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FOUNDATIONS FOR MACHINES : ANALYSIS AND DESIGN

WILEY SERIES IN GEOTECHNICAL ENGINEERING

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WILEY

A Wiley-Interscience Publication
JOHN WILEY AND SONS
New York · Chichester · Brisbane · Toronto · Singapore

Library of Congress Cataloging in Publication Data:

Prakash, Shamsher.
Foundations for machines.

(Wiley series in geotechnical engineering)
"A Wiley-Interscience publication."
Includes bibliographies and index.
1. Machinery—Foundations. I. Puri, Vijay.
II. Title. III. Series.
TJ249.P618 1987 621.8 87-21678
ISBN 0-471-84686-4

Printed in the United State of America
10 9 8 7 6 5 4 3 2 1

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To our friend the enlightened saint, humble philosopher, and friend of all mankind who speaks the language of the heart; whose religion is love; who always aspires to fill lives of one and all with spiritual bliss.

Preface

The design of machine foundations involves a systematic application of the principles of soil engineering, soil dynamics, and theory of vibrations—a fact that has been well recognised during the last three decades. Since the classical work by Lamb in 1904 and the paper on "Foundation Vibrations" by Richart in 1962, the subject of vibratory response of foundations has attracted the attention of several researchers. The state of art on the subject has since made significant strides. Methods are now available not only for computing the response of machine foundations resting on the surface of the elastic half space but also for embedded foundations and foundations on piles. Elastic half space analogs have further simplified the computation process and are a convenient tool for the designer. The linear spring approach of Barkan, which could previously be used only for surface footings, has also been extended to account for the embedment effects. Recent advances dealing with the determination of the dynamic soil properties and rational interpretation of the test data are of direct application to the design of machine foundations. Information on several aspects of machine foundation design such as design of embedded foundations and pile supported machine foundations is either unavailable or only inadequately treated in the presently available texts.

This text has been developed with the object of providing state-of-the-art information on the analysis and design of machine foundations and is intended to cater to the interests of graduate students, senior undergraduates, and practicing engineers. Both authors have offered graduate-level courses on the subject in the United States and India. They also organized many short courses for practicing engineers, including four by the senior author at University of Missouri, Rolla. The authors have also been engaged in the design and performance evaluation of machine foundations. The feedback from the classroom and the professionals in the field has been of immense help in the planning and preparation of this text.

The special features of this book are: (1) analysis of surface and embedded foundations by both the elastic half space method and the linear spring method; (2) analysis of pile supported machine foundations; (3) detailed discussion of the dynamic soil properties, methods for their determination, and evaluation of the test data; (4) detailed design procedure followed by examples; and (5) discussion of design of machine foundations on absorbers and vibration isolation.

Knowledge of soil mechanics and elementary mathematics or mechanics is needed to follow the text.

The reader is introduced to the problem of machine foundation and its special requirements in Chapter 1. In Chapter 2, the elementary theory of vibrations is discussed. Chapter 3 deals with the wave propagation in an elastic medium that provides an important basis for determination of dynamic soil properties as discussed in Chapter 4. Needless to say, soil properties play a critical role in the design of machine foundations. Chapter 4 thus forms a very important component of the text. Also included in this chapter is the procedure for rational selection of soil parameters for a given machine foundation problem. The determination of unbalanced forces and moments occasioned by the operation of a machine is reviewed in Chapter 5. The principal subject of the book, the analysis and design of machine foundations is introduced in Chapter 6, that deals with the design of rigid-block-type foundations for reciprocating machines. In this chapter the reader is made familiar with the concepts of elastic half space method and linear spring method for computing the vibratory response of surface footings. Foundations for impact-type machines such as hammers are discussed in Chapter 7. Foundations for high-speed rotary machines are discussed in Chapter 8 and for miscellaneous machines in Chapter 9. The principles of vibration isolation and absorption are considered in Chapter 10. The design of embedded block foundations for machines is described in Chapter 11 followed by pile supported machine foundations in Chapter 12. A few case histories are discussed in Chapter 13 and construction aspects in Chapter 14.

Computer program for design of a block foundation based on principles discussed in Chapter 6 has been included in Appendix I, and for design of a hammer foundation as in Chapter 7 has been included in Appendix II. A brief description of the commercially available programs PILAY for solution of piles and STRUDL for analysis of turbo-generator foundations is included in Appendix III.

The subject matter has been developed in a logical progression from one chapter to the next. Every effort has been made to make the text self-contained as far as possible. A comprehensive bibliography is included at the end of each chapter so that an interested reader may obtain additional information from published sources.

Development in certain areas, particularly the determination of dynamic soil properties and analysis of embedded foundations and piles under dynamic loads, is taking place at a very rapid rate. Analysis and design procedures may therefore undergo modifications. This fact has also been brought to the attention of the reader at appropriate places in the text.

Thanks are due the American Society of Civil Engineers and National Research Council of Canada for permitting the use of materials from their publication. Acknowledgment to other copyrighted material is given at appropriate places in the text and figures.

In preparing this text, several of our colleagues and graduate students have helped in a variety of ways. The authors wish to express their sincere thanks to them. Special mention must be made of Dr. Krishen Kumar, who read the entire manuscript and made useful suggestions, particularly on Chapter 12, and Dr. A Syed for his useful comments and suggestions and of Mr. Murat Hazinedarogulu for assistance in writing the computer programs.

The manuscript was typed by Janet Pearson, Charlena Ousley, Allison Holdaway, and Mary Reynolds. The authors are most thankful to them for their care, painstaking efforts, and patience. John W. Koeing, technical editor at the University of Missouri, Rolla, provided editorial assistance and deserves our sincere thanks.

Acknowledgments are also due the publishers for their cooperation during various stages of editorial and production work. A special mention must be made of the cooperation received from Everett Smethurst, David Eckroth and Linda Shapiro.

It must also be mentioned that any suggestions or comments by the readers for making any improvements in the text will be highly appreciated.

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1

Introduction

Machine foundations require the special attention of a foundation engineer. Unbalanced dynamic forces and moments are occasioned by the operation of a machine. The machine foundation thus transmits dynamic loads to the soil below in addition to the static loads due to the combined weight of the machine and the foundation. It is the consideration of the dynamic loads that distinguishes a machine foundation from an ordinary foundation and necessitates special design procedures. The foundation for the machine must therefore be designed to ensure stability under the combined effect of static and dynamic loads. In general, a foundation weighs several times as much as a machine, and the dynamic loads produced by the machine's moving parts are relatively small compared to the combined weight of the machine and the foundation (Prakash and Puri, 1969). Even though the magnitude of the dynamic load is small, it is applied repetitively over long periods of time. The behavior of the supporting soil is generally considered elastic. For the range of vibration levels associated with a well-designed machine foundation, this assumption seems reasonable. The vibration response of the machine–foundation–soil system defined by its natural frequency and the amplitude of vibration under the normal operating conditions of the machine are the two most important parameters to be determined in designing the foundation for any machine. In addition, the wave energy, which is transmitted through the underlying soil from the vibrating foundation, must not cause harmful effects on other machines, structures, or people in the immediate vicinity. This consideration and the operational requirements of the machine necessitate that the amplitudes of foundation vibration be limited to small values. Thus the local soil conditions and the foundation–soil interaction are important factors to be considered in the design of foundation for any machine. Satisfactory design of a machine foundation can be accomplished by systematic application of principles of soil mechanics, soil dynamics, and theory of vibrations.

The initial cost of construction of a machine foundation is generally a small fraction of the total cost of the machine, accessories, and the installation, but the failure of the foundation as a result of poor design or construction can interrupt the machine's operation for long periods and cause heavy dollar losses. Great care should therefore be taken at all stages of the soil investigation and in the design and construction of these foundations to ensure their long-term satisfactory performance.

There are many types of machines and each may require a certain type of foundation. The different types of machines, their special features, and the types of foundations commonly used to support them are briefly described now. The criteria used in design of these foundations, the relevant codes of practice, and the data required for their design are also discussed subsequently.

1.1 TYPES OF MACHINES AND FOUNDATIONS

There are many types of machines. All generate unbalanced exciting loads. In general, the various machines may be classified into three categories:

1. *Reciprocating machines*: This category of machines includes internal combustion engines, steam engines, piston-type pumps and compressors, and other similar machines having a crank mechanism. The basic form of a reciprocating machine consists of a piston that moves within a cylinder, a connecting rod, a piston rod and a crank (Fig. 5.1). The crank rotates with a constant angular velocity. The crank mechanism converts the translatory motion into rotary motion and vice versa. The operating speeds of reciprocating machines are usually smaller than 1200 rpm.

The operation of the reciprocating machine or the crank mechanism results in unbalanced forces both in the direction of piston motion and perpendicular to it (Section 5.1). The magnitude of forces and moments will depend upon the number of cylinders in the machine, their size, piston displacement, and the direction of mounting.

If one considers only the unbalanced force in the direction of piston motion in a machine with only one cylinder that is mounted centrally on a rigid foundation (Fig. 1.1a), the motion of the foundation will be only up and down. A two-cylinder reciprocating machine under similar conditions mounted centrally on a rigid foundation, will generate an oscillatory motion and no translation (Fig. 1.1b). Similarly, if a piston is mounted horizontally, it will give rise to an unbalanced force and a moment on the foundation. The foundation will therefore undergo both translation and rotation simultaneously (Fig. 1.1c). In the case of a two-cylinder machine mounted horizontally, the unbalanced forces in a plane parallel to the base of the foundation generate a couple (Fig. 1.1d). This results in a motion that is similar to the motion of a torsional pendulum. It therefore becomes clear