
FOUNDATION
ANALYSIS
AND DESIGN

Third Edition

Joseph E. Bowles

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This book was set in Times Roman by Santype-Byrd.
The editors were Julienne V. Brown and Susan Hazlett;
the production supervisor was Leroy A. Young.
New drawings were done by J & R Services, Inc.
The cover was designed by Charles A. Carson;
the cover photograph was taken by Robert Capece.
R. R. Donnelley & Sons Company was printer and binder.

FOUNDATION ANALYSIS AND DESIGN

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234567890 DODO 898765432

ISBN 0-07-006770-8

Library of Congress Cataloging in Publication Data

Bowles, Joseph E.

Foundation analysis and design.

Bibliography: p.

Includes indexes.

1. Foundations. 2. Soil mechanics. I. Title.

TA775.B63 1982 624.1'5 81-13649

ISBN 0-07-006770-8

AACR2

PREFACE

This edition is the latest in the continuing process of producing an up-to-date compendium of methods and procedures for the analysis and design of foundations. As in the earlier editions the primary focus is on interfacing structural elements with the underlying soil. This is where the major focus of foundation engineering lies in both the author's opinion and that of many others. Engineering of dams, fills, and embankments, and flow of water in soil masses may more properly fall under the general category of geotechnical engineering. In some cases the latter considerations may be major factors in designing or constructing a foundation; therefore, some background material on several of these topics has been included.

Most engineers now recognize that it is not possible or very practical to identify foundation engineering as soil mechanics/properties with structural engineers designing the foundation elements. A foundation engineer must be versed in both the geotechnical aspects of soils as well as the structural behavior produced by the often complex foundation-soil interaction. The latter statement reflects the general design philosophy contained in this text.

I have undertaken a fairly extensive revision; however, none of the chapter titles have been changed and in most cases the section headings have been retained. Chapters 2, 8, 9, and 16 have been almost totally rewritten, with very substantial rewriting undertaken in Chaps. 3, 4, 10, and 11. This was done to produce a more logical sequencing of topics and to include new methodology which was in transition when the second edition was being rewritten. The material is about 80 percent SI to reflect both the general trend in textbooks and the anticipated status of SI for most of the useful life of the book.

In many cases there is no "unique" design equation/methodology and one or more of several alternatives tends to be preferred by certain engineers or in geographical areas. I have attempted to present those alternatives where they seem to be widely enough used to warrant the text space. Where it was practical,

examples are analyzed using one or more of the alternatives so the reader obtains both familiarity and an opinion about the procedure. In several examples a "feel" of a probable answer is produced by use of the alternatives—a common engineering office practice where the input data are uncertain—either as a direct computation or as an average from the several alternatives. I have attempted to include realistic example (and home) problems for the reader, with the examples being somewhat less edited. About 50 percent of the home problems are new, and more answers are included than in the earlier editions.

Several methods such as the footing on slope, grid analysis of mats, and the sheet and lateral pile solutions using the finite-element method have been compared via examples with the solutions of others or with alternative methods. This has been done to illustrate that these new methods are adequate. In passing it should be noted that the finite-element solution contained herein for beams, sheet piles, and lateral piles is extremely widely used. It is the author's opinion that the simplest solution which produces a satisfactory and economical design is preferred. Solutions which require esoteric mathematics to produce miniscule computational refinement in a mathematical model based on soil data which are uncertain at best are not very practical. Many solutions of this type do not get further than the pages of a technical journal and others soon disappear from engineering practice after a short time.

I have included about 560 references so that almost every topic can be researched in depth. I have tried to avoid using obscure references which could be obtained only with great difficulty by the average user. Most worthwhile material eventually gets published in some form by ASCE, ASTM, TRB, CGJ, at a specialty conference, or in the proceedings of the ICSMFE, which are not very difficult to access. I have retained the use of the list of publication abbreviations (above included) at the beginning of the bibliography to reduce its size. It is hoped that no significant work has been omitted; however, in the interest of space, not all the work on a given topic is cited. Generally the most recent or those works with the best bibliography coverage were included. I hope also that I have not offended the junior authors of coauthored references by the use of "et al." when there are more than two authors.

I wish to express appreciation to the many users both in the United States and abroad who have written or called with comments or constructive criticism or simply to make inquiry about a procedure. I should also like to thank those who took part in the McGraw-Hill user survey to provide input for this revision and include: Jack Bakos of Youngstown State University; William Baron of Clemson University; William Gotolski of Pennsylvania State University; and Roy V. Snedden of the University of Nebraska. I would also like to thank the final manuscript reviewer William Baron of Clemson University.

Finally I should like to acknowledge the considerable contribution of my wife Faye, who helped as usual with the typing and the myriad other operations to produce the manuscript.

Joseph E. Bowles

CONTENTS

	Preface	xiii
Chapter 1	Introduction	1
1-1	Foundations—Definition and Purpose	1
1-2	Foundation Classifications	2
1-3	Foundation Site and System Economics	3
1-4	General Requirements of Foundations	5
1-5	Foundation Selection	6
1-6	SI and Fps Units	6
1-7	Computational Accuracy versus Design Precision	9
Chapter 2	Soil Mechanics in Foundation Engineering	10
2-1	Introduction	10
2-2	Foundation Materials	12
2-3	Soil Volume and Density Relationships	13
2-4	Major Factors Which Affect the Engineering Properties of Soils	16
2-5	Routine Laboratory Tests	19
2-6	Soil Classification in Foundation Design	24
2-7	Soil Classification Terms	25
2-8	In Situ Stresses and K_0 Conditions	32
2-9	Soil Water—Soil Hydraulics	35
2-10	Consolidation Principles	41
2-11	Shear Strength	50
2-12	Sensitivity and Thixotropy	60
2-13	Stress Paths	61
2-14	Elastic Properties of Soil	66
2-15	Isotropic and Anisotropic Soil Masses	70

Chapter 3	Exploration, Sampling, and In Situ Soil Measurements	79
3-1	Data Required	79
3-2	Methods of Exploration	80
3-3	Planning the Exploration Program	81
3-4	Soil Boring	84
3-5	Soil Sampling	89
3-6	Marine Sampling	96
3-7	The Standard Penetration Test (SPT)	97
3-8	Other Penetration Methods	102
3-9	Core Sampling	102
3-10	Water-Table Location	105
3-11	Depth and Number of Borings	108
3-12	Presentation of Data	108
3-13	Field Load Tests	110
3-14	Field Vane Testing of Soils	114
3-15	Measurements of In Situ Stresses and K_0 Conditions	117
3-16	Static Penetration Testing—Dutch-Cone Penetration Test (CPT)	121
3-17	The Borehole Shear Test	122
3-18	Seismic Exploration	123
Chapter 4	Bearing Capacity of Foundations	130
4-1	Introduction	130
4-2	Bearing-Capacity Equations	131
4-3	General Comments on Bearing-Capacity Computations	135
4-4	Bearing Capacity—Examples	140
4-5	Footings with Eccentric or Inclined Loadings	143
4-6	Effect of Water Table on Bearing Capacity	147
4-7	Bearing Capacity for Footings on Layered Soils	149
4-8	Bearing Capacity of Footings on Slopes	153
4-9	Bearing Capacity from SPT	155
4-10	Bearing Capacity Using Cone Penetration Test (CPT) Data	159
4-11	Bearing Capacity of Foundations with Uplift or Tension Forces	160
4-12	Bearing Capacity Based on Building Codes (Presumptive Pressure)	163
4-13	Safety Factors in Foundation Design	163
4-14	Bearing Capacity of Rocks	167
Chapter 5	Foundation Settlements	171
5-1	The Settlement Problem	171
5-2	Stresses in a Soil Mass Due to Footing Pressure	172
5-3	The Boussinesq Method for Evaluating Soil Pressure	173
5-4	Westergaard's Method for Evaluating Soil Pressures	178
5-5	Immediate (Elastic) Settlement Computation—Theory	183
5-6	Immediate Settlements—Application	187
5-7	Alternative Methods of Computing Elastic Settlements	192

5-8	Stresses and Displacements in Layered and Anisotropic Soils	19
5-9	Consolidation Settlements	19
5-10	Reliability of Settlement Computations	20
5-11	Proportioning Footings for a Given Settlement or Equal Settlements	20
5-12	Structures on Fills	20
5-13	Structural Tolerance to Settlement and Differential Settlements	20
Chapter 6	Improving Site Soils for Foundation Use	208
6-1	Introduction	208
6-2	Compaction	209
6-3	Precompression to Improve Site Soils	211
6-4	Drainage Using Sand Blankets and Drains	213
6-5	Vibratory Methods to Increase Soil Density	215
6-6	Foundation Grouting and Chemical Stabilization	217
6-7	Altering Groundwater Conditions	218
6-8	Use of Geotextiles to Improve Soil	218
Chapter 7	Factors to Consider in Foundation Design	221
7-1	Footing Depth and Spacing	221
7-2	Displaced Soil Effects	224
7-3	Net versus Gross Soil Pressure—Design Soil Pressures	225
7-4	Erosion Problems for Structures Adjacent to Flowing Water	226
7-5	Corrosion Protection	227
7-6	Water-Table Fluctuation	227
7-7	Foundations in Sand Deposits	227
7-8	Foundations on Loess	228
7-9	Foundations on Expansive Soils	230
7-10	Foundations on Clays and Silts	233
7-11	Foundations on Sanitary Landfill Sites	235
7-12	Frost Depth and Foundations on Permafrost	236
7-13	Environmental Considerations	238
Chapter 8	Spread Footing Design	240
8-1	Footings—Classification and Purpose	240
8-2	Allowable Soil Pressures in Spread Footing Design	241
8-3	Assumptions Used in Footing Design	241
8-4	Reinforced-Concrete Design—USD	241
8-5	Structural Design of Spread Footings	241
8-6	Bearing Plates and Anchor Bolts	253
8-7	Pedestals	261
8-8	Rectangular Footings	261
8-9	Eccentrically Loaded Spread Footings	27
8-10	Unsymmetrical Footings	28
8-11	Wall Footings and Footings for Residential Construction	28
8-12	Spread Footings with Overturning Moment	29

Chapter 9	Special Footings and Beams on Elastic Foundations	295
9-1	Introduction	295
9-2	Rectangular Combined Footings	295
9-3	Design of Trapezoid-Shaped Footings	304
9-4	Design of Strap (or Cantilever) Footings	309
9-5	Footings for Industrial Equipment	312
9-6	Modulus of Subgrade Reaction	320
9-7	Classical Solution of Beam on Elastic Foundation	326
9-8	Finite-Element Solution of Beam on Elastic Foundation	330
9-9	Bridge Piers	339
9-10	Ring Foundations	341
9-11	General Comments on the Finite-Element Procedure	344
Chapter 10	Mat Foundations	349
10-1	Introduction	349
10-2	Types of Mat Foundations	350
10-3	Bearing Capacity of Mat Foundations	351
10-4	Mat Settlements	352
10-5	Design of Mat Foundations	354
10-6	Finite-Difference Method for Mats	361
10-7	Finite-Element Method for Mat Foundations	363
10-8	Mat-Superstructure Interaction	374
10-9	Circular Mats or Plates	374
Chapter 11	Lateral Earth Pressure	378
11-1	The Lateral Earth Pressure Problem	378
11-2	Active Earth Pressure	379
11-3	Passive Earth Pressure	381
11-4	Coulomb Earth-Pressure Theory	381
11-5	Rankine Earth Pressures	388
11-6	Active and Passive Earth Pressure Using Theory of Plasticity	392
11-7	Earth Pressure on Walls, Soil-Tension Effects, Rupture Zone	396
11-8	Reliability of Lateral Earth Pressures	399
11-9	Soil Properties and Lateral Earth Pressure	399
11-10	Earth-Pressure Theories in Retaining-Wall Problems	401
11-11	Graphical and Computer Solutions for Lateral Earth Pressure	404
11-12	Lateral Pressures by Theory of Elasticity for Surcharges	414
11-13	Other Causes of Lateral Pressure	419
11-14	Pressures in Silos, Grain Elevators, and Coal Bunkers	420
Chapter 12	Retaining Walls	431
12-1	Introduction	431
12-2	Common Proportions of Retaining Walls	433
12-3	Soil Properties for Retaining Walls	436
12-4	Stability of Walls	438

12-5	Retaining-Wall Forces	440
12-6	Allowable Bearing Capacity	448
12-7	Settlements	449
12-8	Tilting	450
12-9	Design of Gravity and Semigravity Walls	453
12-10	Wall Joints	457
12-11	Drainage	458
12-12	Abutment Wing and Retaining Walls of Varying Height	459
12-13	Design of a Cantilever Retaining Wall	460
12-14	Design of a Counterfort Retaining Wall	466
12-15	Basement or Foundation Walls; Walls for Residential Construction	468
12-16	Reinforced-Earth Retaining Structures	469
Chapter 13	Sheet-Pile Walls—Cantilevered and Anchored	474
13-1	Introduction	474
13-2	Soil Properties for Sheet-Pile Walls	475
13-3	Types of Sheetpiling	477
13-4	Safety Factors for Sheet-Pile Walls	479
13-5	Cantilever Sheetpiling	481
13-6	Anchored Sheetpiling; Free-Earth Support	489
13-7	Rowe's Moment Reduction Applied to the Free-Earth-Support Method	495
13-8	Finite-Element Analysis of Sheet-Pile Walls	499
13-9	Wales and Anchorages for Anchored Sheetpiling	506
Chapter 14	Braced, Tieback, and Slurry Walls for Excavations	516
14-1	Construction Excavations	516
14-2	Soil Pressures on Braced Sheet piling or Cofferdams	519
14-3	Conventional Design of Single-Wall (Braced) Cofferdams	522
14-4	Estimation of Ground Loss around Excavations	527
14-5	Finite-Element Analysis for Braced Excavations	530
14-6	Instability Due to Heave of Bottom of Excavation	536
14-7	Other Causes of Cofferdam Instability	539
14-8	Construction Dewatering	540
14-9	Slurry-Wall (or -Trench) Construction	544
Chapter 15	Cellular Cofferdams	548
15-1	Cellular Cofferdams: Types and Uses	548
15-2	Cell Fill	551
15-3	Stability and Design of Cellular Cofferdams	551
15-4	Practical Considerations in Cellular Cofferdam Design	561
15-5	Design of Diaphragm Cofferdam Cell	564
15-6	Circular-Cofferdam Design	566
15-7	Cloverleaf-Cofferdam Design	571

Chapter 16	Single Piles—Static Capacity and Lateral Loads; Pile/Pole Buckling	575
16-1	Introduction	575
16-2	Timber Piles	582
16-3	Concrete Piles	584
16-4	Steel Piles	589
16-5	Corrosion of Steel Piles	592
16-6	Soil Properties for Static Pile Capacity	592
16-7	Static Pile Capacity	593
16-8	Ultimate Static Pile Point Capacity	598
16-9	Skin Resistance Capacity	602
16-10	Static Pile Capacity—Examples	610
16-11	Piles in Permafrost	616
16-12	Static Pile Capacity Using Load-Transfer Load-Test Data	620
16-13	Tension Piles—Piles for Resisting Uplift	622
16-14	Laterally Loaded Piles	623
16-15	Buckling of Fully and Partially Embedded Piles and Poles	632
Chapter 17	Single Piles—Dynamic Analysis	638
17-1	Dynamic Analysis	638
17-2	Pile Driving	638
17-3	The Rational Pile Formula	643
17-4	Other Dynamic Formulas and General Considerations	647
17-5	Reliability of Dynamic Pile-Driving Formulas	654
17-6	The Wave Equation	656
17-7	Pile-Load Tests	663
17-8	Pile-Driving Stresses	665
17-9	General Comments on Pile Driving	668
Chapter 18	Pile Foundations—Groups	671
18-1	Single Piles versus Pile Groups	671
18-2	Pile-Group Considerations	671
18-3	Efficiency of Pile Groups	673
18-4	Stresses on Underlying Strata	676
18-5	Settlements of Pile Groups	683
18-6	Pile Caps	687
18-7	Batter Piles	690
18-8	Negative Skin Friction	690
18-9	Matrix Analysis for Pile Groups	696
Chapter 19	Caissons Including Drilled Piers	705
19-1	Types of Caissons	705
19-2	Open-End Caissons	706
19-3	Closed-End, or Box, Caissons	711
19-4	Pneumatic Caissons	715
19-5	Drilled Caissons	717

19-6	Bearing Capacity and Settlements of Drilled Caissons	720
19-7	Design of Drilled Caissons	725
19-8	Laterally Loaded Caissons	729
19-9	Inspection of Drilled Caissons	730
Chapter 20	Design of Foundations for Vibration Control	732
20-1	Introduction	732
20-2	Elementary Vibrations	733
20-3	Forced Vibrations for a Lumped Mass	738
20-4	Approximate Solution of Vibrating Foundation— Theory of Elastic Half-Space	743
20-5	Lumped-Mass Solution of the Vibrating Foundation	749
20-6	Soil Properties—Elastic Constants	757
20-7	Coupled Vibrations	759
20-8	Effect of Piles to Reduce Foundation Vibrations	760
20-9	Other Considerations for Machinery Foundations	761
	Appendixes	
A	General Pile-Hammer and Pile Data Tables	764
A-1	H-Piles	76
A-2	Pile Hammers	76
A-3	Sheet Piles	
A-4	Pipe Piles	170
A-5	Prestressed-Concrete Piles	772
B	Selected Computer Programs	773
B-1	Beam, Lateral- and Sheet-Pile Finite-Element Program	774
B-2	Mat Program	780
B-3	Three-Dimensional Pile-Group Program	786
	References	787
	Indexes	807
	Name Index	
	Subject Index	

INTRODUCTION

1-1 FOUNDATIONS—DEFINITION AND PURPOSE

All structures designed to be supported by the earth, including buildings, bridges, earth fills, and earth, earth and rock, and concrete dams, consist of two parts. These are the superstructure, or upper part, and the substructure element which interfaces the superstructure and supporting ground. In the case of earth fills and dams, there is often not a clear line of demarcation between the superstructure and substructure. The *foundation* can be defined as the substructure and that adjacent zone of soil and/or rock which will be affected by both the substructure element and its loads.

The foundation engineer is that person who by reason of experience and training can produce solutions for design problems involving this part of the engineered system. In this context, *foundation engineering* can be defined as the science and art of applying the principles of soil and structural mechanics together with engineering judgment (the “art”) to solve the interfacing problem. The foundation engineer is concerned directly with the structural members which affect the transfer of load from the superstructure to the soil such that the resulting soil stability and estimated deformations are tolerable. Since the design geometry and location of the substructure element often have an effect on how the soil responds, the foundation engineer must be reasonably versed in structural design.

A number of practical considerations are a part of the engineering of a foundation:

1. Visual integration of geologic evidence at a site with any field or laboratory test data.

2. Establishing of an adequate field exploration and laboratory testing program.
3. Design of the substructure elements so that they can be built—and as economically as possible.
4. Appreciation of practical construction methods and of likely-to-be-obtained construction tolerances. Stipulation of very close tolerances can have an enormous effect on the foundation costs.

These several items are not directly quantifiable and thus require a considerable application of common sense.

A thorough understanding of the principles of soil mechanics in terms of stability, deformations, and water flow is a necessary ingredient to the successful practice of foundation engineering. Of nearly equal importance is an understanding of the geological processes involved in the formation of soil masses. It is now recognized that both soil stability and deformation are dependent on the stress history of the mass. It has been common until recently to associate foundation engineering solely with soil mechanics concerns, leaving the interfacing elements to the structural (or other) designer. Current trends are to recognize that foundation engineering is a systems problem and cannot be nicely compartmentalized as some persons would prefer. Readers may determine the validity of this statement as they progress through the text.

The science of soil mechanics and its relationship to geological processes has progressed considerably over the past fifty years. However, because of the natural variability of soil and the resulting problems associated with testing, which will be elaborated upon in Chap. 3, the design of a foundation still depends to a large degree upon “art,” or the application of engineering judgment. A subset of this application is the assessment of the tolerable risk associated with the foundation.

The primary focus of this text will be on analysis and design of the interfacing elements for buildings and retaining structures and those soil mechanics principles particularly applicable to these elements. These interfacing elements include both near surface members such as footings and mats and deep elements such as piles and caissons. Retaining structures of concrete (commonly termed retaining walls) and metal (as sheetpiling) are considered in later chapters. Soil mechanics principles include both stability, including soil water effects, and deformation analyses. Soil stability can often be enhanced by various improvement techniques, the most common being compaction, and several of the more popular of these methods will be briefly considered in Chap. 6.

1-2 FOUNDATION CLASSIFICATIONS

Foundations for structures such as buildings, from the smallest residential to the tallest high-rise, and bridges are for the purpose of transmitting the superstructure loads. These loads come from column-type members with stress intensities ranging from perhaps 140 mPa for steel to 10 mPa for concrete to the supporting capacity of the soil, which is seldom over 500 kPa but more often on

the order of 200 to 250 kPa. The reader can readily note that this interface connects materials whose differences in useful engineering strength can vary by a factor of several hundred. The transmission of these large superstructure loads to the soil may be by use of:

1. Shallow foundations—termed footings, spread footings, or mats. Foundation depth is generally $D \leq B$ (see Chap. 4).
2. Deep foundations—piles or caissons with $D > 4$ to $5B$ (see Chaps. 16 to 19).

Any structure used to retain a soil or similar mass such as grain, coal, or ore in a geometric shape other than that occurring naturally under the influence of gravity is a *retaining* structure. Any foundation not classed as shallow, deep, or a retaining structure may be termed a *special* foundation.

Typical foundation types are:

1. Foundations for buildings (either shallow or deep)
2. Foundations for smokestacks, radio and television towers, bridge piers, industrial equipment, etc. (either shallow or deep)
3. Foundations for port or marine structures (may be shallow or deep and with retaining structures extensively used)
4. Foundations for rotating, reciprocating, and impact machinery, and for turbines, generators, etc. (either shallow or deep and may require vibration control)
5. Foundation elements to support excavations or retain earth masses as for bridge abutments and piers, or retain grain, ore, coal, etc. (retaining walls or sheet-pile structures)

Foundations for buildings are extremely numerous; foundations for the several other types of superstructures are constructed in somewhat lesser numbers.

1-3 FOUNDATION SITE AND SYSTEM ECONOMICS

A building foundation must be adequate if the structure is to perform satisfactorily and be safe for occupancy. Other foundations must be adequate to perform their intended functions in a satisfactory and safe manner; however, buildings usually have more stringent criteria for safety and performance than other structures—notable exceptions being nuclear-plant facilities, turbines for power generation, and certain types of radio-antenna equipment. Foundations for nuclear plants require extremely rigid design/performance criteria for safety reasons. The other foundations support extremely expensive machinery which is often very sensitive to small soil deformations.

More recently, and after loss of life from several avoidable failures, dam designs where soil is the principal construction material are being more carefully made. One might note that more principles of soil mechanics and geology apply

to earth dams than to the majority of foundation engineering problems. In addition to the stringent criteria of the superstructure, instability and water flow through the base soil are serious considerations. A further area of concern is the inevitable deformation of the base soil and subsidence in the superstructure (dam fill material). Careful attention to the occurrence of the latter deformations can allow the designer to avoid a base crack in the dam and the resulting piping failure, or a crest crack and the associated overtopping failure.

Almost any reasonable structure can be built and safely supported if there is unlimited financing. Unfortunately, in the real situation this is seldom, if ever, the case, and the foundation engineer has the dilemma of making a decision under much less than the ideal condition. Also, even though the mistake may be buried, the results from the error are not and can show up relatively soon—and probably before any statute of limitations expires. There are reported cases where the foundation defects (such as cracked walls or broken mechanical fixtures) have shown up years later—also cases where the defects have shown up either during construction of the superstructure or immediately thereafter.

Since the substructure is buried, or is beneath the superstructure, in such a configuration that access will be difficult should foundation inadequacies develop after the superstructure is in place, it is common practice to be conservative. A one or two percent overdesign in these areas produces a larger potential investment return than in the superstructure.

The designer is always faced with the question of what constitutes a safe, economical design while simultaneously contending with the inevitable natural soil heterogeneity at a site. Nowadays that problem may be compounded by land scarcity requiring reclamation of areas which have been used as sanitary landfills, garbage dumps, or even hazardous waste disposal areas. Still another complicating factor is that the act of construction can alter the soil properties considerably from those used in the initial analyses/design of the foundation. These factors result in foundation design becoming so subjective and difficult to quantify that two design firms might come up with completely different designs that would perform equally satisfactory. Cost would likely be the distinguishing feature for the preferred design.

This problem and the widely differing solutions would depend, for example, on the following:

1. What constitutes satisfactory and tolerable settlement; how much extra could, or should, be spent to reduce estimated settlements from say 30 to 15 mm?
2. Has the client been willing to authorize an adequate soil exploration program? What kind of soil variability did the soil borings indicate? Would additional borings actually improve the foundation recommendations?
3. Can the building be supported by the soil using
 - a. Spread footings—least cost.
 - b. Mats—intermediate in cost.
 - c. Piles or caissons—several times the cost of spread footings.
4. What are the consequences of a foundation failure in terms of public safety?

- What is the likelihood of a lawsuit if the foundation does not perform adequately ?
5. Is sufficient money available for the foundation ? It is not unheard of that the foundation alone would cost so much the project is not economically feasible. It may be necessary to abandon the site in favor of one where foundation costs are affordable.
 6. What is the ability of the local construction force ? It is hardly sensible to design an elaborate foundation if no one can build it, or if it is so different in design that the contractor includes a large "uncertainty" factor in the bid.
 7. What is the engineering ability of the foundation engineer ? While this factor is listed last, this is not of least importance in economical design. Obviously engineers have different levels of capability just as in other professions (lawyers, doctors, professors, etc.) and in the trades such as carpenters, electricians, and painters.

If the foundation fails because of any cost shaving (in reality implicitly accepting a higher risk), the client tends to quickly lose appreciation for the temporary financial benefit which accrued. At this point, facing heavy damages and/or a lawsuit, the client is probably in the poorest mental state of all the involved parties. Thus, one should always bear in mind that absolute dollar economics may not produce good foundation engineering.

The foundation engineer must look at the entire system: the building purpose, probable service-life loading, type of framing, soil profile, construction methods, and construction costs to arrive at a design that is consistent with the client/owner's needs and does not excessively degrade the environment. This must be done with a safety factor which produces a tolerable risk level to both the public and the owner.

Considering these several areas of uncertainty, it follows that risk and liability insurance for persons engaged in foundation engineering is very costly. In attempts to reduce these costs as well as produce a design which could be obtained from several engineering firms (i.e., a "consensus" design) there is active discussion (and the practice has already been undertaken in several areas) of having the foundation engineer submit the proposed design to a board of qualified engineers for a "peer review."

1-4 GENERAL REQUIREMENTS OF FOUNDATIONS

A foundation must be capable of satisfying several stability and deformation requirements such as:

1. Depth must be adequate to avoid lateral expulsion of material from beneath the foundation—particularly for footings and mats.
2. Depth must be below the zone of seasonal volume changes caused by freezing, thawing, and plant growth.