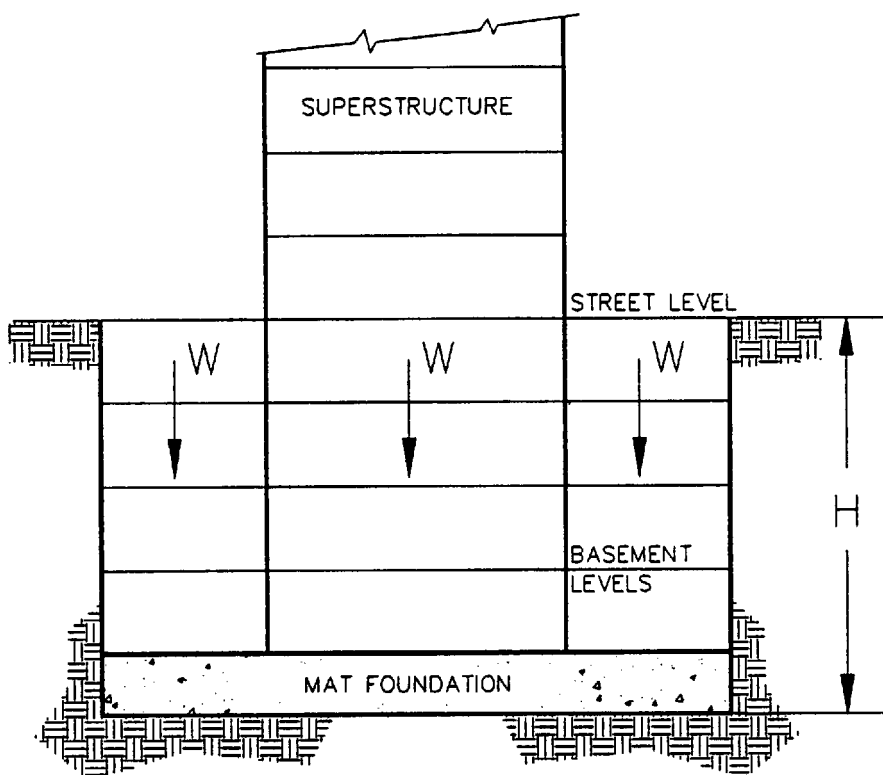


Design and Performance of Mat Foundations

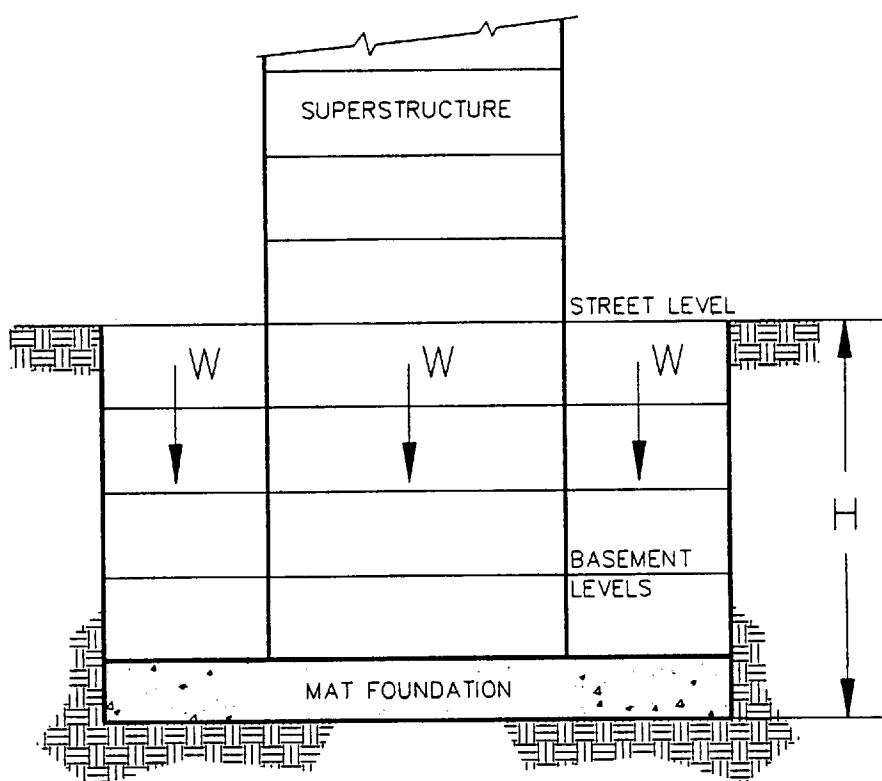
State-of-the-Art Review



Edward J. Ulrich
Editor

Design and Performance of Mat Foundations

State-of-the-Art Review



Edward J. Ulrich
Editor


SP-152
Documents
 Document Sharing Hub

DISCUSSION of individual papers in this symposium may be submitted in accordance with general requirements of the ACI Publication Policy to ACI headquarters at the address given below. Closing date for submission of discussion is September 1, 1995. All discussion approved by the Technical Activities Committee along with closing remarks by the authors will be published in the January/February 1996 issue of either ACI Structural Journal or ACI Materials Journal depending on the subject emphasis of the individual paper.

The Institute is not responsible for the statements or opinions expressed in its publications. Institute publications are not able to, nor intended to, supplant individual training, responsibility, or judgment of the user, or the supplier, of the information presented.

The papers in this volume have been reviewed under Institute publication procedures by individuals expert in the subject areas of the papers.

Copyright © 1995
AMERICAN CONCRETE INSTITUTE
P.O. Box 19150, Redford Station
Detroit, Michigan 48219

All rights reserved including rights of reproduction and use in any form or by any means, including the making of copies by any photo process, or by any electronic or mechanical device, printed or written or oral, or recording for sound or visual reproduction or for use in any knowledge or retrieval system or device, unless permission in writing is obtained from the copyright proprietors.

Printed in the United States of America

Editorial production Victoria Wieczorek

Library of Congress catalog card number 95-75980

PREFACE

Nearly a half century ago, Karl Terzaghi (1955) rationalized the analysis and design of mat foundations with "Evaluation of Coefficients of Subgrade Reaction." The rationalization was based on the fundamental concept of Hooke's Law and the subgrade reaction on the base of a rigid centrally loaded plate resting on the horizontal surface of the subgrade has the same value at every point of the base. Subgrade reaction was considered the most important variable in the analysis and design of a mat foundation. Soon after the Terzaghi declarations, Teng (1962) emphasized the importance of the subgrade reaction concept in connection with mat properties and the variations in subgrade response, yet the unfortunate use of a single value of subgrade reaction was seen to be specious to most structural engineers throughout the decades.

Now, nearly a half century later, distinguished engineers have reported the results of structure-mat-subgrade interaction studies, mat-subgrade interaction studies, case histories, and experience related to the design and performance of mat foundations. The conclusions are still consistent with those of the eminent predecessors in that the subgrade response is the most important parameter in the analysis and design of mat foundations. The subgrade reaction concept declared by Terzaghi (1955) and clarified by Teng (1962) is indeed valid and can be properly used with the Discreet Area Method (Ulrich, 1991) for the appropriate loading conditions. The subgrade reaction beneath a mat foundation will vary and the use of a single subgrade reaction value for an entire mat foundation will lead to wrong designs.

Construction procedures and actual site conditions are vital to successful mat performance. Prudent analysis and design of mat foundations can be achieved only by a team approach consisting of the architect, structural engineer, and geotechnical engineer. Responsible contract documents are the product of design along with geotechnical field monitoring to evaluate actual conditions and construction procedures.

Committee 336 is indebted to the authors who prepared papers for the session because each are outstanding engineers and researchers. Special thanks is extended to Mr. Hugh Lacy for his encouragement and review of the papers.

Edward J. Ulrich
Editor

ACI Committee 336
COMBINED FOOTINGS AND PIER FOUNDATIONS

Hugh S. Lacy
Chairman

Edward J. Ulrich
Secretary

Clyde N. Baker, Jr.
Steven C. Ball
Prabodh V. Banavalkar
Joseph A. Bohinsky
Joseph P. Colaco
M. T. Davisson
M. Gaynor

William P. Hackney
Fritz Kramrisch
Jim Lewis
John F. Seidensticker
Jagdish S. Syal
Samuel S. White
John J. Zils

CONTENTS

PREFACE	iii
AN INTRODUCTION TO THE STATE-OF-THE-ART MAT FOUNDATION DESIGN AND CONSTRUCTION by E. J. Ulrich, Jr.	1
MAT FOUNDATION AND ITS INTERACTION WITH THE SUPERSTRUCTURE by P. V. Banavalkar	13
MAT FOUNDATION DESIGN — A SOIL-STRUCTURE INTERACTION PROBLEM by J. F. Horvilleur and V. B Patel	51
SUBGRADE REACTION IN MAT FOUNDATION DESIGN by E.J. Ulrich, Jr.	95
SUBGRADE MODELING FOR MAT FOUNDATIONS: A REVIEW AND CRITIQUE OF ANALYTICAL METHODS by J. S. Horvath	117
MESSETURM, FOUNDATIONS FOR THE TALLEST BUILDING IN EUROPE by G. J. Tamaro and A. H. Brand	161
MASS CONCRETE POUR TECHNIQUES FOR THE MAT FOUNDATION OF 1100 ALAKEA PLAZA By A. R. Dar, J. C. Bravo, A. Sarwar, and H. Hamada	187
GEOTECHNICAL-STRUCTURAL INTERACTION FOR INNOVATIVE MAT DESIGN by C. N. Baker, Jr.	203

TALLEST BUILDING IN THE TEXAS MEDICAL CENTER: ST. LUKE'S MEDICAL TOWER
by E. J. Ulrich, Jr. and C. J. Ehlers 219

LARGE MAT ON DEEP COMPRESSIBLE SOIL
by J. P. Stewart, K. H. Pitulej, and H. S. Lacy 245

SI (Metric) TABLES 265

INDEX 267

SP 152-1

An Introduction to the State-of-the-Art Mat Foundation Design and Construction

by E. J. Ulrich, Jr.

Synopsis: Subgrade response is the most important parameter in analyzing and designing mat foundations. Rational design of a mat foundation requires the consideration of immediate and long term subgrade response. The soil response determines mat behavior and differential movement exacerbates moments. Often the long term movement provide the most severe mat behavior characteristics.

The popular use of a single modulus of subgrade reaction, k , to model subgrade response is wrong and will lead to wrong designs. Mat analysis and design should be performed using the Discrete Area Method (9, 10) wherein the subgrade responses can be properly modeled resulting the use of varying moduli of subgrade reaction.

The geotechnical engineer and structural engineer must form a solid bond to cope with mat foundation design from early planning through construction. Often construction details and procedures will govern performance and can ruin any analysis. Hence, the geotechnical engineer should be on site accessing conditions. Neither group should work independently and expect successful performance.

Keywords: Mat foundations; soil mechanics; subgrades

Edward J. Ulrich: Over his 25 year career and as a principal with Ulrich Engineers, Inc. Mr. Ulrich has consulted on the foundation engineering for the world's tallest soil supported buildings. He has a BCE from Georgia Tech and an MSCE from the University of Illinois. He is secretary and past chairman of ACI 336.

In behalf of Committee 336, I welcome you to reflect on our present experience in the design and construction of mat foundations. To those of you who have anguished over the preparation of a technical presentation, I applaud you. To those of you who have inquired, attended the sessions, and have come to ponder these shared experiences, I salute you. There is so much yet to be accomplished.

What indeed is our objective in the first state-of-the-art review on the design and construction of mat foundations? The answer can best be discovered by searching the origins of foundation engineering founded by Professor Karl Terzaghi who, as a structural engineer, developed this new branch of structural analysis before World War II. This new engineering discipline was founded upon the fundamental principle, foundation engineering is ... "one ounce of geology for every pound of theory of structures and soil mechanics. The one ounce of geology is as essential as the yeast in the processes of fermentation, but it represents only a minute fraction of the vast domain covered by the sciences of the earth" (7).

The profession was borne as earthwork and foundation engineering but has been diluted to geotechnical consulting and structural engineering with each group following different paths.

Our session objective may be illustrated by a simple story about a mature married couple who has reached a warm healthy bond during the many years of crossing the ocean of life together. The bond extends beyond carnal love to dependence, need, mutual respect, and a commitment to cope with the challenges of life as a team. Then, one evening a spouse drives to the store and is involved in an accident on the way home. The victim recovers but with severe amnesia. The husband and wife continue to live together but not as a whole. The bond is broken because only one remembers, and the relationship slowly deteriorates until they realize they no longer cope with life; each lives for self.

Yes, our objective here today is to re-establish that lost relationship, that bond between the structural and geotechnical engineer so that together they will cope with the design and construction of mat foundations, or the foundation engineer will be forced to design mat

foundations. The present course ruled by economics, politics, and ignorance continues to be a courtship to danger.

HISTORICAL PERSPECTIVE

To better understand the needs related to the design and construction of mat foundations, let us first review the guidance of our early predecessors as they developed this profession of foundation engineering. These comments form the real foundation upon which designers are to practice if we are to cope with the design and construction of mat foundations.

Every civil engineer should be prepared to deal with soil engineering and foundation problems and should therefore have a general knowledge of the fundamentals involved. However, the first thing to be learned about soils is that they differ in several important aspects from other materials which civil engineers have to handle. An essentially different approach to their study is therefore indicated. The strength and the deformation characteristics and other engineering properties are not constant for a given soil but may be altered appreciably with time and by the manner in which construction operations are carried out. Stress analyses in soil masses are much more complex than in other civil engineering structures. Rigorous solutions are therefore often based on oversimplified assumptions and hence have only a limited value. By contrast, experimental procedures, which include measurements on full-scale structures, often yield information of decisive importance. Previously accepted theories frequently have to be modified or even rejected on the basis of new experimental data. Such data are far from easy to obtain and at present are rather limited, so that some latitude is still left for the exercise of judgment as to the proper use of existing theories. Hence the strong element of art in all soil and foundation engineering work should not be overlooked. The acknowledgement of its existence is necessary for the understanding of the present status of this field of knowledge and endeavor, as well as of the methods of approach which are essential for its further advancement. This requires the cooperation of the entire civil engineering profession...

(1951) Gregory P. Tschebotarioff

Soil mechanics originated several decades ago under the pressure of necessity. As the practical problems involving soils broadened in scope, the inadequacy of the scientific tools available for coping with them became increasingly apparent. Efforts to remedy the situation started almost simultaneously in the United States and in Europe, and within a short period they produced an impressive array of useful information.

The initial successes in this field of applied science were so encouraging that a new branch of structural analysis appeared to be in the making. As a consequence, the extent and profundity of the theoretical investigations increased rapidly, and experimental methods were developed to a high degree of refinement. Without the results of these painstaking investigations a rational approach to the problems of earthwork engineering could not have been attempted.

Unfortunately, the research activities in soil mechanics had one undesirable psychological effect. They diverted the attention of many investigators and teachers from the manifold limitations imposed by nature on the application of mathematics to problems in earthwork engineering. As a consequence, more and more emphasis has been placed on refinements in sampling and testing and on those very few problems that can be solved with accuracy. Yet, accurate solutions can be obtained only if the soil strata are practically homogenous and continuous in horizontal directions. Furthermore, since the investigations leading to accurate solutions involve highly specialized methods of sampling and testing, they are justified only in exceptional cases.

On the overwhelming majority of jobs no more than an approximate forecast is needed, and if such a forecast cannot be made by simple means it cannot be made at all. If it is not possible to make an approximate forecast, the behavior of the soil must be observed during construction, and the design may subsequently have to be modified in accordance with the findings. These facts cannot be ignored without defying the purpose of soil mechanics....

The art of getting satisfactory results in earthwork and foundation engineering at a reasonable cost, in spite of the complexity of the structure of natural soil strata and in spite of the inevitable gaps in our knowledge of the soil conditions, is the most important goal. To achieve this goal the engineer must take advantage of all the methods and resources at his disposal--experience, theory, and soil testing included. Yet all these resources are of no avail unless they are used with careful discrimination, because almost every practical problem in this field contains at least some features without precedent.

The details of the methods for coping with the practical problems ... may change as experience increases, and some of them may become obsolete in a few years because they are no more than temporary expedients. Yet the merits of the semiempirical approach advocated are believed to be independent of time...

(1967) Karl Terzaghi and Ralph B. Peck

In a broad sense, foundation engineering is the art of selecting designing, and constructing the elements that transfer the weight of a structure to the underlying soil or rock. In practice, however, the actual construction is usually not carried out by the organization responsible for the design; the role of the engineer is generally considered to consist only of the selection of the type of foundation, the design of the substructure, and the supervision of construction.

The art of foundation engineering had its origins in antiquity. It developed with the accumulation of experience but without the aid of science until, in about 1920, it had reached a considerable degree of refinement. Yet, occasional inexplicable failures indicated that the limitations of the empirical procedures were not properly understood.

In the early 1920's there began a concerted scientific effort to determine the physical laws responsible for the behavior of the subsurface materials from which foundations derive their support. The new field of endeavor, known as soil mechanics, attracted and still holds the attention of many workers. It has provided new techniques for selecting the appropriate types of foundation under a given set of conditions and for predicting the performance of the completed substructure. It has by no means decreased the importance of the accumulated experience of the ages, but it has defined the limits within which the traditional techniques are applicable and has provided new techniques suitable under the circumstances in which the traditional procedures are not valid.

In recent years the power of science has become increasingly apparent, and there has been a tendency to discount the importance of the vast store of knowledge acquired during past generations by trial and error. This attitude has been reflected in many engineering schools by the replacement of courses in foundation engineering by others in soil mechanics, and by the prevalent opinion that detailed training in soil mechanics must precede and may even eliminate the need for training in foundation engineering.

In reality, soil mechanics is only one of the bodies of knowledge upon which the foundation engineer may draw. If studied to the exclusion of the other aspects of the art, it leads to the erroneous and dangerous impression that all problems in foundation engineering are susceptible of direct scientific solution. Unfortunately, the vagaries of nature and the demands of economy combine to eliminate this possibility.

(1974) Ralph B. Peck * Walter E. Hanson * Thomas H. Thornburn

...A second change and challenge is the continuing growth of the fundamental sciences and their applications to the solution of problems. We have more elegant theories, more sophisticated techniques for field and laboratory measurement, and more powerful computational tools--from the electronic calculator that has replaced the traditional slide rule to the advanced computers that even present their results in the form of graphs and drawings. Paradoxically, these advances have not always been helpful. We have some solutions to problems that are insignificant but none to some of the more pressing problems. For example, we can analyze the ground motion generated by an earthquake, but we cannot predict when and where the earthquake will occur. We can measure the movement in a landslide and evaluate its mechanism, but we are not sure why one mountainside moves and a similar adjacent one remains stable. Science and engineering have become so intoxicated by the elegant tools and techniques for analysis that they forget that the ultimate aim of engineering is to solve problems--the problems of society that are related to both the natural and man-made environment.

Unfortunately, they are also blamed for the effects of misuse of technology brought on by the nearsighted demands of the public and politicians for instant solutions to the problems. For example, the billion-dollar Teton Dam failure has been rightly blamed on errors in engineering judgment. However, public demand and political expediency determined that the dam should be built, and economic pressures from established bureaucracy made it impossible to build the dam in a safe manner. The engineer must be aware of the limitations of technological solutions to problems; both those limitations of the state of scientific knowledge and engineering experience and the limitations imposed by political expediency, economic inadequacy, and public misinformation. The engineer is obligated to resist misapplied political and bureaucratic pressure and to inform the public of the risks of the project as well as its benefits.

The students remain a fourth challenge. They have been exposed to a more sophisticated education and have at their command more powerful tools for solving problems. However, these tools can be the student's enemy because they focus the student's attention on the techniques for problem solving instead of on the problem. The result is that a problem is solved with great precision, but sometimes the wrong problem!

The author hopes that the users of the text will be intrigued by solving real problems, using not only the tools of analysis, but also their intuition and growing experience where no analyses are available.

Creating new solutions for old problems and for those of the future using knowledge and ingenuity is the real challenge of engineering and its greatest ingenuity, and add enjoyment to the practice of engineering...

(1979) George F. Sowers

MESSAGE

The common message by our predecessors is that successful foundation design solves real problems and is achieved by experience developed, by knowledge of precedents, familiarity with soil mechanics, and a working knowledge of geology. The structural and geotechnical engineer bonded together throughout design or the earthwork and foundation engineer will cope with foundation problems. The design, however, is not complete until the structure is built and the need for design adjustments is assessed during construction to finalize the compatibility between foundation and earth.

Does the geotechnical report based often on a scope of work developed by others satisfy the requirements for design? No. While the earth may be continuous, the mass is neither homogeneous, isotropic, nor elastic and construction procedures often govern the earth properties along with the character of response to load. With these realities, the geotechnical report can only be considered the first step of the design process and the initial phase of involvement by the geotechnical engineer. If the geotechnical consultant is required to guide the design and construction of foundations, who should provide the experience and judgement needed to complete the design and produce contract documents after the soils report is finished?

The industry has become intoxicated with the computer and engineers tend to believe that a few simple parameters will satisfy the design needs, instead of allowing the design to proceed with the bonded relationship of the structural and geotechnical engineer. How often is the question asked? "Can you give me a spring constant so I can design my mat?" The answer to coping with the design and construction of mat foundations lies in the past... and we must recall the experience of our predecessors and their visions to be successful as we forge into the 21st Century. The structural and geotechnical engineers with a strong bond can cope with mat foundations or the earthwork and foundation engineer must accept the challenge.

MAT FOUNDATION OVERVIEW

In the most simplest terms, the mat foundation is a beam, not supported at points by columns, but supported at all points by the earth. Since the earth is far weaker than the mat foundation and the earth response is the most important parameter in the design of mats, compatibility of the mat deflections and earth response is vital to coping with mat foundation design. The design foundation-earth compatibility must also be examined during construction because site conditions may be different from those concluded for design or the construction procedures may change the properties of subsurface conditions. And unlike other elements of a structure, foundation contract documents must address installation procedures because of the relationship of construction to performance.

The mat foundation has two broad objectives to a project:

- o transfer applied structural loads
- o provide predicted movements consistent with architectural, structural and mechanical requirements anticipated in design

Most Finite Element Methods of analyzing foundations require the use of a spring constant (coefficient of subgrade reaction) to model the subgrade response (9, 10). The character of the term "spring constant," implies linear elastic response, isotropy, homogeneity and many text books have fallen into the associated pit by furnishing values which are compatible only to very stiff elastic earth responses.

The roots of mat subgrade response extend to Terzaghi (6), who first applied the theory of subgrade reaction to foundation engineering in the analysis and design of mat foundations. Terzaghi (6, 7) emphasized the simplifying assumptions and limitations of the theory of subgrade reaction because of the keen awareness of the variability of the earth as a subgrade reaction to a loaded system. Soon after Terzaghi presented the application of subgrade reaction to mat foundation design, Teng (8) extended the presentation to remind engineers that the subgrade response is not elastic and actually consists of three components:

<u>Description</u>	<u>Stiffness</u>
distortion (immediate) settlement	: elastic - plastic
primary (consolidation) settlement	: elastic - plastic
secondary compression	: plastic

The subgrade reaction in mat foundation design should consider the real earth response. Case histories (2, 9, and 10) of the performance large mat foundations have confirmed the theory of subgrade reaction assumptions are indeed simplifications. The analyses of modern case studies demonstrated that oversimplification of the mat subgrade reaction by an individual value for the coefficient of subgrade reaction can misguide the engineer and lead to wrong designs (10). The new ACI report on Suggested Design and Construction Procedures for Combined Footings and Mats (ACI 336.2) provides the only modern report on mat foundations aside from our session.

The subgrade response model should be selected by the geotechnical engineer on a site-specific basis for mat foundation design and will depend upon load transfer, earth conditions and construction procedures. The subgrade response may be elastic, elastic-plastic, up, or down. Ulrich presented the Discrete Area Method (DAM) to allow the foundation engineer or structural-geotechnical team to properly consider the mat subgrade response using subgrade reaction theory with the principles of soil mechanics (10). With the DAM, the geotechnical engineer selects a subgrade model using the principles of soil mechanics and values of coefficients of subgrade reaction are calculated based on applied contact pressures and subgrade response to the system of contact pressures. The subgrade response can be modelled as a combination of elastic, elastic-plastic, plastic materials, finite elements, consider layering, and evaluate other environmental influences such as adjacent lightly loaded excavations. Finite elements are available to model subgrade response in place of classical soil mechanics models, but the relationship between the finite element model and site specific conditions is highly elusive.

COPING WITH MAT FOUNDATION DESIGN

How then does the engineer cope with the design of mat foundations? Does the structural engineer ask for a "spring constant" to insert into a finite element mat analysis program? We must cope with mat foundation design by team work between the structural engineer and geotechnical engineer working together with a common bond to be the foundation engineer in mat design.

Mat analysis is subject to significant limitations in spite of the advances in computer technology. Though not often admitted, the degree of confidence in predicting load transmitted to the mat decreases dramatically as the structure becomes larger and more complex. Some engineers acknowledge that loads cannot be computed reliably for service

load conditions. The subgrade response models and parameters are not precise and are an idealization of a material that has inherent variability. These variables challenge the most sophisticated models.

The methods available to model the subgrade response require the results of well instrumented performance studies of major structures, near flawless knowledge of subsurface conditions and accurate structural load values to precisely predict the subgrade response. Although the natural point-to-point variability of the subsurface condition is real and magnifies the uncertainty of the subgrade response model, the design-construction details are probably the most important limitation to accurate mat analysis and prediction. Slight departures during construction from responsible contract document details can ruin the results of the most sophisticated analyses.

While a uniform value of subgrade reaction may allow a mat design to be completed, use of uniform coefficient of subgrade reaction to analyze and design mat foundations is an oversimplification of the soil response and can lead to wrong designs. The coefficient of subgrade reaction may vary considerably across a mat, and the nonuniformity of the values has the most influence on bending moments. After analysis of bearing capacity, the Discrete Area Method should be used to analyze mat-subgrade interaction.

Although the Discrete Area Method is available to allow the mat analysis to properly model subgrade response for the effects of complicated mat loading on the subgrade, the subgrade model and parameters contain imperfections that can be improved only through more rigorous construction observations with comprehensive measurements of the mat and subgrade behavior. Inadequate construction quality control and inadequate observations with unsatisfactory measurements continue to contribute to unsuitable mat performance.

We must reestablish that loose bond to cope with mat foundation design or become foundation engineers. The analysis and design of mat foundations are too complex to allow a designer to proceed only on the basis of a soils report.

SESSION DEVELOPMENT

The 1991 ACI session on the design and construction of mat foundations was conceived to provide a state-of-the-art review for engineers and builders. The session was first proposed by Dr. Shyam N. Shukla in 1988 who later passed the baton to Edward J. Ulrich. A call for papers was issued in 1990 for the Spring 1992 ACI Conference in Washington, D.C. A total of 10 technical presentations from distinguished

international engineers were accepted, but the session volume will include an additional paper, "Subgrade Reaction in Mat Foundation Design" (13) to complete the volume.

The honorable Dr. P. V. Banavalkar will give the first presentation of Session I. He presents the results of a parametric study to determine the most critical parameter in mat foundation design. Dr. Banavalkar directed research that included the design of a tall building with a perimeter tubular structural frame to examine mat interaction with a super structure, effects of subgrade reaction, and mat structural properties.

The second presentation is given by Dr. John S. Horvath who presents the results of analyses from two case studies using the finite element method to model both the foundation and subgrade. Javier Horvilleur shares the results of analysis, design, and performance of two mat foundations in different geologic environments wherein the mats were analyzed using finite elements with the Discrete Area Method. Mat subgrade response models considered both long term and short term load applications. The final presentation of Session I is given by Hugh Lacy regarding the design and performance of a mat foundation on deep compressible soil. Results of the analyses indicated the deflections under long term loading conditions were severe using the Discrete Area Method and provisions were made at each of the 2500 columns to relevel the superstructure using hydraulic jacks and shims.

Session II focuses on case studies and begins with a presentation by Al Brand on the Tallest Building in Europe. John C. Bravo reviews temperature characteristics of a 9500 cu yd mat built in Hawaii's deepest building excavation. Florian G. Barth presents design and construction details on a post tensioned mat. Session II concludes with presentations by Clyde Baker on structural interaction for innovative mat design and Ed Ulrich reports on the Tallest Building in the Texas Medical Center.

Once again, "WELCOME!"

REFERENCES

1. Casagrande, A., (1965). Journal of the Soil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers, Vol. 91, No. SM4, part 1, July.
2. Focht, J. A.; Khan, F. R.; and Gemeinhardt, J. P. (1978). "Performance of One Shell Plaza Deep Mat Foundation". Vol 104, GT-5, pp 593-608.
3. Peck, Ralph B., Hanson, Walter E., and Thornburn, Thomas H. (1974). Foundation Engineering, John Wiley and Sons Inc., New York, pp. v-x.
4. Sowers, George F. (1979). Introductory Soil Mechanics and Foundations: Geotechnical Engineering, 4th ed. The MacMillan Publishing Company, Inc. New York, pp. v-vii.
5. Teng, Wayne C. (1962). Foundation Design, Prentice Hall, Inc., Englewood Cliffs.
6. Terzaghi, K. (1955). "Evaluation of Coefficients of Subgrade Reaction," Geotechnique, Vol. 5, No. 4., pp 297-326.
7. Terzaghi, Karl (1960). From Theory to Practice. Selections from the Writings of Karl Terzaghi, John Wiley & Sons, N. Y., pp 1-425.
8. Tschebotarioff, Gregory P. (1951). Soil Mechanics, Foundations and Earth Structures, McGraw-Hill, Inc., New York, pp. vii-x.
9. Ulrich, E. J. (1988). Geotechnical Considerations in Mat Foundation Design, "Soil Structure Interaction", ASCE, Illinois Section, pp 1-33.
10. Ulrich, E. J. (1991). "Subgrade Reaction in Mat Foundation Design," Concrete International, American Concrete Institute, Vol. 13, No. 4, April, pp. 41-50, Detroit.

SP 152-2

Mat Foundation and Its Interaction with the Superstructure

by P. V. Banavalkar

Synopsis:

Over the years the methods of analysis, design and construction for structures have gone through major modifications, however, the use of mat foundations to support building loads is ancient and very well documented. The mat foundation is a result of merging individual spread footings which support column loads and rest on soil strata, piles or piers. The size of the mat foundation partially or fully covers the footprint of the tower structure and usually extends well beyond its footprint. The bearing strata of a mat foundation is determined by the allowable soil bearing capacity, the mat performance in terms of its settlement and its impact on the structural behavior of the superstructure. This paper discusses the analysis of a soil supported mat foundation with emphasis on the variation of both structural members and soil properties as they impact the design. The different parameters considered in this study are structural property of concrete mat, variation of modulus of subgrade reaction both in spatial and time domain and variation in the loading pattern imposed on the mat. An interaction between a realistic superstructure having a perimeter tubular structural frame and a corresponding mat foundation is investigated for different parametric values such as the stiffness of structural frame and soil properties.

Keywords: Creep properties; frames; mat foundations; settlement (structural); soil mechanics; soil stabilization; stiffness; superstructures

ACI member P. V. Banavalkar is Executive Vice President and Chief Engineer of CBM Engineers, Inc., a consulting structural engineering firm in Houston, Texas. Dr. Banavalkar received his B.Tech/Engineering degree from the Indian Institute of Technology, Bombay; M.S./Civil Engineering from the University of Illinois; and Ph.D./Civil Engineering from Cornell University.

INTRODUCTION

Over the years the methods of analysis, design and construction for structures have gone through major modifications; however, the use of mat foundations to support building loads is ancient and very well documented. The mat foundation is a result of merging individual spread footings which support column loads and rest on soil strata, piles or piers. The size of the mat foundation partially or fully covers the footprint of the tower structure and usually extends well beyond its footprint. The bearing strata of a mat foundation is determined by the allowable soil bearing capacity, the mat performance in terms of its settlement and the settlement's impact on the structural behavior of the superstructure. This paper discusses the analysis of a soil supported mat foundation with emphasis on different structural parameters which impact the design. The interaction between a realistic superstructure with a perimeter tubular structural frame and a corresponding mat foundation is investigated for different parametric values.

DETERMINATION OF BEARING STRATA FOR THE MAT

The net allowable soil pressure based upon a shear failure must be verified, but it has seldom been a factor in determining the bearing strata of mat foundations. Based upon the stratigraphy underneath, the bottom elevation of the mat depends primarily upon the net sustained pressure on the soil mass (see Fig. 1). The net sustained pressure is defined as the difference between the pressure due to the sustained load from the superstructure along with the weight of the mat and the pressure released due to the excavation of the soil mass. In soils of the Beaumont clay formation, found in the southwestern United States, mats designed for a net sustained pressure between 1,000 psf to 2,500 psf have performed satisfactorily. The determination of the allowable net sustained pressure depends upon the differential settlement under the mat and the stability

characteristic of the soil mass below. The differential settlement of a mat is proportional to its net sustained pressure.

Since the mat foundation is to be located at a certain depth below the ground level, the space below ground is usually utilized by providing basement floors. Traditionally these floors are retail or parking levels as chosen by the Owner.

The consistency of the vertical soil surcharge pressure adjacent to the edges of the mat is important in determining the uniformity of behavior of the mat foundation. Sometimes the tower structure occupies only a part of the city block as was the case in Texas Commerce Tower, Houston, the tallest soil supported structure in the world. The loss of soil surcharge pressure over almost half the perimeter of the mat, as shown in Fig. 2, reduced its safety factor against overturning. The required soil surcharge for the desired factor of safety against overturning was provided at the perimeter by elimination of one basement level (Fig. 2).

ANALYSIS AND DESIGN

Several simplified methods of mat analysis such as the strip method, equivalent flat slab, beam on elastic foundation or a complex method such as soil line theory (1) have been used in the past. However, in recent years with the advent of finite element techniques, a plate on elastic foundation method of analysis for mat foundations is common.

In order to analyze a mat foundation as a plate on elastic foundation, the following design parameters are addressed:

- I) The Structural Properties of the Concrete Mat
- II) The Soil Spring Constant (Modulus of Subgrade Reaction)
- III) The Interaction of the mat with the Superstructure

The Structural Properties of the Concrete Mat

The thickness of the concrete mat foundation is based on the design bending moments and the punching shear capacity underneath the applied loads. A finite element program, with a plate bending element depends only on the flexural stiffness of the element and does not account for shear

distortion. Not recognizing the shear distortion tends to overestimate the mat stiffness, the magnitude of which depends upon the shear span-to-depth ratio. Use of multilayered solid or isoparametric elements would be a more accurate simulation of a thick mat. The use of orthotropic plate bending elements to simulate mat properties varying in mutually orthogonal directions is perhaps justified only for a waffle type mat construction. Because of simplicity both in modelling and interpretation of the analysis results, plate bending elements have been used extensively.

The flexural properties of the mat are quite important in its analysis and design. The author developed a program whereby, on the basis of designed or anticipated amounts of steel reinforcement, variable flexural properties consistent with the force levels in the mat segment can be used. An average property of cracked moment of inertia of 0.6 times I_{gross} has been found to be satisfactorily accurate. As demonstrated later in the paper, the variation in the flexural rigidity, "EI," impacts the design moments in the mat.

The Spring Constant

The determination of the spring constant depends upon three specific parameters:

- A) Variations in the Spring Constant across the mat to Produce the Settlement Contour Consistent with the Soil Analysis
- B) Time Dependant Behavior of the Soil
- C) Dependence of the Spring Constant on the Loading Pattern

Variation of the Spring Constant -- Customarily, a soil spring constant is determined by a unit load method and further modified for the size effect of the mat foundation (2). Such simplification is an approximation of global behavior of the mat foundation, but it is erroneous as far as the design shear and moments are concerned.

A uniformly loaded mat foundation analyzed for a uniform spring constant will indicate uniform deflections (Fig. 3a). However, in reality, mat behavior is contrary to this. A uniformly loaded mat shows a dishing effect at the center. Because of the soil pressure surcharge and infinite soil mass continuum beyond the edge of the mat foundation, the settlement profile of the mat demonstrates a dishing effect with smaller displacement at the edge and larger vertical displacement at the center (Fig. 3b). The spring

constants used in the analysis should depict this dishing behavior. A variable spring constant with lower values at the interior portion and higher values at the outer edge models this effect in the analysis. (See Fig. 3c.) This particular variation of spring constant is applicable to a uniformly loaded structure.

Time Dependant Behavior of Soil -- The time dependant settlement behavior of the soil is to be reflected in the analysis and design of the mat.

Typically sandy soil responds fairly instantaneously to the applied loads. The response to loading of clay soil is dramatically different. For sustained dead loads, mat settlement extends over a long period of time, eventually forming a stable deflected profile. However, for transient wind or seismic loads, clay responds elastically. In clay, the spring constant to produce deflections consistent with actual transient wind or seismic deflections of the mat may be $2\frac{1}{2}$ to 3 times greater than the spring constant for sustained loads. The design of reinforcement has to envelop the conditions of the sustained and the transient loads. The disregard of this time dependant behavior can result in an erroneous steel reinforcement both from the standpoint of magnitude and distribution.

The Loading Pattern -- Since the deflected profile of the mat foundation has to coincide with the final stable configuration, the settlement profile including the effects of dishing and rigid body rotation and possible twisting about the axis of the mat has to be reflected in the spring constants used for the design (Fig. 4).

Republic Bank Center in Houston represents the behavior of an unevenly loaded mat foundation (Fig. 5). Because of the segmental building profile the net sustained load on the mat foundation varied as shown in the (Fig. 6). Further, because the adjacent banking hall reduced the overburden surcharge on the east side of the high rise segment of the tower, the mat showed a tendency to twist about the longitudinal axis. A 2" differential settlement at the edge of the mat next to the lightly loaded Banking Hall Section is apparent in Figure 7. Such differential settlements are discussed near the end of this paper. The variable spring constants to reflect the behavior of the rigid body rotation coupled with the twist are shown in the Fig. 8.

The construction of future adjoining structures can influence the settlement characteristics of the existing mat structure depending upon the magnitude of new load, and the depth of excavation relative to the previously completed existing structure. When such future construction is anticipated, the resulting settlement characteristics imposed on the mat can be represented by modified spring constants.

Another loading which changes the mat settlement pattern is the relative magnitude of load distribution during the completion process of the structure. Buildings with heavy precast skin loads have higher intensity of load on the perimeter of the building during the early life of the structure until the interior core and tenant work is completed. Buildings which remain unoccupied for a long period of time with heavy skin loads will have a different settlement profile which will influence the design.

The Interaction with Structural Frame

Structural Systems -- The structural frame interaction with the mat foundation depends primarily upon the ratio of shear stiffness between the mat foundation and structural frame. It is further affected by the sequential build up of stiffness which occurs simultaneously with the application of loads.

Because of the insignificant or very low shear stiffness of structures such as a simple span steel beam supported floor, concrete flat plate or even a long span beam-column system (Figs. 9a, 9b, and 9c), they have practically no influence on the mat design. However, individual structural elements are affected by the differential settlement of their supports and must be checked for serviceability.

In other groups of structural systems such as outrigger vierendeel girders, trusses or floor-deep concrete beams designed to provide lateral resistance to the building, though they do not offer redistribution of forces in the mat itself, they need careful evaluation of their own structural response to deflections induced by mat settlement (Fig. 9d, 9e, and 9f). A ductile moment resisting frame, such as an outriggered vierendeel girder (Fig. 9f), offers less resistance to differential settlement than truss type elements (Fig. 9e). Differential settlement between core and perimeter columns can lead to excessive bending moment and shear in concrete panel girders (Fig. 9d) or to overstressing of truss members (Fig. 9e). The deformation to be considered for such analysis should be based on the anticipated differential mat settlement between the core and the perimeter structure after the installation of the structural element as opposed to the total differential settlement.

A third type of structural system is a tubular structure, either with closely spaced beam-column assemblies or a braced frame (Fig. 9g). During the case studies presented in the latter part of this paper an interaction between the tubular structure and the mat foundation is studied in detail.

Impact of Mat Rotation on Dynamic Characteristics of the Building -

- Structural steel buildings which are at times sensitive to wind loads in terms of motion perception at the top occupied floor of the building can derive some of their desired structural damping from the rotation of mat foundations. Halvorsen and Isyumov (3) reported a measured critical damping of 1.5% for the wind induced motion for Allied Bank Tower, Houston, which is a steel building with a mat foundation. Damping for steel buildings on more rigid foundations is in the range of 1.0%. Since the acceleration is inversely proportional to the square root of critical damping, the increased damping has a desired effect on reducing the motion perception for the occupant of the top floor of the building.

A perimeter partial tube superstructure with restricted available mat area beyond its footprint is subjected to a larger base rotation resulting in an increased fundamental period of the building. This results in increased lateral load on the building and higher horizontal acceleration at the top floor of the building.

Heritage Plaza, a 53-story office building in Houston, has a lateral load resisting system of partial braced tube along its two short ends. Without considering the base mat rotation, the fundamental period of the building along the short axis of the building was 6.56 seconds/cycle. In spite of the thickened mat (Fig. 10) along its short sides, the fundamental period of the building including the mat rotation increased to 6.81 seconds, thereby increasing the dynamic wind loads and the wind induced acceleration at the top occupied floor of the building.

PARAMETRIC CASE STUDIES

To establish the influence of variations in structural properties of the mat, soil spring constant and the interaction between the mat and the superstructure, two case studies were examined in detail.

In the first case, the mat foundation for Republic Bank Center (Fig. 5) which had variable mat properties and soil spring constants was analyzed by varying the values of the different design parameters.

In the second case, a realistic 50-story building with a continuous composite concrete frame on the perimeter, with and without a mat foundation at its base, was analyzed by varying the values of the design parameters.

Case I - Republic Bank Mat Foundation

The 8'-0" minimum thickness mat foundation for this building had to address variation in the loading pattern along with different perimeter soil surcharge pressures. As discussed earlier, these design parameters were addressed by variation in the spring constants (Fig. 8). In order to study the effects of variable versus uniform spring constants and of the full moment of inertia for the mat versus a cracked moment of inertia of .6 I_{gross} , three separate analyses of the mat were accomplished. They were:

1. Use the full moment of inertia of I_{gross} of the mat foundation and variable soil spring constant as shown in Fig. 8.
2. Mat moment of inertia of 0.60 I_{gross} and the same variable spring constant shown in Fig. 8.
3. Mat moment of inertia of 0.60 I_{gross} with a uniform soil spring constant of 15 pci as opposed to variable spring constants.

Under sustained dead load the variation in bending moments and the settlement profile of the mat along longitudinal section AA and transverse section BB are plotted in Fig. 11 and 12.

The sensitivity of the bending moment results and the deflection profile to the use of the variable spring versus the uniform spring is quite apparent from the figures. The results for bending moments along AA direction varied as much as 600% in places from the design condition. A variation of 29% in the deflection profile along the AA direction is observed in Fig. 12a. For the magnitude of the variable spring constants used, the changes in the mat effective moment of inertia had little influence on the moments and deflections.

Case II - 50-story Structure with Perimeter Tube

A composite concrete perimeter tubular structure (Fig. 13) supported on an 8'-0" thick mat foundation was analyzed. The mat was assumed to have a uniform surcharge pressure all around its perimeter. In order to simulate a realistic variation of soil stiffness at the base of the mat, the interior spring constant was assumed to be approximately 62.5% that of the perimeter spring constant. The properties of the superstructure along with the supporting mat are given in Table I.

In order to simulate the loading of the frame as it is being built and thus provide a more accurate load distribution along the perimeter tube, the structure was loaded with stacks of 10-story frames. The magnitude and variation of the bending moments along different sections of the mat is used as an indicator to study its response to the variation of different parameters.

The following studies were conducted with the results as shown in the relevant figures and tables.

Influence of Mat on Column Load Distribution -- Two separate structures were analyzed to establish the influence of the mat foundation on the distribution of column loads.

1. The structure was analyzed with an unyielding base without the mat foundation.

2. The same structure was analyzed with the mat foundation supported on soil springs.

Both gravity and wind load conditions were studied. The reactions at the base of the tower are given in Table II. As seen from the table, the variation in the base reactions is in the range of approximately 10%. The traditional separate analysis of structure and the mat foundation appears to be reasonable for the spring constants (25/40 pci) used for this analysis. Based upon subsequent studies, it appears that this variation will be greater if a lower spring constant is used in supporting the mat foundation.

Property of the Mat -- The structure was also analyzed with the full stiffness of the building superstructure and flexural stiffnesses of the mat which varied from 0.40 to 1.0 of I_{gross} . Two spring constant values were considered:

1. A spring constant variation of 25/40 pci.
2. A constant spring of 25 pci.

From the plots of bending moment diagrams along Section 2 on Figure 13 (Fig. 15a and 15b), it is evident that the mat foundation is more sensitive to changes in flexural stiffness for variable spring constants than for a uniform spring constant. The larger curvatures of mats with variable spring constants are associated with larger changes in moments for various flexural stiffnesses. As the flexural property of I_{gross} varies from 0.40 I_{gross} to 1.0 I_{gross} , the bending moment in the mat increases by 80% at the center of the mat (Section 2, Fig. 15a). However, the variation along the Section 1 (Fig. 14a and 14b) for both variable and uniform spring constants is only

of the order of 10%. This smaller variation along Section 1 is due to the smaller curvature of the mat along Section 1.

Variation in the Soil Spring Constant -- The structure was next analyzed with a constant stiffness of mat and superstructure for soil spring constants which varied from values of 36/60 to 12/20 pci. The distortion and the bending moments in the mat increased with the more flexible spring constants (Fig. 16a and 16b). It should be noted that the variation in the spring constants influenced the mat bending moment along the short direction (Section 2) more so than along the long direction (Section 1). The bending moment results showed a variation of approximately 60% along the short direction (Section 2) of the mat.

Variation of the Superstructure Stiffness -- To establish the impact of the variation of superstructure stiffness on the mat foundation, two loading conditions, namely gravity and wind, were investigated. Keeping the property of the mat (0.60 Igross) constant and using a specific value of spring constants, the stiffness of the superstructure was varied between the limits of 200% of the stiffness of the structure as defined in Table I to a superstructure stiffness of zero. Furthermore, an academic study of an infinitely stiff structure was made by attaching an infinitely rigid bending element to the mat continuously along the perimeter tubular structure. The results of bending moment variations along Sections 1, 2, 3, and 4 (Fig. 17 through 20) indicate that dead load moments are relatively unaffected by variations in the building stiffness ranging from 0% to 200% (except for directly under the short direction columns as shown in Fig. 19a). Similarly, the wind load moments for building stiffness variations from 50% to 200% typically vary by only 25%. These small influences are in contrast to the remarkable variation found in the infinite building stiffness analyses. This indicates that the mat stiffness is many times larger than the building stiffness and therefore insensitive to changes in the building stiffness until those changes are dramatic. Another implication is that practically non-deformable wall elements on mat foundations, such as multi-story basement walls, need careful evaluation during the design process.

To simulate the stiffness of a tubular superstructure in the analysis of a mat foundation it is recommended to incorporate a linear beam element in the finite element model of the mat. The beam element should be attached to the finite element model only at column locations. Due to the sequential build up of stiffness of the superstructure during construction, a reduced stiffness of 60% of the stiffness of the shear panels of beam-column assemblies of the entire superstructure should be used.

Type of Structural Frame -- Though not studied in the detail, the perimeter tubular structure was modified by eliminating the middle portion

of the long side of the tube. As noted in the lateral deflection for wind loads on the structure (Table I) the lateral stiffness contribution of the center portion of the frame, which primarily contributes to X-direction stiffness, is not really necessary. The modification was done by removing each alternate column and replacing the rigidly connected spandrel beams with simply supported ones. The influence of the two C shaped partial tubes on the behavior of the mat foundation was then studied. For the mat described in Table I, the mat dead load bending moments were affected insignificantly (Fig. 21) by this change in structure.

STRUCTURAL DETAILS

Two main areas of concern have to be addressed due to mat settlement as it relates to the structural frame:

1. The joint between the surrounding lightly loaded structure and the main tower frame always presents an interesting problem (Fig. 22a). The lightly loaded surrounding structure shows a tendency of heaving as opposed to settlement thereby creating a "step" between the surrounding structure and the tower. The problem can be addressed in two ways. One approach is to delay the construction of the lightly loaded surrounding structure until after the majority of the tower settlement takes place. However, this solution is not always practical. To have the surrounding area open during construction is not feasible from both a construction and an economic standpoint. It also extends the liability exposure of the Owner. A mat foundation founded on overconsolidated clay soils may go through 50 to 60% of its final settlement at the time of topping out of tower. The remaining 50 to 40% of its final settlement can also be of a substantial magnitude which needs to be accommodated between the interface of these structures. The alternate approach is to set the surrounding area lower than its final grade and provide pin type or bearing type hinge joints between the surrounding area and the tower structure. (Fig. 22b and 22c).

2. Just as with the axial shortening problem in tall buildings, mat settlement can cause unwarranted uneven floors or even cracking. The unevenness in the floor can be minimized by setting the base of the tower structure so as to offset the anticipated differential elevation between the interior core and the perimeter columns. The difference in the elevation can be accommodated by cambering the mat foundation or by setting the base plates of columns at elevations higher than the theoretical ones. However, over-compensation of the settlement at the base can also be detrimental, particularly at the time of placement of finishes in the tower.

CONCLUSION

Based upon the parametric study conducted for a realistic tubular structure resting on a mat foundation along with the case study of Republic Bank, the following conclusions can be drawn.

1. The most significant parameter in the design of the mat foundation is the variation of the spring constant (modulus of subgrade reaction) and its magnitude. An assumption of uniform spring constant or an inaccurate variation can lead to major errors in the mat design moments.
2. The flexural property of the mat assumed in the analysis and design is quite important particularly for low values of modulus of subgrade reaction.
3. Combining 1 and 2 above, the most important property in the mat design is the ratio between modulus of subgrade reaction and the mat stiffness itself. This ratio is usually expressed as a constant of $\left(\frac{k}{EI}\right)^{1/4}$ in discussions of the behavior of beams on elastic foundations.
4. The variation in the stiffness of the tubular superstructure did not appear to be critical in a redistribution of mat forces and also in the forces in the spandrels of the superstructure. However, its influence on the mat supported on flexible springs is relatively more significant. Also, the influence of a rigid wall type structure on both the foundation and the superstructure should be considered in the design.
5. The design assumption, that the base of the superstructure is rigid, which is reasonable most of the time, needs to be examined further for low subgrade soil moduli.
6. The analysis of a mat should be performed accounting for two-way plate action.

A qualitative parametric analytical study of an instrumented mat foundation should be conducted so that the analytical study could be supplemented by experimental verification.

REFERENCES

1. Baker, A. L. "Raft Foundations: The Soil-Line Method," 1957. 148 pp. I2S, by post I3S. Published by Concrete Publications Limited, 14 Dartmouth St., London, S.W.I.
2. Teng, Wayne C. "Foundation Design," Prentice-Hall, 1964.
3. Halvorson, R. and Isyumov, N. "Comparison of Predicted and Measured Dynamic Behavior of Allied Bank Plaza." Paper presented at ASCE Spring Convention, Seattle, Washington, April 7 - 11, 1986.

TABLE I — DATA OF BASE STRUCTURE FOR FIG. 13

MAT					
Size	=	260'-0" x 140'-0" x 8'-0" thick			
F'c	=	5,000 psi			
Spring Constant (base) Zone A	=	25 pci			
Spring Constant (base) Zone B	=	40 pci			
Transient Spring Constant	=	125 pci			
Moment of Inertia	=	0.6 Igross			
Total Superimposed Load	=	184,400 kips			
Dead Load Net Sustained Pressure	=	1,100 psf			

COLUMN SIZES					
Floors	C-1	C-2	C-3	C-4	Concrete f'c psi
Fdn - 10	(D x W) 36 x 30	36 x 24	36 x 18	30 x 30	6,000
10 - 20	36 x 27	36 x 21	36 x 18	30 x 30	6,000
20 - 30	36 x 24	36 x 18	36 x 18	30 x 30	5,000
30 - 35	36 x 21	38 x 18	36 x 18	30 x 30	5,000
35 - 40	36 x 21	36 x 18	36 x 18	30 x 30	4,000
40 - 50	36 x 18	36 x 18	36 x 18	30 x 30	4,000

Note: Spandrel width same as column.
The I spandrel = 0.6 Igross.
The I column = 1.0 Igross.

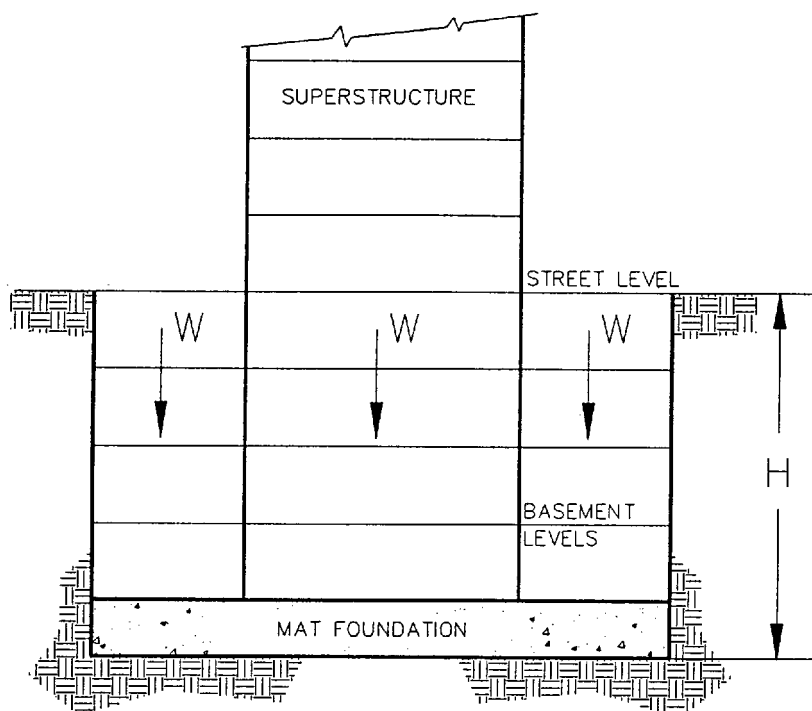
LOADING	
<u>Gravity Floor</u>	- Steel beam supporting 5 1/4" thick lightweight concrete slab on 2" deep deck. Superimposed Loads are 10 psf ceiling + 20 psf partition. Self weight of interior steel structure is 12 psf. Perimeter columns and spandrel beams are normal weight concrete. Perimeter is clad with granite.
<u>Wind Loads</u>	- ANSI "B" 90 mph Deflection: Wind Z - 23" Wind X - 6"
	Shear stiffness ratio mat/structure: Along section 3 = 5.0 Along section 4 = 6.8

TABLE II — VERTICAL REACTIONS. UNIT = KIPS

Col. Mark	Dead Load		Live Load		Wind (Z-Dir)		Wind (X-Dir)	
	(A)	(B)	(A)	(B)	(A)	(B)	(A)	(B)
1	1,578	1,617	241	240	321	394	3	5
2	1,574	1,612	240	239	328	403	10	14
3	1,564	1,603	238	236	343	421	17	24
4	1,547	1,587	235	232	366	448	24	34
5	1,524	1,563	231	226	398	483	29	44
6	1,492	1,527	224	218	443	527	32	51
7	1,450	1,478	215	208	505	583	25	46
8	1,874	1,895	274	264	784	866	21	47
9	1,831	1,827	265	259	922	935	108	125
10	1,795	1,786	256	261	1,146	1,088	171	173
11	1,765	1,787	250	277	1,578	1,442	260	244
12	1,812	2,102	254	377	2,639	2,510	521	483
13	2,142	2,109	298	320	1,790	1,588	375	341
14	2,113	2,003	293	279	1,155	1,016	277	264
15	2,091	1,957	289	257	749	672	232	237
16	2,077	1,930	286	245	425	391	209	225
17	2,071	1,917	285	238	138	129	199	220

(A) Without mat interaction.

(B) With mat interaction.



$$P_{\text{NET}} = \frac{W}{A} - H\rho_s + \frac{W_m}{A}$$

P_{NET} = NET SUSTAINED PRESSURE

W = SUPERIMPOSED SUSTAINED LOAD FROM TOWER AND BASEMENTS

A = AREA OF MAT

H = DEPTH OF EXCAVATION

ρ_s = DENSITY OF SOIL

W_m = WEIGHT OF MAT

Fig. 1—Pressure on mat

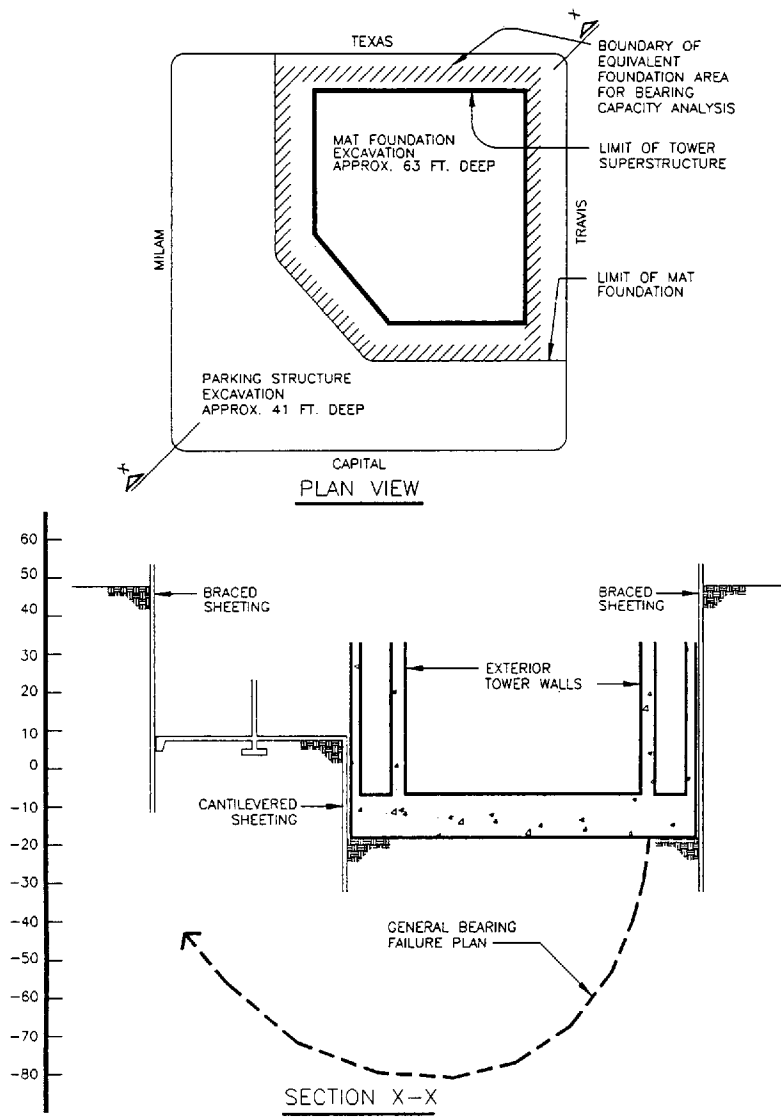
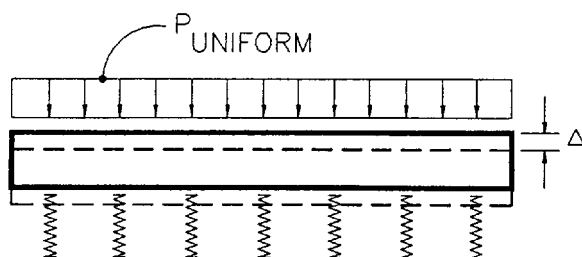
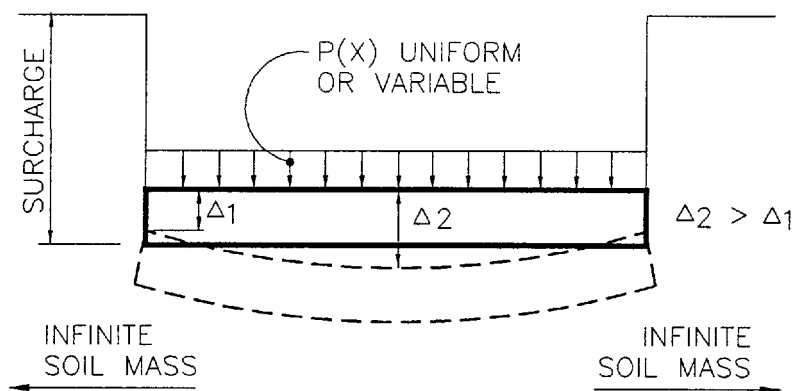


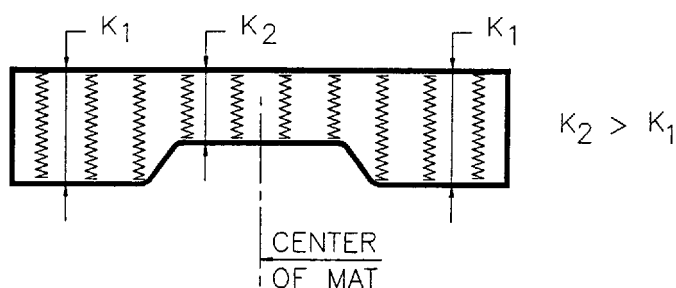
Fig. 2—Texas Commerce Tower — Mat foundation



a. UNIFORM LOAD AND CONSTANT SPRING



b. DEFLECTED PROFILE OF MAT



c. VARIATION OF SPRING CONSTANT

Fig. 3—Spring constants

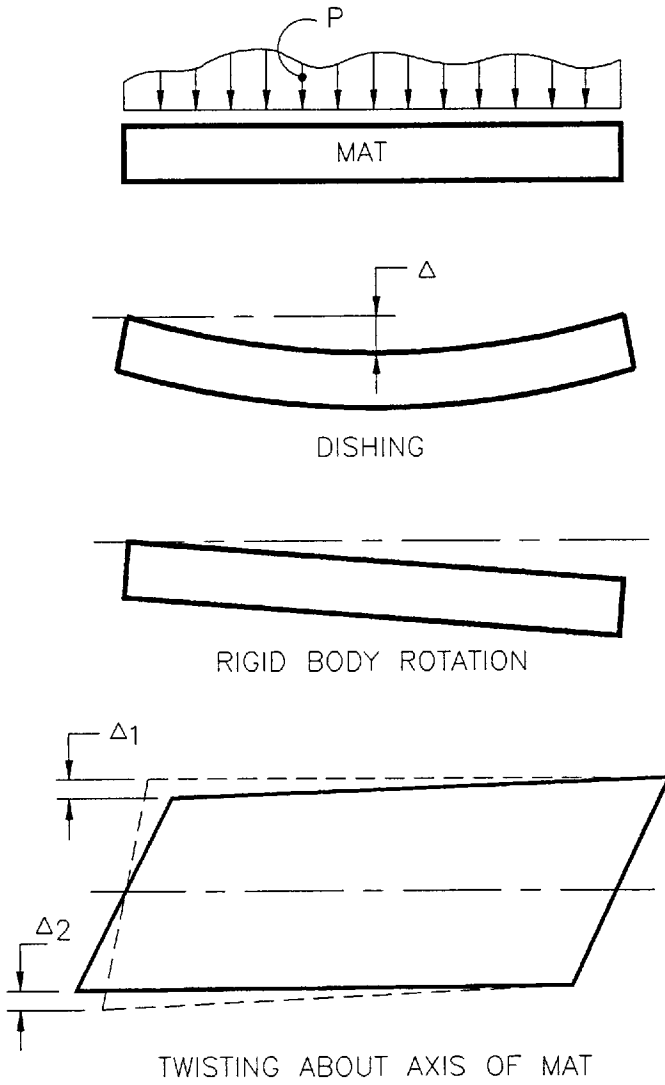


Fig. 4—Mat deflection profiles

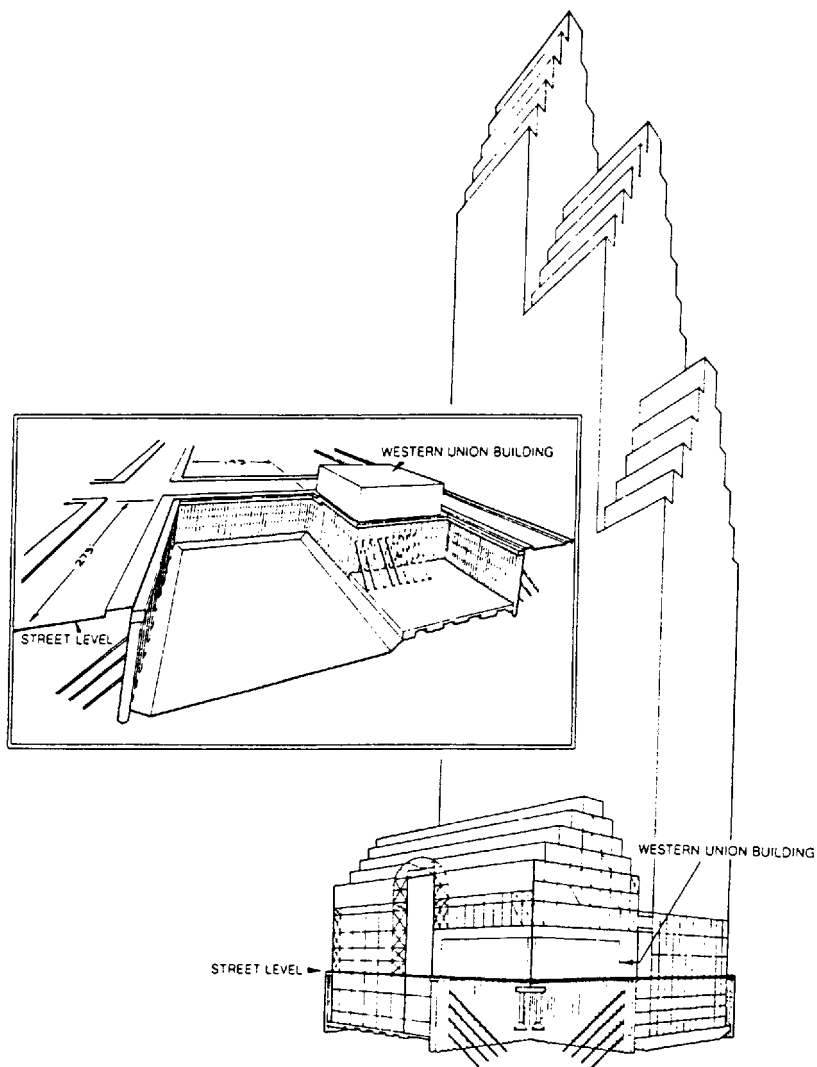


Fig. 5—Republic Bank Tower

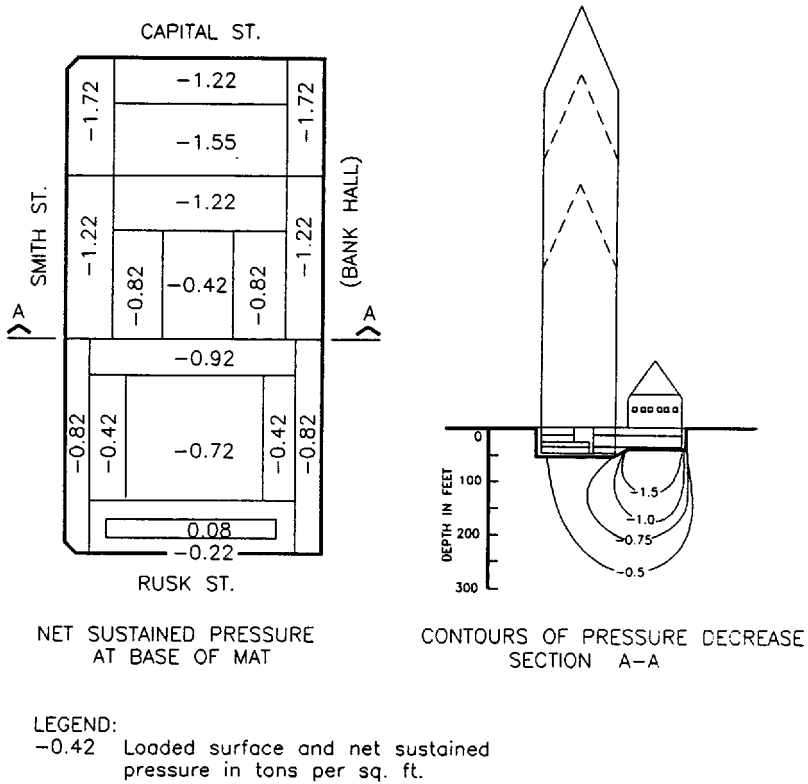


Fig. 6—Pressure distribution settlement analysis (McClelland Engineers)

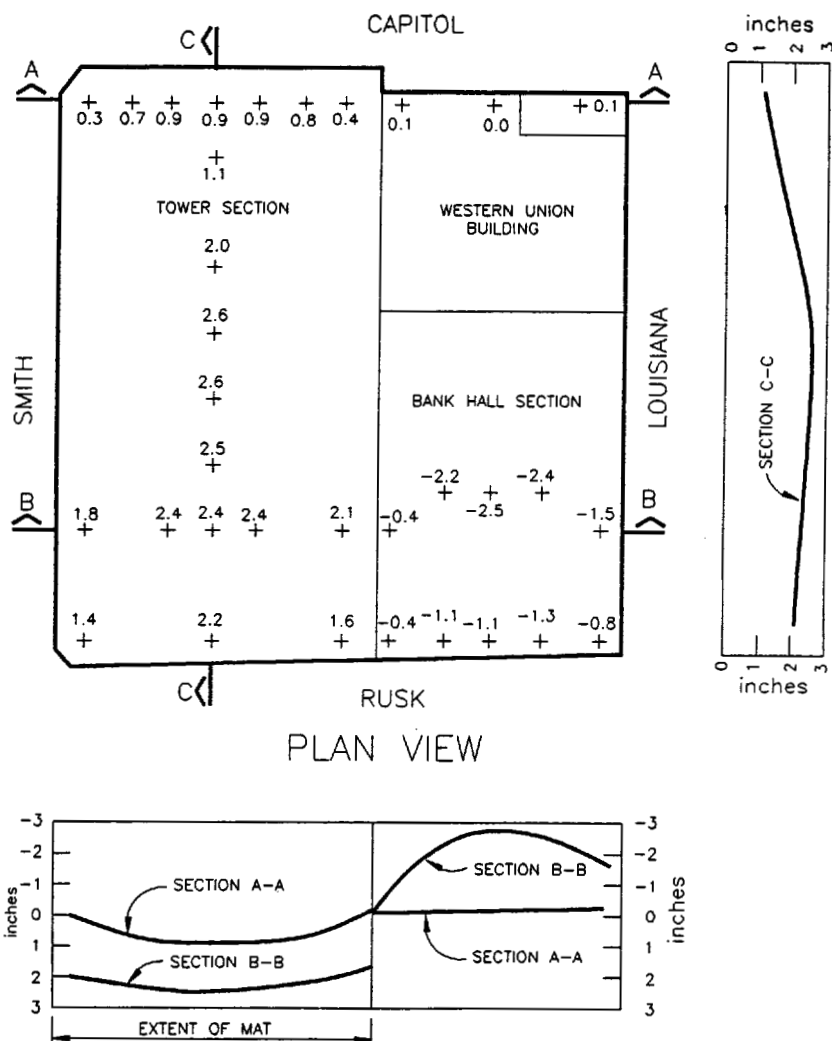


Fig. 7—Estimated long-term movement profile (McClelland Engineers)

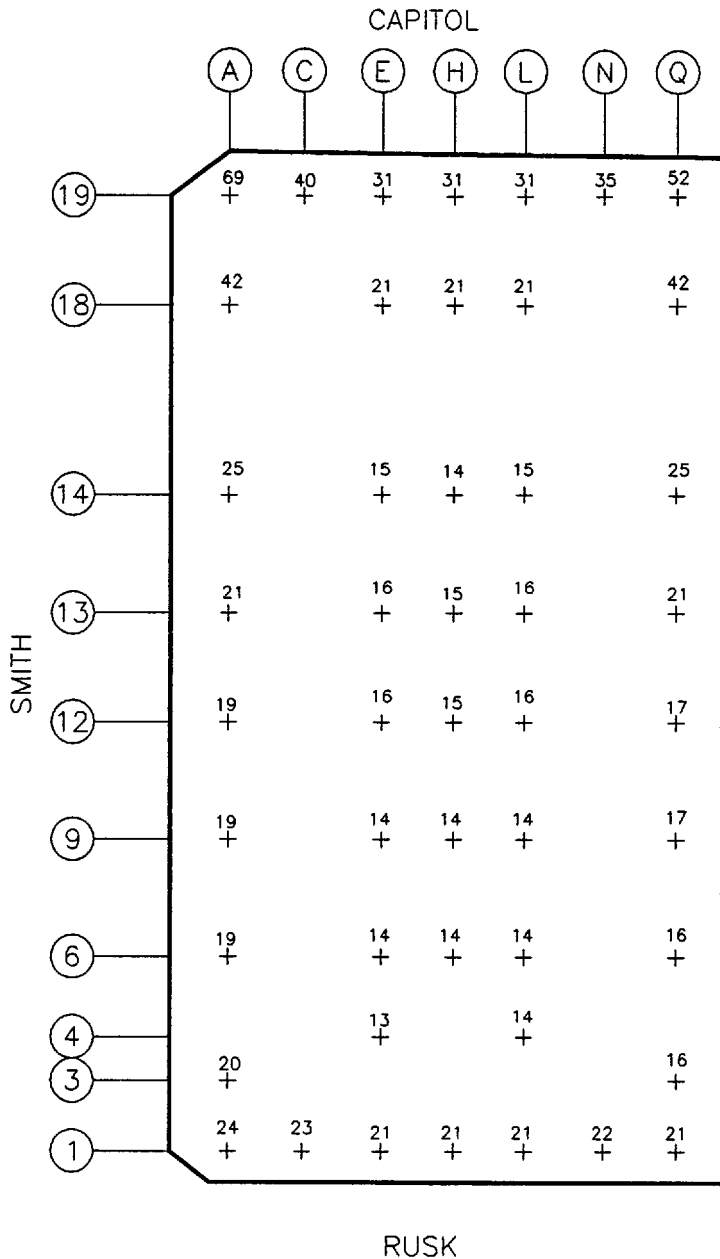


Fig. 8—Estimated subgrade moduli for gross sustained pressure in lbs/cu. in. (McClelland Engineers)

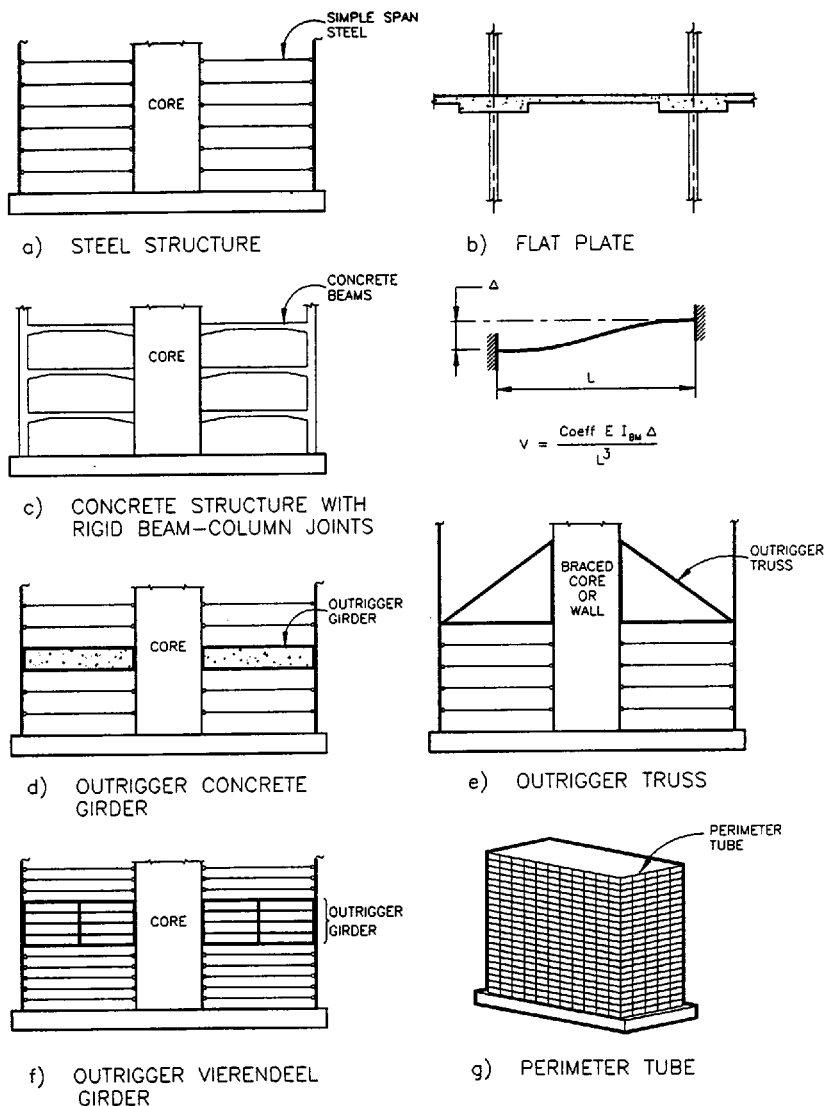


Fig. 9—Structural systems

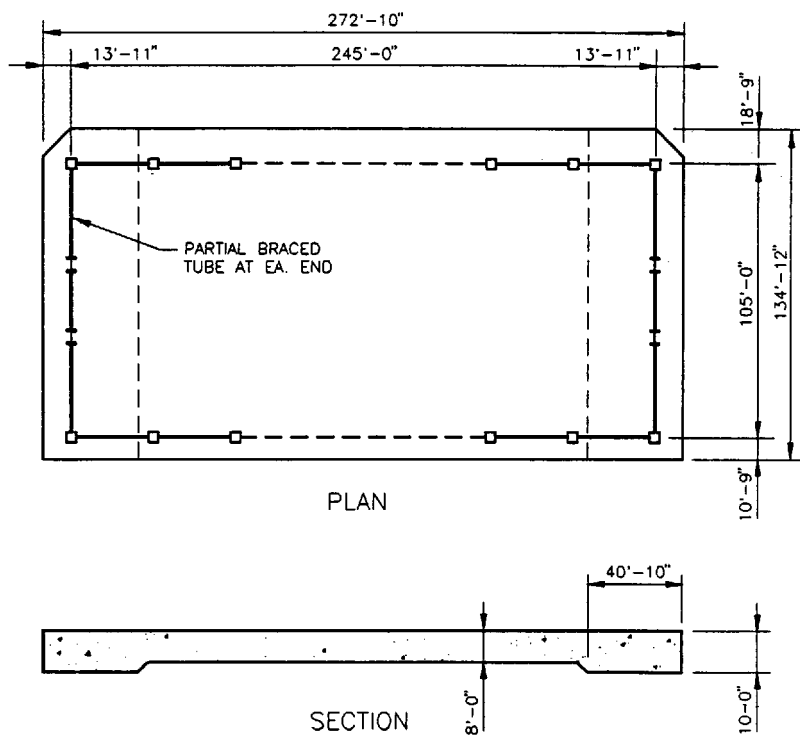
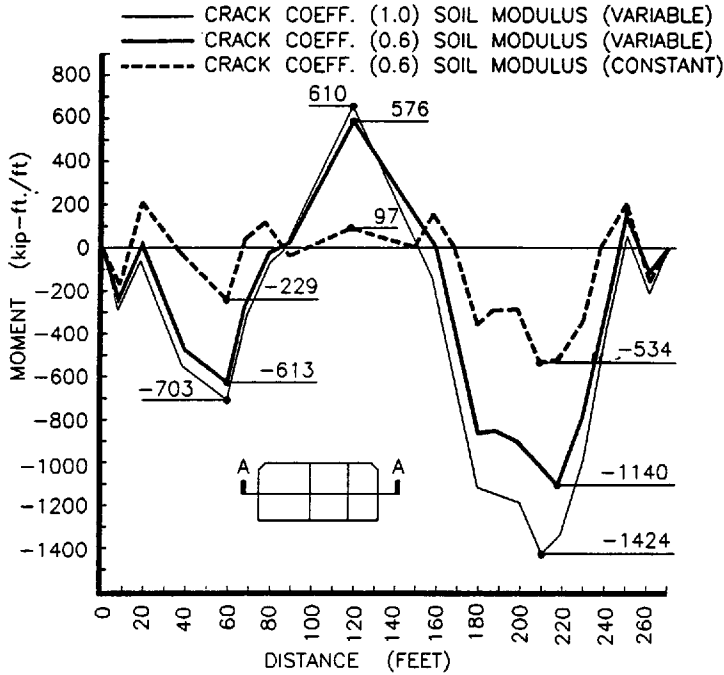
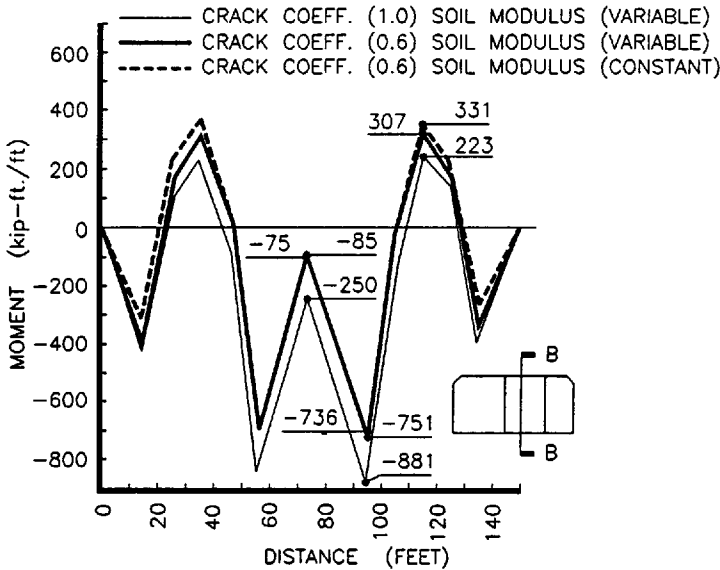


Fig. 10—Heritage Plaza mat foundation



a. TOTAL DEAD LOAD MOMENT ALONG SECTION A-A
 REPUBLIC BANK



b. TOTAL DEAD LOAD MOMENT ALONG SECTION B-B
 REPUBLIC BANK

Fig. 11—Republic Bank dead load moment profiles

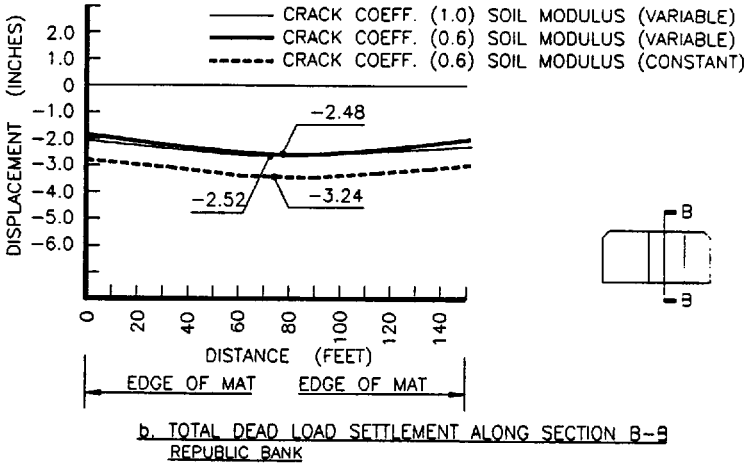
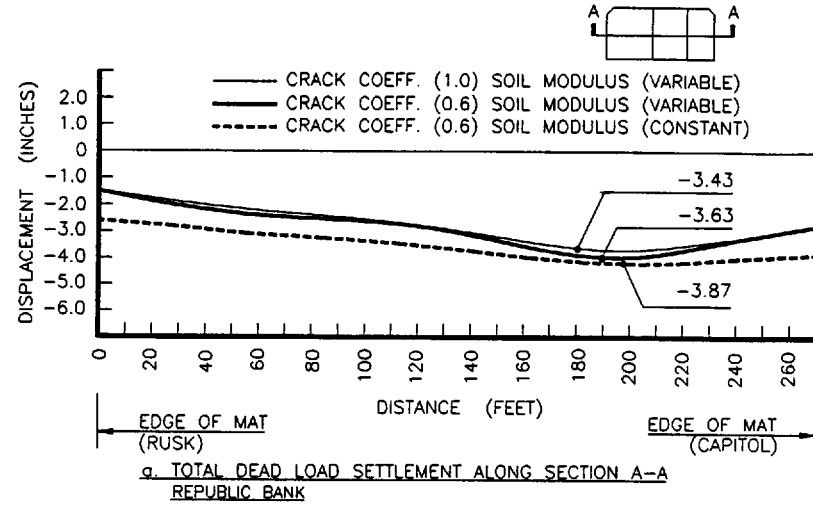
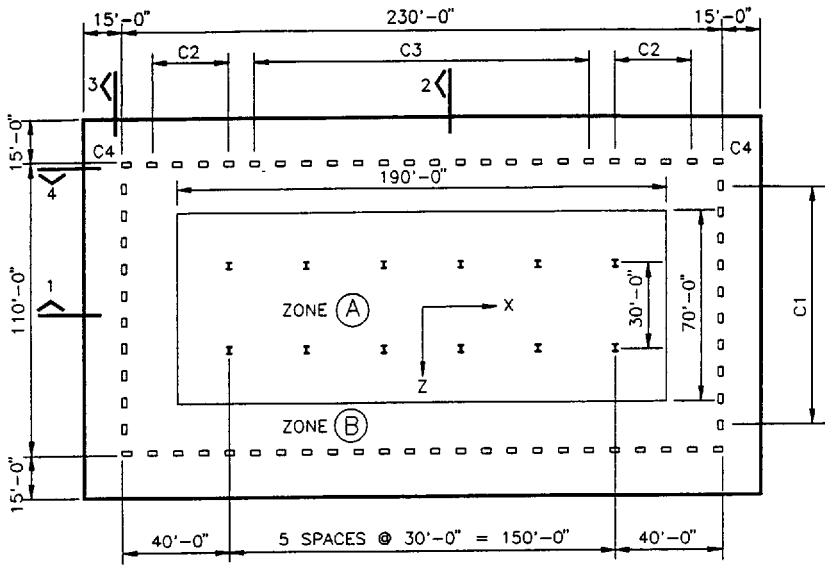
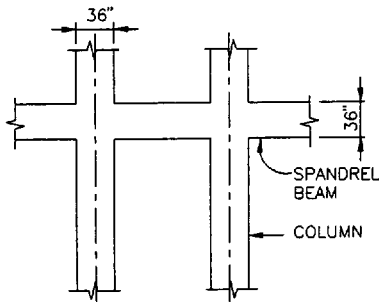


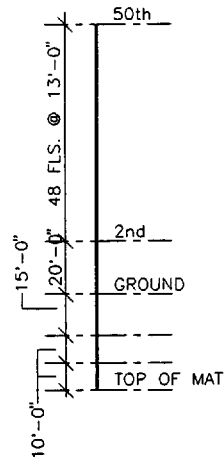
Fig. 12—Republic Bank settlement profiles



PLAN

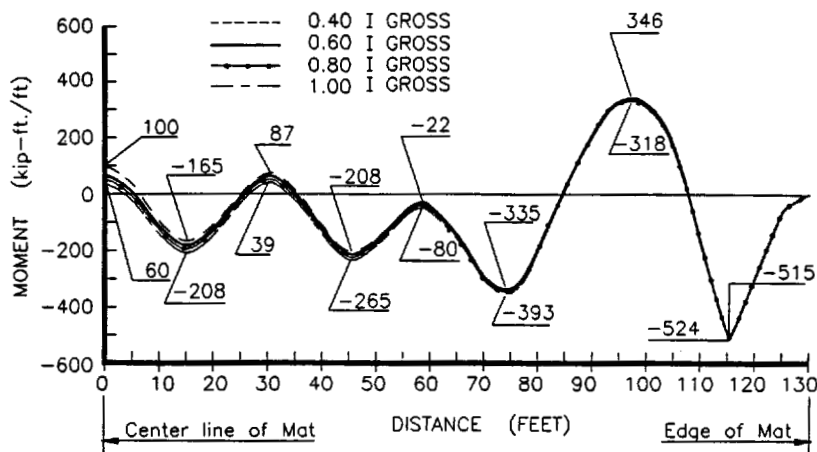


TYPICAL BEAM AND COLUMN
(FOR THICKNESS OF SPANDREL BEAM
AND COLUMN SEE TABLE I)

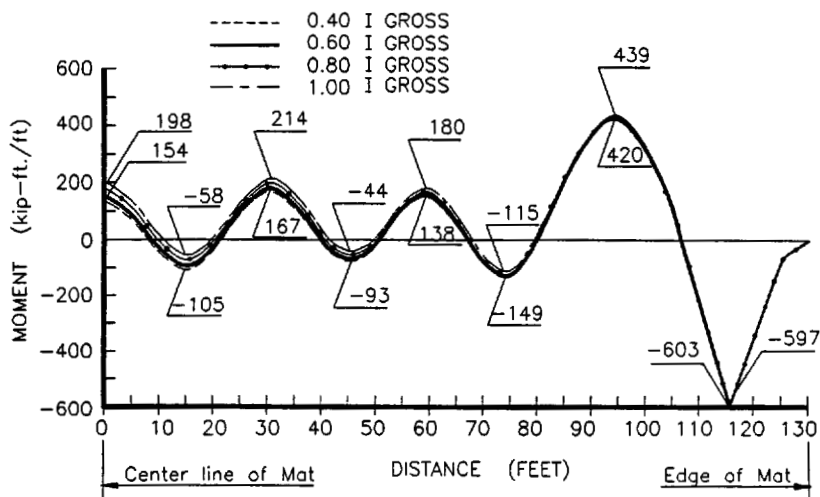


FLOOR TO FLOOR HEIGHT

Fig. 13—Tubular frame example building

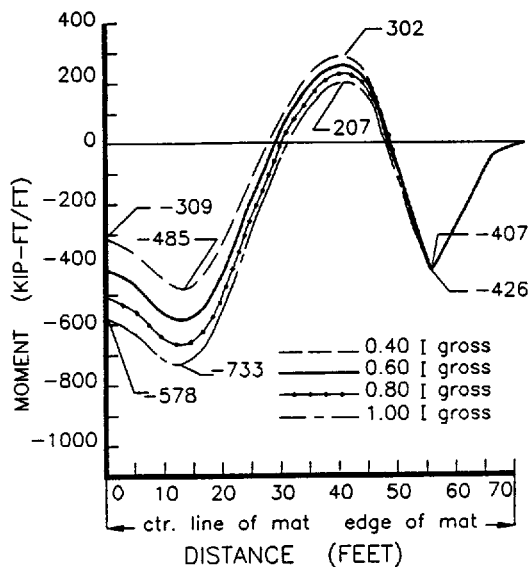


a. TOTAL DEAD LOAD MOMENT ALONG SECTION - 1
VARIATION OF MAT PROPERTIES
SOIL MODULUS 25, 40 pci

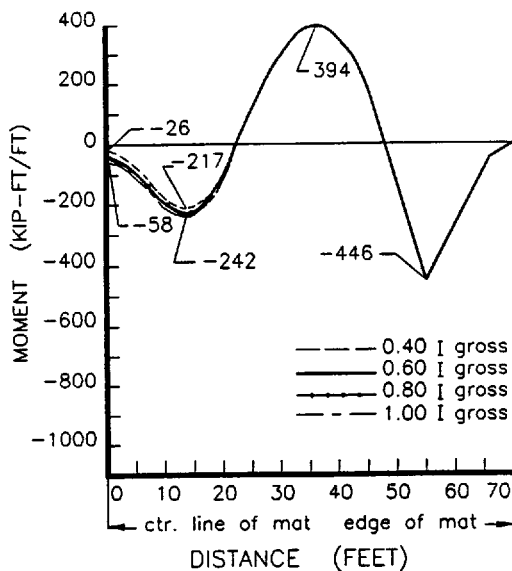


b. TOTAL DEAD LOAD MOMENT ALONG SECTION - 1
VARIATION OF MAT PROPERTIES
SOIL MODULUS 25 pci constant

Fig. 14—Moments at Section 1 for various mat stiffnesses

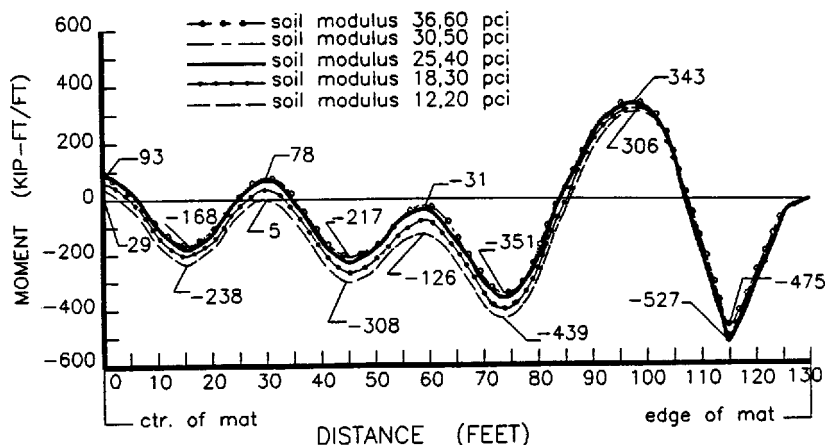


a. TOTAL DEAD LOAD MOMENT ALONG SECTION 2
VARIATION OF MAT PROPERTIES
soil modulus 25,40 pci

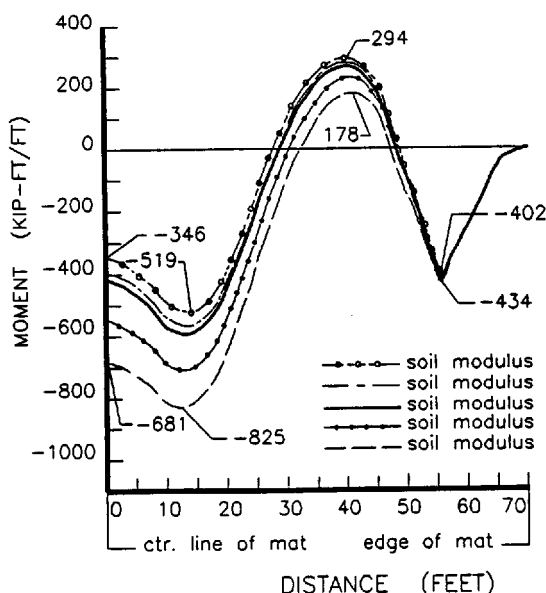


b. TOTAL DEAD LOAD MOMENT ALONG SECTION 2
VARIATION OF MAT PROPERTIES
soil modulus 25 pci constant

Fig. 15—Moments at Section 2 for various mat stiffnesses



a. TOTAL DEAD LOAD MOMENT ALONG SECTION 1
VARIATION IN SOIL MODULUS



b. TOTAL DEAD LOAD MOMENT ALONG SECTION 2
VARIATION IN SOIL MODULUS

Fig. 16—Moments for various soil stiffnesses