in 1994. In 1999, he was appointed Chang Jiang Chair professor by the Chinese Ministry of Education. Currently, he is a chair professor of railway engineering at Southwest Jiaotong University, and the chair of the Academic Committee of Southwest Jiaotong University. He is one of the leading international experts in railway engineering. His research activities are mainly in the field of railway system dynamics, focusing on vehicle-track dynamic

interaction and train–track–bridge interactions. He established a new theoretical framework for vehicle–track coupled dynamics and invented new methodologies for solving large-scale train–track–bridge interaction problems. He proposed a method to assess the running safety and ride comfort of high-speed trains passing over different types of bridges at the design stage. His models and methods, well-known as the Zhai model and Zhai method, have been successfully applied to more than 20 large-scale field engineering projects for the railway network in China, mostly for high-speed railways. He is the editor-in-chief of the *International Journal of Rail Transportation*. He is also the president of Chengdu Association for Science and Technology, the vice president of the Chinese Society of Theoretical and Applied Mechanics, and the vice president of the Chinese Society for Vibration Engineering. He is Academician of the Chinese Academy of Sciences (CAS) and the only voting member in CAS in railway engineering.

List of abbreviations

2D	two dimensional
2.5D	2.5 dimensional
3D	three dimensional
BAM	Federal Institute for Materials Research and Testing
BEM	boundary element method model
CA	concrete–asphalt
CLM	coupled lumped-mass model
CSTB	Centre Scientifique et Technique du Bâtiment
CV	critical velocity
DAF	dynamic amplification factor
DOF	degrees of freedom
DP	double pole
DRR	double real root
EDT	ElastoDynamics Toolbox
FE	finite-element
FEA	finite-element analysis
FEM–BEM	finite-element–boundary element method model
FEM	finite-element method model
FFT	fast Fourier transform
FRA	Federal Railroad Administration
ICE	Institution of Civil Engineers
MBS	multibody system
MOTIV	Modelling of Train Induced Vibration
MTVV	maximum transient vibration value
PCV	pseudo-critical velocity
PiP	pipe in pipe
PSD	power spectral density
RMS	root mean square
SSR	simplified shear resistance
ZHD	zero horizontal displacement
ZSS	zero shear stress