CRC Press
Taylor & Francis Group

Ground Improvement by Deep Vibratory Methods

SECOND EDITION

Klaus Kirsch and Fabian Kirsch

Ground Improvement by Deep Vibratory Methods

SECOND EDITION

Klaus Kirsch

Fabian Kirsch

CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Printed on acid-free paper
Version Date: 20160531

International Standard Book Number-13: 978-1-4822-5756-4 (Hardback)

Library of Congress Cataloging-in-Publication Data

Names: Kirsch, Klaus, author. | Kirsch, Fabian, author.
Title: Ground improvement by deep vibratory methods / authors: Klaus Kirsch and Fabian Kirsch.
Description: Second edition. | Boca Raton : Taylor & Francis, CRC Press, 2017. | Includes bibliographical references and index.
Identifiers: LCCN 2016024076 | ISBN 9781482257564 (alk. paper)
Subjects: LCSH: Soil stabilization. | Vibratory compacting. | Foundations.
Classification: LCC TA749 .K57 2017 | DDC 624.1/51363--dc23
LC record available at https://lccn.loc.gov/2016024076

Visit the Taylor & Francis Web site at
http://www.taylorandfrancis.com

and the CRC Press Web site at
http://www.crcpress.com

Printed and bound in the United States of America by Publishers Graphics, LLC on sustainably sourced paper.

Preface to the Second Edition

Ground improvement by deep vibratory methods continues to be the most used in situ dynamic soil improvement method today, representing well over 10% of all special foundation work. Its versatility in improving the soil conditions in difficult site conditions—be it in view of the treatment depth, over water, or with restricted head room—and its economical and ecological advantages in comparison with other foundation solutions are recognized and form the basis for further development.

Our publishers proposed this second edition that encompasses the content of the first edition, dealing with a number of corrections and necessary clarifications. In addition, it provides a new Section 5.2 on the use of depth vibrators in constructing so-called vibro concrete columns. Although this method improves the soil characteristics only marginally, these small diameter in situ concrete piles are increasingly used for moderately loaded large spread foundations.

All chapters were updated with equipment improvements and have also received new additional case histories highlighting new method applications or special features and advantages. The increasing productivity as a result of the progress made with efficient special plant and effective data acquisition systems has led to a considerable growth of the special foundation market.

In Section 4.6, the partial security concept for slope stability and bearing capacity calculations with stone columns are presented in addition to the conventional safety concept.

Chapter 6, also includes comments on the *Carbon Calculator for Foundations,* which was published in 2013 by the European Federation of Foundation Contractors and the Deep Foundations Institute, providing a simple and efficient procedure to calculate CO_2 emissions of various foundation methods. It is hoped that this tool helps promote those methods that are characterized by high sustainability and low greenhouse gas emissions. Unfortunately, experience tells us that the lowest price of a project is still the decisive factor for the contract award, and as long as the CO_2 emissions of construction works are not considered a price worthy item, you should think that the society is prepared to pay the price for a clean environment these considerations remain just an idealistic exercise.

It is nevertheless hoped that this book will help to appreciate not only the economical and technical advantages of ground improvement by deep vibratory methods, but also to recognize their ecological advantages.

This book is written for civil and geotechnical engineers and for the contractors who are engaged in foundation and ground engineering. Students will find this book helpful in their advanced and postgraduate studies.

March 2016

Klaus Kirsch (Retired)
Keller Group plc

Fabian Kirsch
GuD Consult GmbH

Preface and Acknowledgments to the First Edition

The use of depth vibrators for the improvement of soils that are unsuitable as foundations for structures in their original state dates back to more than 70 years. Over the course of time, the deep vibratory methods have become probably the most used dynamic in situ soil improvement methods today. They have not only experienced a continuous development of plant and equipment to carry it out in practice, but also design methods have been proposed and refined to predict the degree of soil improvement that can be achieved.

Today the importance of deep vibratory soil improvement is unrivalled among modern foundation measures; the demand for in situ deep treatment of soils that introduces, if any, only environmentally harmless materials into the ground continues to increase with the rising level of awareness for the environment. Continued development of plant and process controls has resulted in considerable increase in production rates.

When looking at the design concepts in use today, the reader will realize that experience with the system in different soil conditions still plays an important role. Sand compaction, because of the relative simplicity and convincing economy of the system, and the familiar testing methods for the estimation of settlements have probably inhibited the development of theories that would allow the calculation of the improved properties of granular material based upon the fundamentals of soil dynamics. Recent developments show encouraging attempts to correlate the characteristic motion of the depth vibrator working in the ground with the achieved soil properties. The composite system of vibro stone columns and the surrounding cohesive soil has become a challenging field for engineers to apply finite element analyses particularly to the foundation of more complex structures and single foundations. This computational tool supports the designer in his endeavor to find the most economical solution by optimizing the foundation system.

It was the son who encouraged the father to embark on this book project, after the latter had collected knowledge and experience in the field of ground improvement over a period of almost 35 years of his professional life. This book aims to give an insight into deep vibratory soil improvement methods, both from the contractor's view (Klaus) and from the perspective of the consulting engineer (Fabian), whose dissertation on experimental and numerical investigations of the load-carrying mechanism of vibro stone column groups provided an interesting aspect in this context. We are grateful to our publisher, Taylor & Francis Group, for its support in bringing out this book, which highlights its continued interest in ground improvement methods.

We hope that this book provides the practicing engineer and the design engineer with a comprehensive insight into deep vibratory soil improvement methods. The historical development of these ground improvement methods is presented in Chapter 2, which is based on an earlier publication, Kirsch (1993) "Die Baugrundverbesserung mit Tiefenrüttlern," in Englert and Stocker (eds) *40 Jahre Spezialtiefbau 1953–1993: Technische und rechtliche Entwicklungen* (Werner Verlag, Düsseldorf, Germany). We thank Werner Verlag for its kind permission to use it in this book.

We also hope that we will succeed in demonstrating the astounding versatility of these methods as reflected in a number of international case histories from recent years. The reader will hopefully also realize that vibro compaction and vibro replacement stone columns are presently meeting—and will continue to do so—all the requirements of sustainable construction. We will demonstrate in a separate chapter that these methods require only natural materials for their execution, leaving behind only a minimal carbon footprint.

Finally, we do hope that this book will help stimulate further work and research on the subject and on those problems that are not yet satisfactorily resolved or are still the subject of controversy to enable further plant development and to improve ground engineering.

We thank Keller Group plc for their noble assistance in preparing this book, for funding the preparation of graphs and diagrams but especially for allowing access to the technical archives, and for allowing use of data in preparing most of the case histories. In this context, our foremost thanks go to Justin Atkinson, the chief executive of Keller. With the publication of this book in 2010, we would like to take this opportunity to extend our best wishes for continued development and success to Keller Group plc, which pioneered deep vibratory soil improvement and which celebrates its 150th anniversary this year.

Invaluable support has also been given by our former and present colleagues on technical matters. Our thanks go especially to Dr. Alan Bell who has critically reviewed the manuscript based on his long experience of working in ground engineering. Thanks are also due to George Burke, Jonathan Daramalinggam, Guido Freitag, Johannes Haas, Dieter Heere, Gert Odenbreit, Dr. Vesna Raju, Dr. Thomas Richter, Raja Shahid Saleem, Raja Samiullah, Dr. Stavros Savidis, Dr. Lisheng Shao, Barry Slocombe, Dr. Wolfgang Sondermann, Reiner Wegner, and Dr. Jimmy Wehr. Special thanks go to Christine Trolle for her patience in supporting us to organize the design of graphs for the manuscript.

In preparing case histories of recent applications of vibro compaction and vibro stone column methods, we gratefully acknowledge the support of special contractors in providing valuable data and information: Keller Holding GmbH for Sections 3.6.1 through 3.6.4 and 4.7.1 through 4.7.3, Hayward Baker Inc for Section 3.6.5, Keller Limited for Section 4.7.4, and Bauer Gruppe for Section 4.7.5.

December 2009

Klaus Kirsch
Keller Group plc

Fabian Kirsch
GuD Consult GmbH

Acknowledgments to the Second Edition

We thank our publisher, Taylor & Francis Group, for its encouragement and support to write this second edition, which shows its great interest in ground improvement methods. Thanks are also due to Dr. Wolfgang Sondermann, the chairman of the German Geotechnical Society and director of Keller Group plc (London, UK) for valuable advice and information on the international foundation market.

We also thank Dr. Wilhelm Degen of Betterground (Germany) for information on special plant and equipment as well as on the newly developed quality control and operator guidance system for stone columns.

We are grateful for the support and suggestions given by our former and present colleagues Johannes Haas of Keller Holding and Nikolaus Schneider of GuD (Berlin, Germany) on the use and development of the deep vibratory methods. Information on recent case histories were gratefully provided by Eric Droof and Jim Hussin of Hayward Baker, Hassan Ahmed and Guido Freitag of Keller Holding, and Jonathan Daramalinggam and Dr. Venu Raju of Keller Asia.

Special thanks go to Prof. Stavros Savidis, Technical University Berlin, Germany, who allowed access to Degebo archives, and to Dr. Ralf Glasenapp, who helped tracing their invaluable documents of the first use of the vibro compaction method.

Thanks are also due to Christine Trolle of Keller Holding, Michael Schluchter of GuD and Gunter Raabe of Gr Grafico, who supported us in designing new line drawings for this book.

Authors

Klaus Kirsch was born in 1938 in Chemnitz, Germany and graduated in 1964 as a civil engineer (Dipl.-Ing.) from the Technical University Darmstadt, Germany. Until 1969, he worked with Gruner AG in Basel, Switzerland, and later he joined Keller in Germany as site and project engineer. From 1972 to 1975, he was heading the R&D department and gained comprehensive knowledge in the use and application of ground improvement technologies worldwide, helping to introduce the vibro replacement stone column technology in the United States. He was instrumental in the development of a new generation of depth vibrators and their worldwide use for all types of structures.

From 1976 to 1985, he was responsible for Keller's overseas activities, mainly in the Middle and Far East and Africa. Major contracts included the drilling and grouting works for large dams such as the Tarbela dam in Pakistan and the Mosul dam in Iraq. After the completion of individual ground improvement contracts in Singapore and Malaysia, he also opened up new subsidiaries for Keller in this part of the world.

From 1985 onward, he was in charge of Keller's operations in Continental Europe and Overseas and was a main board director of Keller Group plc until his retirement in 2001. During this period, new subsidiaries were set up in France and Italy and, following the reunification of Germany, Keller expanded into Eastern Europe with new subsidiary companies in the Czech Republic, Poland, and Slovakia.

After his retirement from active service, he was a consultant to the Board of Keller Group plc until 2008, chairing at the same time its Group Technology Committee and the Supervisory Board of Keller in Germany. He is a member of the German Geotechnical Society (DGGT) and author and editor of numerous publications in ground engineering.

Fabian Kirsch was born in 1971 in Frankfurt am Main, Germany, and studied civil engineering at the Technical University, Braunschweig, Germany, graduating as Dipl.-Ing. in 1997 after spending visiting terms at the Indian Institute of Technology, New Delhi, India, and at the University of Glasgow, Scotland, United Kingdom. He worked from 1998 to 2003 as research engineer at the Institute for Ground Engineering and Soil Mechanics at the Technical University, Braunschweig, Germany, from where he also obtained his Dr.-Ing. in 2004 for his work on "Experimental and numerical investigations of the behaviour of vibro replacement stone column groups."

Since 2004, he has been working with GuD Consult GmbH, Berlin, Germany, a major geotechnical consultant in Germany with special expertise in soil dynamics. He is a managing partner of GuD since 2008 and was responsible for a number of projects in Germany and abroad including tunneling works in Berlin, Leipzig, and Cologne; wind park foundations in North Sea and Baltic Sea; and ground improvement and piling projects for power plants in India, Turkey, and the Philippines. He is a member of the DGGT where he works in Working Group 2.1 on Recommendations for Static and Dynamic Pile Tests. He is also a member of the German Association of Consulting Engineers (VBI), the Research Association for Underground Transportation Facilities (STUVA), the German Port Technology Association (HTG), and the Berlin Chamber of Engineers. Since 2012, he is a government-approved checking engineer for geotechnical engineering and is also the author of many publications in soil mechanics and ground engineering.

Contents

Chapter 1

An overview of deep soil improvement by vibratory methods

Realization of structures always makes use of the soil on which, in which, or with which they are built. Whenever engineers find that the natural conditions of the soil are inadequate for the envisaged work, they are faced with the following well-known alternatives of

1. Bypassing the unsuitable soil in choosing a deep foundation.
2. Removing the bad soil and replacing it with the appropriate soil.
3. Redesigning the structure for these conditions.
4. Improving these conditions to the necessary extent.

When the Committee on Placement and Improvement of Soils of the ASCE's Geotechnical Engineering Division published its report *Soil Improvement: History, Capabilities, and Outlook* in 1978, it concluded that "it is likely that the importance of the fourth alternative will increase in the future" (p. 1). Indeed, in the decades since "the need for practical, efficient, economical, and environmentally acceptable means for improving unsuitable soils and sites" (p. 3) has increased.

Before selecting the appropriate soil improvement measures, it is necessary to determine the requirements, which follow from the ultimate and serviceability limit state of design. These are

- Increase of density and shear strength with a positive effect on stability problems.
- Reduction of compressibility with a positive effect on deformations.
- Reduction/increase of permeability to reduce water flow and/or to accelerate consolidation.
- Improvement of homogeneity to equalize deformation.

When leaving aside the method of exchanging the soil, ground improvement can be categorized into compaction and reinforcement methods. Table 1.1 shows a classification of the methods of ground improvement that are of practical relevance today.

Table 1.1 Ground improvement methods

Ground improvement methods				
Compaction		*Reinforcement*		
Static methods	*Dynamic methods*	*Displacing effect*	*No displacing effect*	
			Mechanical introduction	*Hydraulic introduction*

• Preloading
• Preloading with consolidation aid
• Compaction grouting
• Influencing groundwater
	• Compaction by vibration:
	  • Using depth vibrators
	  • Using vibratory hammers
	• Impact compaction:
	  • Drop weight
	  • Explosion
	  • Air pulse method
		• Vibro stone columns
		• Vibro concrete columns
		• Sand compaction piles
		• Lime/cement stabilizing columns
			• MIP[a] method
			• CMI[b] method
			• Permeation grouting
			• Freezing
				• Jet grouting

Source: Sondermann, W. and Kirsch, K. Baugrundverbesserung. In *Grundbautaschenbuch, 7. Auflage. Teil 2: Geotechnische Verfahren.* Hrsg.: Witt, K.J., Ernst und Sohn, Berlin, Germany, 2009; Topolnicki, M., In situ soil mixing, in Moseley, M.P. and Kirsch, K. (eds), *Ground Improvement,* Spon Press, London, UK, 2004.

[a] Mixed-in-place.
[b] Cut-mix-inject.

This book deals with the important soil improvement methods that utilize the depth vibrator as the essential tool for their execution. Granular soils are compacted making use of the dynamic forces emanating from the depth vibrator when positioned in the ground. The reinforcing effect of stone columns, constructed with modified depth vibrators, in cohesive soils improves their load-carrying and shearing characteristics, and, as a modification of the vibro replacement technique, vibro concrete columns are constructed in a similar process by further modified depth vibrators to construct small diameter concrete piles in borderline soils with characteristics that cannot be improved anymore by the basic vibro techniques.

Since the development of vibro compaction during the 1930s and vibro replacement stone columns in the 1970s, they have become the most frequently used methods of soil improvement worldwide because of their unrivalled versatility and wide range of application.

As we will see, deep vibratory sand compaction is a simple concept, and, therefore, design and quality control of compaction in cohesionless soils have remained almost entirely empirical. The development of predictive design methods based on fundamental soil dynamics was probably inhibited by the simplicity of in-situ penetration testing for settlement and bearing capacity calculations. The study of the effect of resonance developing during compaction in granular soils surrounding the vibrator and improved mechanical and electronic controls of the compaction process have, only relatively recently, opened opportunities for significant advances in this field.

The introduction of coarse backfill during vibro compaction and the resulting formation of a granular or stone column was a logical and almost natural development when unexpectedly cohesive or noncompactable soils were encountered. The composite of the stone column and surrounding soil stimulated theoretical studies on settlements and shear resistance by applying standard soil mechanics principles.

When soils needing improvement of their characteristics contain layers of organic material or are too soft to allow the safe formation of a stone column, with a modified depth vibrator columns can be built in the ground using dry or liquid concrete as backfill material, which, after curing of the cementitious material, act like small diameter concrete piles, frequently with enhanced soil characteristics below the toe of the pile and alongside its shaft.

Each of the systems, vibro compaction, vibro stone columns, or vibro concrete columns, has its characteristics and method of execution, and even machine types are different for the two systems of ground improvement, as are design principles, field testing, and quality control.

When in motion, depth vibrators send out horizontal vibrations, and are all excellent boring machines in loose sandy and soft cohesive soils.

The horizontal motion emanating from the depth vibrator being positioned in the ground is the distinctive characteristic that differentiates this method from all the other methods, which utilize vertical vibrations. These methods, which are in general less effective for the compaction of granular soils and which cannot be used for the improvement of fine-grained cohesive soils, are generally not recognized as true vibro compaction methods and hence are not discussed here in great detail.

Depth vibrators are normally suspended like a pendulum from a standard or special crane for vertical penetration into the ground. The vibrator sinks by the desired depth, sometimes assisted by water or air flushing, additional weight when necessary, or even by downward thrust developed by special cranes with vertical leaders. In granular soils, the surrounding sand is compacted in stages during withdrawal, and in cohesive soils imported backfill is employed to form a stiffening column.

The choice of technique follows from the soil and groundwater conditions given in site investigation reports. As will be explained later, the grain size distribution diagram of the soil to be improved is a valuable tool for this choice. Sand and gravel with negligibly low plasticity and cohesion can be compacted by the vibrations emanating from the depth vibrator (vibro compaction), while with an increasing content of fines vibrations are dampened rendering the method ineffective. Experience shows that the limit of vibro compaction is reached with a silt content of more than approximately 10%. Clay particles at even smaller percentages (1%–2%) cause a similar