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

Unfortunately, they are also blamed for the effects of misusec technology brought on by the nearsighted demands of the public anc 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 determinec 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 if 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 21nd 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 form 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:

- transfer applied structural loads
- 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:

Description	Stiffness
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 an 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