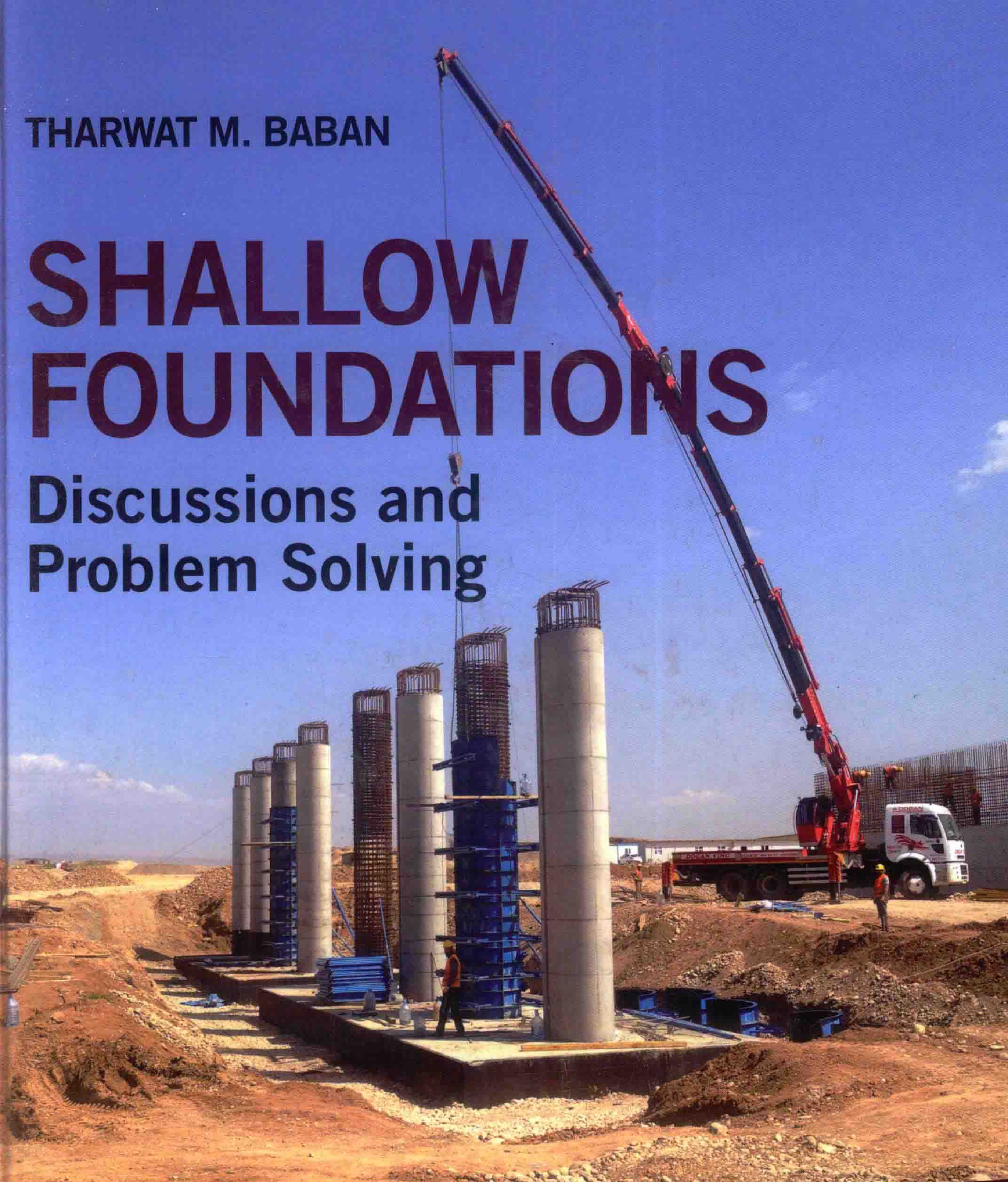
THARWAT M. BABAN

SHALLOW FOUNDATIONS

Discussions and Problem Solving



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Discussions and Problem Solving

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This edition first published 2016

Registered Office
John Wiley & Sons, Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

Editorial Offices
9600 Garsington Road, Oxford, OX4 2DQ, United Kingdom
The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

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Library of Congress Cataloging-in-Publication Data applied for.

Hardback ISBN: 9781119056119

A catalogue record for this book is available from the British Library.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Cover image: Courtesy of the Author

Set in 9.5/11.5pt Minion by SPi Global, Pondicherry, India

Printed in Singapore by C.O.S. Printers Pte Ltd

1 2016

Preface

This book is intended primarily to introduce civil engineers, especially geotechnical engineers and all civil engineering students reading the specialist subjects of soil mechanics and geotechnical engineering, to the fundamental concepts and application of shallow foundation analysis and design. Also, the furnished material can be considered as an essential reference work for practising civil engineers, consulting engineers and government authorities. The primary focus of this book is on interfacing structural elements with the underlying soil, which is, in the author's opinion, where the major focus of shallow foundation engineering lies.

The book is not intended to be a specific text book on soil mechanics or geotechnical engineering. Therefore, there is no part of the text alone that could be used as a core syllabus for a certain course. However, it is the author's opinion that more than 70% of the book is core material at the advanced undergraduate levels. It is expected that civil engineering students will find the text helpful in better understanding the fundamental concepts and their implications for the analysis and design of shallow foundations. The author tried to present the material such that separable topics and subtopics are covered in separate sections, with clear and unambiguous titles and subtitles. Thus, it would not be difficult for a university lecturer to draw up a personalised reading schedule, appropriate to his or her own course. It is hoped that the book can establish itself as an effective reference and a useful text in most of the engineering colleges and technical institutions.

Generally, the given material is of an advanced level and, therefore, it is assumed that the reader has a good understanding of basic statics and the mechanics of materials and has studied the basic principles of soil mechanics, lateral earth pressures and reinforced concrete. SI units are used throughout all the chapters and, therefore, the reader also needs to have sufficient background knowledge regarding the use of these units.

The book would be very beneficial to the reader, since it provides essential data for the design of shallow foundations under ordinary circumstances. The necessary background concepts and theories are generally presented clearly in concise forms of formulas or charts, and their applications are highlighted through solving a relatively large number of realistic problems. Moreover, the worked problems are of the types usually faced by civil engineers in practice and, therefore, the obtained information will be most valuable.

Generally, the subject matter is introduced here by first discussing the particular topic and then solving a number of pertinent objective problems that highlight the relevant theories, concepts and analysis methods. A list of crucial references is given at the end of each chapter. Thus, each chapter consists of three parts: *discussions*, *problem solving* and *references*.

The "discussion" part is presented in a clear and concise but precise manner, keeping in view the avoidance of unnecessary details. In some chapters, where the topics are of special difficulty, full guiding explanations are given; where the subject of study is simpler, less detailed treatment is provided.

The "problem solving" part gives a relatively comprehensive range of worked out problems to consolidate an understanding of the principles and illustrate their applications in simple practical situations. A total of 180 worked problems have been provided. The author's academic and professional career has proved to him that geotechnical engineers and civil engineering students need to be well acquainted with the correct and effective use of the theoretical and empirical principles and formulas they have learned. An effective way to lessen the deficiency may be through solving, as much as possible, a variety of problems of the type or nearly similar to those engineers face in practice. For these reasons the author considers the "problem solving" part, on which the book is partially based, as a vital portion of the text.

The "references" part that comes directly at the end of each chapter enriches the discussions part with valuable sources of information and increases its reliability. Moreover, the furnished references will be very beneficial to any ambitious fresh civil engineer or undergraduate student who may wish later to undertake higher studies in the subject.

The text comprises six chapters. The chapters are devoted mostly to the geotechnical and structural aspects of shallow foundation design. A brief overview of each chapter follows:

- *Chapter 1* deals with site investigation in relation to the analysis and design of shallow foundations. Unlike the other chapters, this chapter requires various topics, field tests in particular, to be discussed separately. Therefore, only a general and relatively brief overview of the overall subject matter, consistent with the chapter title, is given in the main "discussion" part. Discussion individual topics is given in the "problem solving" part directly below the relevant problem statement. Solutions of 27 problems have been provided. These solutions and those of the other five chapters have fully worked out calculations.
- *Chapter 2* presents introductory discussions and explanations of various topics pertaining to shallow foundations, their analysis and design. It discusses type and depth of shallow foundations, performance requirements, sulfate and organic acid attack on concrete, distribution of contact pressures and settlements and vertical stress increase in soils due to foundation loads. Solutions of 21 problems are presented.
- *Chapter 3* concerns settlements due to foundation loads. The chapter discusses various types of settlements of foundations on both coarse- and fine-grained soils, methods of settlement estimation, methods of estimating and accelerating consolidation settlement, settlement due to secondary compression (creep), estimation of settlements over the construction period and settlement of foundations on rock. Solutions of 56 problems are introduced.
- *Chapter 4* deals with the bearing capacity of shallow foundations. The chapter discusses most of the significant aspects of the subject matter, among them: bearing capacity failure mechanism, bearing capacity equations, bearing capacity of footings with concentric and eccentric vertical loads, bearing capacity of footings with inclined loads, effects of water table and other factors on bearing capacity, uplift capacity of shallow foundations, bearing capacity of foundations on layered soils and on slopes, and bearing capacity of rock. Solutions of 40 problems are provided.
- *Chapter 5* deals with the structural design of different types of shallow foundations. Structural design of plain concrete spread footings, pedestals, pile caps and the foundations of earth-retaining concrete walls are also included. The discussion part of the chapter covers most of the major aspects of the subject matter such as: selection of materials, design loads, structural action of isolated and continuous footings, eccentrically loaded footings, modulus of subgrade reaction and beams on elastic foundations, rigid and flexible design methods and so on. Design calculations of 28 typical problems are presented in a step by step order. All the structural designs conform to the Building Code Requirements for Structural Concrete (ACI 318) and Commentary, USA.
- *Chapter 6* deals with Eurocode Standards in relation to the design of spread foundations. The discussion part of the chapter covers certain important topics such as: Eurocode background and applications, basis of design and requirements, principles of limit states design, design approaches, partial factors and load combinations, geotechnical and structural designs of spread foundations and so on. The problem solving part of the chapter provides design calculations of eight typical

problems, as an attempt to introduce the concerned engineer to application of the design rules stipulated by Eurocodes 2 and 7 (or EN 1992 and 1997) rather than the geotechnical and structural related issues.

It is well known that not all civil engineers are acquainted with all internationally recognised codes, such as the ACI Code and Eurocodes, at the same time. Therefore, this chapter is especially written for those civil engineers, specially geotechnical engineers, who are unfamiliar with the technical rules and requirements of the Eurocode Standards (Structural Eurocode). The implementation of the Eurocode is extended to all the European Union countries and there are firm steps toward their international adoption.

It must be clear that, despite every care taken to ensure correctness or accuracy, some errors might have crept in. The author will be grateful to the readers for bringing such errors, if any, to his notice. Also, suggestions for the improvement of the text will be gratefully acknowledged.

Tharwat M. Baban

Acknowledgements

The author wishes to express his gratitude to those writers and researchers whose findings are quoted and to acknowledge his dependence on those authors whose works provided sources of material; among them are:

Giuseppe Scarpelli, Technical University of Marche Region, Ancona, Italy
Trevor L.L. Orr, Trinity College, Dublin, Ireland
Andrew J. Bond, Geocentrix Ltd, Banstead, UK
Andrew Harris, Kingston University, London, UK
Jenny Burridge, The Concrete Center, London, UK

The author is truly grateful to Dr. Paul Sayer, who was kind enough to suggest the inclusion of Chapter 6.

The author wishes to thank all the members of his family, especially his wife Mrs. Sawsan Baban, for their encouragement, assistance and patience in preparing the manuscript of this book.

Finally, the author likes to thank John Wiley and Sons, Ltd and their production staff for their cooperation and assistance in the final development and production of this book.

Contents

CHAPTER 1

Site Investigation in Relation to Analysis and Design of Foundations

1.1 General

The stability and safety of a structure depend upon the proper performance of its foundation. Hence, the first step in the successful design of any structure is that of achieving a proper foundation design.

Soil mechanics is the basis of foundation design since all engineered constructions rest on the earth. Before the established principles of soil mechanics can be properly applied, it is necessary to have a knowledge of the distribution, types and engineering properties of subsurface materials. Therefore, an adequate site investigation is an essential preliminary to enable a safe and economic design and to avoid any difficulties during construction. A careful site investigation can minimise the need for overdesign and reduce the risks of underdesign. A designer who is well equipped with the necessary reliable information can use a lower factor of safety, thereby achieving a more economical design. With enough information available, construction troubles can be decreased and, therefore, construction costs are decreased too.

A site investigation usually costs a small percentage of total construction costs. According to Bowles (2001), elimination of the site exploration, which usually ranges from about 0.5 to 1.0% of total construction costs, only to find after construction has started that the foundation must be redesigned is certainly a false economy. However, a geotechnical engineer planning a subsurface exploration program for a specific job must keep in mind the relative costs of the exploration versus the total construction costs. It is understood that there is no hard and fast procedure for an economical planning a site investigation programme. Each condition must be weighed with good judgment and relative economy.

Nowadays, it is doubtful that any major structures are designed without site exploration being undertaken. Sometimes, for small jobs, it may be more economical to make the foundation design on conservative values rather than making elaborate borings and tests, especially, when the condition of the adjacent structures is an indication that the site is satisfactory. However, generally, design of structures without site investigation is not recommended by civil engineers.

The cheapest and most common method of subsurface exploration is by drilling boreholes. Test pits are too expensive for general exploration, but they may be used for more careful examination if found to be needed.

Shallow Foundations: Discussions and Problem Solving, First Edition. Tharwat M. Baban.

1.2 Site Investigation

A successful investigation of a site for an important structure will generally falls under the following five headings:

(1) Reconnaissance
(2) Subsurface exploration
(3) Laboratory tests
(4) Compiling information
(5) Geotechnical report.

1.2.1 Reconnaissance

Office Reconnaissance: This phase of reconnaissance comprises the following duties:

- Review of plans, boring logs and construction records of existing structures in the area.
- Study of the preliminary plans and designs of the proposed structure, including the approximate magnitude of the loads to be transmitted to the supporting material.
- Review of other backlogs of information already compiled on the same general area and similar structures.
- Review of other information pertaining to the site area obtained from such sources as different types of maps (i.e., topographic, geologic and agricultural maps), photographs, records of adjacent bridge if exists, underground utility constructions and well drilling logs.
- Formulation of a boring plan should be made during the latter phases of the office reconnaissance. This prepared boring plan should be reviewed during the field reconnaissance. The objective should be the development of a maximum of subsurface information through the use of a minimum number of boreholes. Spacing, number and depth of boreholes will be discussed later in conjunction with the Solution of Problem 1.4.

Field Reconnaissance: This phase of reconnaissance should commence with a visit to the site of the proposed structure. It should always be made by a Soils or Foundation Engineer who will complete the Geotechnical Report. Whenever possible, it is desirable that this engineer be accompanied by the driller or the driller foreman. Notes on items to be observed are as follows:

- Surface Soils: Surface soils are easily revealed through the use of a shovel or post-hole diggers. These soils may sometimes be identified as belonging to some particular formation, and usually they indicate the underlying material.
- Gullies, Excavations and Slopes: Any cut or hole near the proposed structure site is a subsurface window, and for its depth it will provide more information than borehole since it may be examined in detail.
- Surface and Subsurface Water: The presence of either surface or subsurface water is an important factor in both preparation of boring plans and foundation design. All surface flows should be noted, and all opportunities should be taken to observe the groundwater level.
- Study of Existing Structures: The existing structures within an area are valuable sources of information. A very close examination of them with regard to their performance, type of foundation, apparent settlement, load, location and age will yield a wealth of data.
- Topography: To some extent, topography is indicative of subsurface conditions. In narrow, steep stream beds, rock is likely to be near the surface with little overlying stream-deposited soil. On the other hand, wide, flat valleys indicate deep soil deposits.

- Information required by the Drill Crew. The drill crew needs to know how to get to the site, where to drill, what equipment to take, and what difficulties to expect. Generally, the following types of information are usually needed:
- Information regarding verification of the boring plan which was already prepared during the office reconnaissance phase. The proposed locations of boreholes should be checked for accessibility. Desirable deletions, additions, and relocations should be made as are necessary to better suit the crew's capabilities and to add completeness to the subsurface information.
- Type of drilling and equipment needed. Notes should be made as to which type of drilling is best suited to the site (i.e., rotary, auger, etc.).
- Reference points and bench marks. The reconnaissance should determine if reference points and bench marks are in place adjacent to the site and properly referenced on the plans.
- Utilities. Underground and overhead utilities located at the site should be accurately shown on the plans or their locations should be staked on the ground.

- Geophysical Survey: The field reconnaissance may require a geophysical survey of the site. The use of geophysical methods provides information on the depths to the *soil* and *rock layers*, the homogeneity of the layer and the type of soil or rock present. This information can be used to supplement the boring plan.
- Field Reconnaissance Report: A concise and informative field reconnaissance report, in which all decisions concerning the boring plan and the drill crew are delineated, should be prepared. It can be facilitated by the use of a special check list or form.

1.2.2 Subsurface Exploration

General: After the reconnaissance has been completed, the results should be given to the foreman of the drill crew in order to carry out the foundation investigation at the site. Briefly, the subsurface or foundation exploration consists of making the borings and collecting the pertinent samples (i.e., drilling and sampling), performing the required field tests in conjunction with the drilling, coring, and identification of materials. Each job site must be studied and explored according to its subsurface conditions and the size and type of the proposed structure. The civil engineer or the experienced geologist in charge of the exploration task should endeavour to furnish complete data such that a reliable study of practical foundation types can be made.

Before the arrival of the drill crew at the exploration site, enough survey control should have been previously carried out with reference to at least one bench mark already established at the site. The borehole locations should be staked in conformity with the boring plan. The stakes could indicate the borehole number and the existing ground surface elevation.

Drilling: It is defined as that process which advances the borehole. There are various methods of drilling or boring, namely: auger drilling, rotary drilling, wash boring, drilling by continuous sampling, percussion drilling and rock coring. Most of these methods are best suited for some particular problem or type of information sought. It is doubtful if an organisation (authority responsible for site investigation) would adopt any one method for all of its work unless the work was limited to one particular area. The same argument is true with respect to the various types of equipment used in drilling and coring.

Sampling: It is defined as that process wherein samples of the subsurface materials are obtained. As there are various methods of drilling and various equipment types, also there are different types of sampling, namely: split-barrel or spoon sampling, push barrel or thin-walled Shelby tube and stationary piston type sampling, wet barrel or double wall and dry barrel or single wall sampling, retractable plug sampling and rock coring.

Samples: The samples obtained during subsurface exploration should always represent the material encountered, that is, representative samples. These samples are disturbed, semi-disturbed or undisturbed. Usually, disturbed and semi-disturbed samples are used for identification and classification of the material. Undisturbed samples are used for determining the engineering properties such as strength, compressibility, permeability and so on, density and natural moisture content of the material. Disturbed samples are those in which the material (soil or rock) structure has not been maintained, and they are used in those tests in which structure is not important. On the other hand, relatively undisturbed samples have structures maintained enough that they could be used in engineering properties determination of the material. The degree of disturbance depends upon several factors such as type of materials being sampled, sampler or core barrel used, the drilling equipment, methods of transporting and preserving samples and driller skill. Extended exposure of the sample material to the atmosphere will change relatively undisturbed sample into an unusable state; therefore, the methods of obtaining and maintaining samples cannot be overemphasised.

Field Tests: there are various types of tests performed in the field, in conjunction with the drillings, in order to determine soil properties in situ. These tests are: dynamic penetration tests, such as standard (SPT) cone penetration and driven probe and driven casing; static cone penetration (CPT); in-place vane shear; plate-load (may not be in conjunction with the drillings); pressuremeter; flat-plate dilatometer; and other tests made in field laboratories, such as classification tests and unconfined strength test. Rock quality designation (RQD) test is performed on rock core samples. *Note:* Discussion of a particular field test will be given in the "*Problem Solving*" part of this chapter directly below the relevant problem statement.

Field Boring Log and Borehole Logging: The log is a record which should contain all of the information obtained from a boring whether or not it may seem important at the time of drilling. The process of recording the information in a special field log form is "logging". It is important to record the maximum amount of accurate information. This record is the "field" boring log. The importance of good logging and field notes cannot be overemphasised, and it is most necessary for the logger (who may be a soil engineer, a geologist, a trained technician or a trained drill crew foreman) to realise that a good field description must be recorded. The field boring log is the major portion of the factual data used in the analysis of foundation conditions.

Groundwater Table: The location of the groundwater level is an important factor in foundation analysis and design, and emphasis should be placed upon proper determination and reporting of this data.

In order to determine the elevation of groundwater it is suggested that at least two boreholes be left open for the duration of the subsurface exploration and periodically checked as to water level. These two boreholes should have their final check made no earlier than 24 h after the completion of exploration. The depth to the water level should be recorded on the boring log each time a reading is made, along with the time lapse since completion of the boring. When there is significant difference between the two borings checked, or when the logger deems it otherwise necessary, the water level in other boreholes should be checked.

Note: It is obvious that details of all the various methods and descriptions of the above mentioned drilling, samples and sampling, field tests, field boring log and borehole logging are too large in bulk for inclusion in the discussions. However, those interested in further information and details, should see various standards, practice codes and manuals, such as AASHTO Manual on Subsurface Investigations (1988), ASTM, BSI and Eurocode standards.

1.2.3 Laboratory Tests

Economical foundation design requires the use of the physical properties of the foundation material (soil or rock). The physical properties may be determined by in situ tests, load tests and laboratory tests. Results of laboratory tests, in addition to their use in foundations design, are used to predict the foundation behavior based on the experience of similar tested materials and their performance in the field. The two main reasons for making these laboratory tests are first to verify classification and second to determine engineering properties. An adequate amount of laboratory testing should be conducted to simulate the most sever design criteria. Generally, the amount of testing performed will depend on the subsurface conditions, laboratory facilities and type of the proposed structure.

Laboratory tests for foundations design will generally fall into four categories: classification, strength, compressibility and swelling and soil collapsibility. Other tests, such as permeability and compaction tests, may be required, especially when the proposed structure is a bridge or a dam.

Note: Significance, apparatus and procedure of various types of laboratory tests can be found in geotechnical books and recognised laboratory standard manuals (ASTM, AASHTO, BSI, etc.). The detailed description of these items is too bulky for inclusion in these discussions. The author assumes that the reader will have access to the latest volumes of the standards just mentioned. Nevertheless, Table 1.1 presents a summary list of ASTM and AASHTO tests frequently used for the laboratory testing of soils.

Table 1.1 ASTM and AASHTO standards for frequently used laboratory testing of soils.

		Test designation	
Test category	**Name of test**	**ASTM**	**AASHTO**
Visual identification	Practice for identification of soils (visual-manual procedure)	D 2488	—
	Practice for description of frozen soils (visual-manual procedure)	D 4083	—
Index properties	Test method for determination of water (moisture) content of soil by direct heating method	D 4959	T 265
	Test method for specific gravity of soils	D 854	T 100
	Method for particle-size analysis of soils	D 422	T 88
	Test method for amount of material in soils finer than the no. 200 sieve	D1140	—
	Test method for liquid limit, plastic limit and plasticity index of soils	D 4318	T 89
			T 90
	Test method for laboratory compaction characteristics of soil using standard effort (600 kN.m/m^3)	D 698	T 99
	Test method for laboratory compaction characteristics of soil using modified effort (2700 kN.m/m^3)	D 1557	T 180
Corrosivity	Test method for pH of peat material	D 2976	—
	Test method for pH of soils	D 2972	—
	Test method for pH of soil for use in corrosion testing	G 51	T 289
	Test method for sulfate content	D 4230	T 290
	Test method for resistivity	D 1125	T 288
		G 57	
	Test method for chloride content	D 512	T 291
	Test method for moisture, ash and organic matter of peat and other organic soils	D 2974	T194
	Test method for classification of soils for engineering purposes	D 2487	M 145
		D 3282	
Strength Properties	Unconfined compressive strength of cohesive soil	D 2166	T 208
	Unconsolidated, undrained compressive strength of clay and silt soils in triaxial compression	D 2850	T 296

(*Continued*)

Table 1.1 (*Continued*)

Test category	Name of test	Test designation	
		ASTM	AASHTO
	Consolidated undrained triaxial compression test on cohesive soils	D 4767	T 297
	Direct shear test of soils for unconsolidated drained conditions	D 3080	T 236
	Modulus and damping of soils by the resonant-column method (small-strain properties)	D 4015	—
	Test method for laboratory miniature vane shear test for saturated fine-grained clayey soil	D 4648	—
	Test method for bearing ratio of soils in place	D 4429	—
Strength Properties	California bearing ratio (CBR) of laboratory-compacted soils	D 1883	—
	Test method for resilient modulus of soils	—	T 294
	Method for resistance R-value and expansion pressure of compacted soils	D 2844	T 190
Permeability	Test method for permeability of granular soils (constant head)	D 2434	T 215
	Test method for measurement of hydraulic conductivity of saturated porous materials using flexible wall perameters	D 5084	—
Compression Properties	Method for one-dimensional consolidation characteristics of soils (oedometer test)	D 2435	T 216
	Test method for one-dimensional swell or settlement potential of cohesive soils	D 4546	T 258
	Test method for measurement of collapse potential of soils	D 5333	—

1.2.4 Compiling Information

General: Having carried the investigation through the steps of reconnaissance, subsurface exploration and laboratory testing, the next step is obviously the compilation of all the information.

Prior to preparing finished (final) logs, all samples should be checked by the Engineer in charge. This should ideally be performed immediately after the borings are completed and even while the boring program is still in progress. Significant soil characteristics that may have been omitted from the field logs may be identified, and the Engineer thus alerted to a potential foundation problem that might otherwise have gone undetected.

Finished Boring Log: It is important to differentiate clearly between the “field” boring log and the “finished” boring log. The field log is a factual record of events during boring operation, whereas the finished log is a graphical representation. The field log gives a wide range of information in notes or tabular form. The finished log is drawn from the data given in the field log as well as from results of visual inspection of samples; it represents a graphical picture of subsurface conditions. Information obtained from laboratory test results along with other necessary information are also utilised in its preparation. Also, various data such as results of field tests, depth location of different samples and groundwater level are superimposed upon it. It is important that the *soil* or *rock* in each stratum be clearly described and classified. A typical finished boring log is shown in Figure 1.1.

Soil Profile: In many cases it may be advantageous to plot a soil profile along various longitudinal or transverse lines. This should be done by plotting the boreholes in their true location, but with vertical scale exaggerated, connecting the similar strata by lines and shading similar areas by means of an identifying cross-section mark. The groundwater level should also be shown on the plot. Thus a probable representation of the subsurface conditions between the boreholes can be given, although a pocket or more of different formation may exist between any two adjacent boreholes. A representative example of an interpreted subsurface profile is shown in Figure 1.2.

Boring Log

Name of the Project: Two-story apartment building

Location: Johnson & Olive St. Date of Boring: March 2, 2005

Boring No. 3 Type of Boring: Hollow-stem auger Ground Elevation: 60.8 m

Soil description	Depth (m)	Soil sample type and number	N_{60}	w_n (%)	Comments
Light brown clay (fill)					
Silty sand (SM)	1				
	2	SS-1	9	8.2	
°G.W.T. 3.5 m	3	SS-2	12	17.6	LL = 38 PI = 11
Light gray clayey silt (ML)	4				
	5	ST-1		20.4	LL = 36 q_u = 112 kN/m^2
	6	SS-3	11	20.6	
Sand with some gravel (SP)	7				
End of boring @ 8 m	8	SS-4	27	9	

N_{60} = standard penetration number
w_n = natural moisture content
LL = liquid limit; PI = plasticity index
q_u = unconfined compression strength
SS = split-spoon sample; ST = Shel by tube sample

Groundwater table observed after one week of drilling

Figure 1.1 A typical finished boring log (from Das, 2011).

1.2.5 Final Geotechnical Report

After information compiling has been successfully completed, a final written Geotechnical Report should be prepared and presented to the designer for use in the foundations design. Additionally, this report will furnish the Resident Engineer with data regarding anticipated construction problems, as well as serving to establish a firm basis for the contractor to estimate costs, unless the organisation's policies or regulations restrict the release of such information. A good policy may be of releasing such information, which should be as accurate as possible, provided that it is expressly and formally understood that the organisation will not be liable for any damages or losses incurred as a result of reliance upon it in the bidding or in the construction operations.

The Geotechnical Engineer who writes the Report should avoid including extraneous data which are of no use to the Designer or Resident Engineer. Also, his recommendations should be brief, concise and, where possible, definite. The Report should include:

- Authorisation of the site investigation and the job contract number and date.
- A description of the investigation scope.
- A description of the proposed structure for which the subsurface exploration has been conducted.