NOTES ON FOUNDATION ENGINEEERING

by

JOSE O. CHAVEZ

Diploma in Civil Engineering
Universidad Nacional Autonoma de Honduras
Honduras, 1981

A MASTER'S REPORT

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Civil Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1985

Approved by:

Wayne W. Williams
Major Professor

ACKNOWLEDGEMENTS

First of all, I wish to express my deepest gratitude to LASPAU (Lationo-American Scholarship Program for American Universities) and to the U.NAH (Universidad Nacional Autonoma de Honduras) which are the two organizations that provided the support to make my graduate student possible at Kansas State University.

Also, I would like to express my gratefulness to Dr. Robert Snell who, as Head of the Civil Engineering Department, accepted me as one of his graduate students to pursue my master's degree.

My appreciation, my gratefulness and my sincere acknowledgement are also extended to my major advisor, Professor Wayne Williams, who, through his lectures and his advice, guided me through my graduate work. I am very thankful to him.

Finally, I wish to express my gratitude to those professors who, in some way or another, helped me to better understand the complex field of the Civil Engineering, thank you for giving me your time.

THIS BOOK WAS BOUND WITH TWO PAGES NUMBERED 31. THESE PAGES ARE DIFFERENT. THE BOOK WAS BOUND WITHOUT A PAGE NUMBERED 32.

THIS IS AS RECEIVED FROM CUSTOMER.

THIS BOOK CONTAINS NUMEROUS PAGES WITH DIAGRAMS THAT ARE CROOKED COMPARED TO THE REST OF THE INFORMATION ON THE PAGE.

THIS IS AS RECEIVED FROM CUSTOMER.

Purpose of the study

As a LASPAU scholar, part of my duty will be to teach at a university in Honduras at the time I return there. Therefore, the purpose of the work presented in this report is to prepare a set of notes on Foundation Engineering using recent literature available. Those notes should be used as a guide that may be added to the actual program of study at the University of Honduras.

Scope of the Study

The study basically tends to present methods of analysis on Foundation Engineering. These methods of analysis cover the design of spread footing, mat foundations, piles and retaining walls. In addition to that, a soil mechanics review is included.

The material included here could be used in a three-hour-per-week class during a fourteen-week semester.

TABLE OF CONTENTS

CHAPTER I

INTRODUCTION

It is recognized that soils can be considered as the oldest and the most complex of the construction materials used by civil engineers. In the first place, soils have been available since ancient times and man has used them for different purposes. For example, there are evidences that the Romans built notable engineering structures including an important network of durable and excellent roads where they followed two important principles: a solid foundation and good drainage. In spite of the fact that soils have been used a lot, the progress in learning and understanding their behavior has been slow because of the complexity of their structure, the variability in properties and their behavior in presence of water.

Successful foundation design was a matter of experience until the Terzaghi's work of 1925. Until the middle of the nineteenth century, most footings were built of masonry. These were of two types: a) dimension-stone footings consisting of stone cut and dressed to specific sizes, and b) rubble-stone footings which were made of pieces of random size joined by mortar. In some cases, to increase the size of the footings without increasing their weight, timber grillages were built and conventional masonary footings were placed on them. Later, the timber grillages were replaced by grillages composed of steel railroad rails embedded in concrete, that improvement saved weight and increased space in the basement. At the beginning of the twentieth century, the steel rails were replaced by steel I beams but, early in 1900, with the advent of reinforced concrete, grillage footings were replaced almost totally by reinforced concrete footings, which are still the common type. Typical grillage foundations are shown in Fig. 1.1.

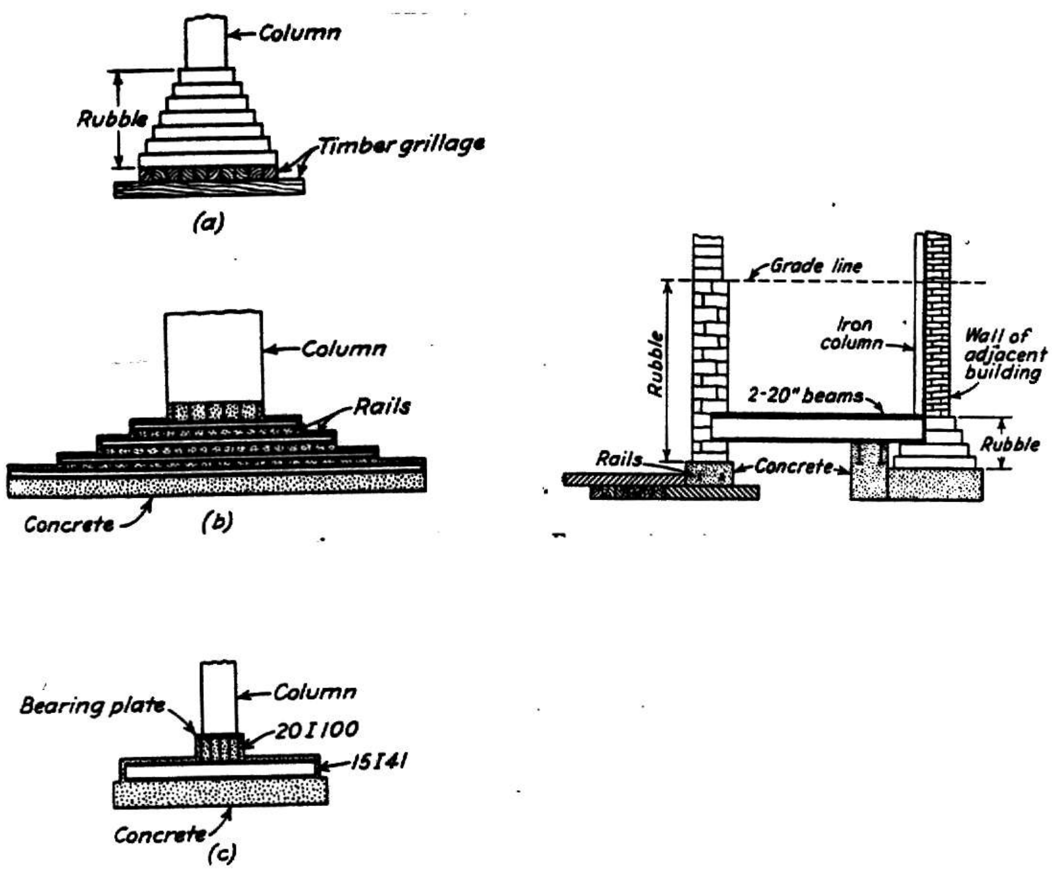


Figure 1.1. Historical development of grillage foundations of (a) timber, (b) railroad rails, (c) steel I-beams, (d) Cantilever footing supporting exterior column of Auditorium Building, Chicago, 1887.

The materials used to build the footings has been discussed and in addition to that, it is important to mention that in earliest times, the area of a footing was chosen based on good guessing and experience. For instance, in some parts of the United States, the width of a continuous footing in feet was made equal to the number of stories in the structure. In the early 1870's, some engineers suggested that the area of the footings should be selected proportional to the loads on the footings and that the centers of gravity of the loads should coincide with the centroids of the footings, so that tilting problems could be avoided. This did not always assure success because the principles of soil consolidation were not understood. To alleviate this, "allowable soil pressures" were recommended in building codes based upon experience within a given area.

Finally, because of the misunderstanding of the soil behavior under load, many failures have occurred and some of the causes are listed below:

a) uncontrolled water flow adjacent to a footing.

b) unexpected settlement of soils.

c) unbalanced soil pressure conditions from differences in elevations.

d) loss of vertical support from the removal of the lateral support of the soil.

e) seismic disturbance.

Some examples of failure foundations are shown in Fig. 1.2.

Figure 35 — Clay backfill after a storm.

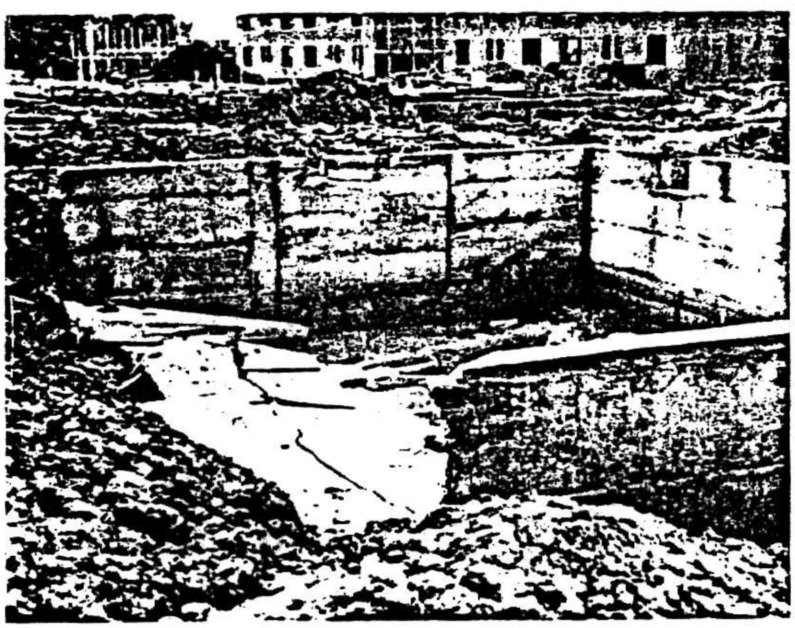


Figure 1.2. Clay backfill and water collapsed the wall.

Clay backfill which became liquid after a heavy storm provoked lateral pressures greater than for which it was designed.

In 1934, Terzaghi published a paper in which he showed that the settlement and the leaning of the tower are due to the gradual consolidation of the clayey soil located 8 m underneath the footing.

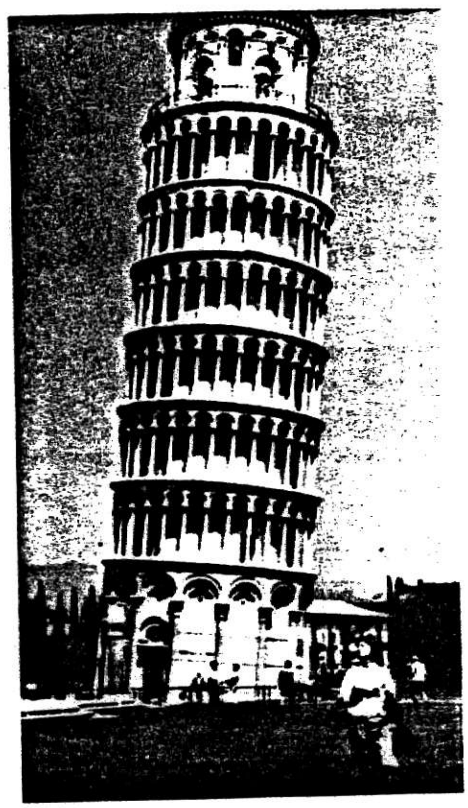


Figure 1.3. Pisa Tower. The most successful foundation failure.

The flow of the soft clay under the gravel bed which formed the support of the buildings may have been the cause of structural damage occurring during the Anchorage earthquake.

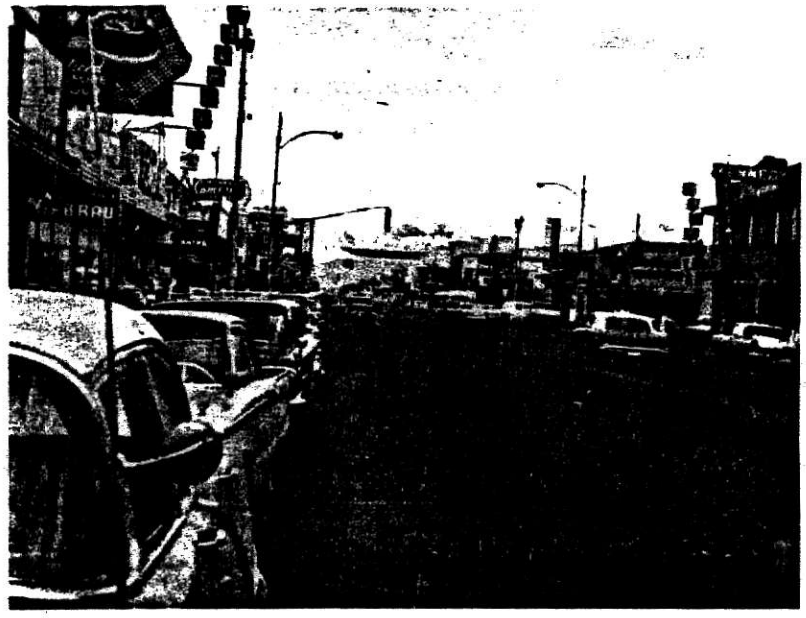


Figure 1.4. 4th Avenue, Anchorage, May 1963.

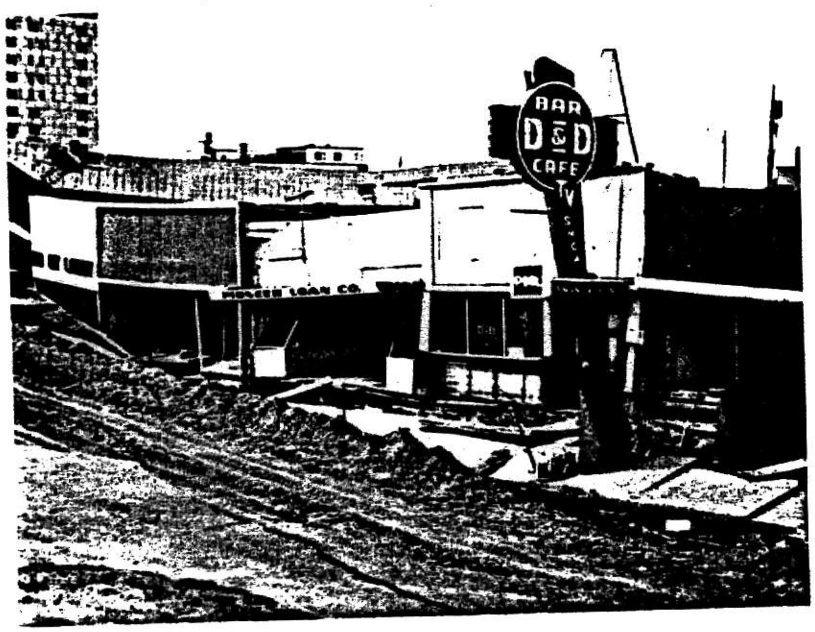


Figure 1.4. 4th Avenue, Anchorage, April 1, 1964, after earthquake.

Having mentioned that the practice of foundation engineering was based on empirical rules, it is evident that the main purpose of foundation engineering is to replace the empirical rules with scientific methods of analysis that require quantitative soil data such as classification, shearing strength and compressibility of the soil.

Today, the philosophy followed in the design of foundations is that they must have two main characteristics:

1) The foundation should be safe against shear failure in the soil that supports it.

2) The foundation should not undergo excessive settlements.

Hence, the scientific methods mentioned above try to give mathematical relationships which are able to predict the capability of the soil to support loads as well as to predict the settlement that the soil could suffer under those loads.

The main types of foundations used today and their general applications are shown in Table 1.

Foundation type	Use	Applicable soil conditions
Spread footing, wall footings	Individual columns, walls, bridge piers	Any conditions where bearing capacity is adequate for applied load. May use on single stratum: firm layer over soft layer or soft layer over firm layer. Check immediate, differential, and consolidation settlements
Mat foundation	Same as spread and wall footings. Very heavy column loads. Usually reduces differential settlements and total settlements	Generally soil bearing value is less than for spread footings: over one-half area of building covered by individual footings. Check settlements
Pile foundations Floating	In groups (at least 2) to carry heavy column, wall loads: requires pile cap	Poor surface and near surface soils. Soils of high bearing capacity 20–50 m below basement or ground surface, but by distributing load along pile shaft soil strength is adequate. Corrosive soils may require use of timber or concrete pile material
Bearing	In groups (at least 2) to carry heavy column, wall loads: requires pile cap	Poor surface and near-surface soils: soil of high bearing capacity (point bearing on) is 8–50 m below ground surface
Caisson (shafts 75 cm or more in diameter) generally bearing or combination of bearing and skin resistance	Larger column loads than for piles but eliminates pile cap by using caissons as column extension	Poor surface and near-surface soils: soil of high bearing capacity (point bearing on) is 8–50 m below ground surface
Retaining walls, bridge abutments	Permanent retaining structure	Any type of soil, but a specified zone (Chaps. 11, 12) in back of wall usually of controlled backfill
Sheet-pile structures	Temporary retaining structures as excavations, waterfront structures, cofferdams	Any soil: waterfront structure may require special alloy or corrosion protection. Cofferdams require control of fill material

Table 1. Foundation types and typical usage.

CHAPTER II

SOIL MECHANICS REVIEW

a. Soil Deposits

Soil "can be defined as naturally occurring mineral aggregations that can be separated easily into smaller particles and in mass form contains numerous voids." It is also defined as a natural occurring material that can be moved by conventional earth moving equipment. Soil deposits can be divided in three general categories: 1) residual soils, 2) transported soils, and 3) organic soils. Residual soils are those which develop in the place of their formation from the underlying rock. Transported soils are those which have been removed from the place of their formation by wind, water, ice or gravity to the current location. Based on the transporting agent, transported soils can be subdivided into three categories.

1) Aeolian -- deposited by wind action

2) Alluvial -- deposited by running water

3) Glacial -- deposited by glacier action

4) Talus and Creep -- deposited by gravity.

The organic soils are those derived from the decomposition of organic materials and usually are found only in swamps and northern latitudes.

The engineering properties are different for each of these deposits, in general, residual deposits tend to have better foundation characteristics in terms of strength and deformation than the other two but, when the residual soil above the bedrock is normally consolidated, heavy loads on large foundations could cause serious settlements. In general, alluvial deposits have noticeable variation in physical properties (void ratio, unit weight), altering the load capacity of the soil. The physical characteristics of the unstratified deposits laid down by glaciers when they melt (till), may vary from glacier to glacier and during field exploration programs, erratic values of standard penetration tests can be obtained. Aeolian deposits such as loess can be considered a collapsing soil because it looses its strength when it becomes saturated. Therefore, special precautions should be taken for building foundations on loessial deposits. Finally, the organic deposits have a high natural moisture content and are highly compressible causing a large amount of settlement under load due to secondary consolidation.

The skilled geotechnical engineer recognizes that each of the soil classes vary in a uniform and predictable manner. Most soil stratums will have a decreasing void ratio with depth (probably due to the weight of the superimposed overburden) and this alone will increase the shearing resistance and decrease the compressibility.

The water transported alluvium will vary with the velocity of the transporting water since the slower the velocity of the stream, the finer the deposited sediment will be. Thus, most river valleys are aggraded with coarser material at the bottom with finer material at the top. These materials will always be well rounded sand and gravel.

The wind deposited stratum will become finer grained and the thickness of the stratum less in thickness with increasing distance from the source of the soil particles. These stratum are always composed of silt sized particles.

The ice transported materials are always unsorted and will contain particles from boulder to clay size. Any stratification or sorting indicates a reworking by water.

Gravity transported materials are found only at the base of mountains and consist of very large angular blocks or rock with the voids filled with angular granular materials. Although vast amounts of rocks are transported down minor slopes by soil creep mechanisms, these materials retain the characteristics imparted by the original agent of transportation.

b. Physical Characteristics of the Soils.

In nature, the soil is composed of solid particles, water and air (or gas). The mathematical relationships for the three phases can be defined as follows:

Void ratio, e: The ratio of the volume of voids v_v to the volume of solids v_s in a given soil mass and can be written:

$$e = \frac{v_v}{v_s} \qquad (2.1)$$

Porosity, n: The ratio of the volume of voids to the volume of the soil specimen v.

$$n = \frac{v_v}{v} \qquad (2.2)$$

Water content, w: The ratio of the weight of water w_w in a given soil mass to the weight of soil solids w_s in the same mass.

$$w(\%) = \frac{w_w}{w_s} \times 100 \qquad (2.3)$$

Unit weight, : The ratio of the weight of soil to the corresponding volume.

$$\gamma = \frac{W_t}{v} \qquad (2.4)$$

Since water is present, the weight has to be obtained as: unit weight, dry unit weight, submerged unit weight and saturated unit weight. They can be written as

$$\text{moisture unit weight} \quad \gamma_m = \frac{W_t}{v}$$

where $W_t = W_s + W_w$. Assuming the weight of the air is equal to zero.

Dry unit weight $\gamma_d = \frac{W_s}{V}$

Saturated unit weight $\gamma_s = \gamma_m$ if $V_v = V_w$

Submerged unit weight $\gamma_{sub} = \gamma_s - \gamma_w$

Degree of saturation, S: the ratio of the volume of water to the total volume of soil voids.

$$S(\%) = \frac{V_w}{V_v} \times 100 \qquad (2.5)$$

The soil is completely saturated when all the void volume is occupied by water, usually below the water table.

Specific gravity, G_s: The ratio of the unit weight of a material in air to the unit weight of distilled water at 4°C.

$$G_s = \frac{W_s/V_s}{W_w/V_w} = \frac{W_s/V_s}{w} \qquad (2.6)$$

γ_w = 62.4 pcf or 1.00 g/cm^3

Representative values of G_s, e and d for natural soils are shown in Table 2.1 and 2.2.

Table 2-1. Specific Gravities of Some Soils.

Soil type	G_s
Quartz sand	2.64–2.66
Silt	2.67–2.73
Clay	2.70–2.9
Chalk	2.60–2.75
Loess	2.65–2.73
Peat	1.30–1.9

Table 2-2. Void Ratio, Moisture Content, and Dry Unit Weight for Some Soils.

Type of soil	Void ratio e	Natural moisture content in saturated condition (%)	Dry unit weight γ_d (kN/m^3)
Loose uniform sand	0.8	30	14.5
Dense uniform sand	0.45	16	18
Loose angular-grained silty sand	0.65	25	16
Dense angular-grained silty sand	0.4	15	19
Stiff clay	0.6	21	17
Soft clay	0.9–1.4	30–50	11.5–14.5
Loess	0.9	25	13.5
Soft organic clay	2.5–3.2	90–120	6–8
Glacial till	0.3	10	21

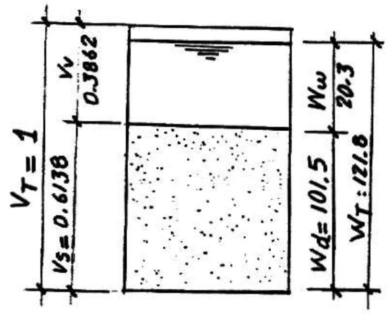
Example 2.1

- Underlined information in Table is the data given:

- Obtain the required data in each case.

G Specific Gravity	Moisture w(%)	Saturation S %	e Void Ratio	n Porosity	γ_d. (pcf)	$\gamma_{sat.}$ (pcf)	$\gamma_{sub.}$ (pcf)	$\gamma_{total.}$ (pcf)
2.65	20	84.2	0.6292	0.3862	101.50	125.6	63.2	121.8
2.65	18	66.2	0.72	0.4186	96.14	122.1	59.8	113.44
2.65	20	100	0.5300	0.3464	108.08	129.6	67.2	129.69
2.65	20	50	1.060	0.5146	80.27	112.3	49.9	96.32

Soil 1



$$w = \frac{w_w}{w_s}, \quad 0.20 = \frac{w_w}{w_s}, \quad 0.20\, w_s = w_w \quad (1)$$

$$G = \frac{w_s}{v_s\, 62.4}, \quad 2.65(6.24)v_s = w_s \quad (2)$$

$$\gamma_{sub} = \gamma_{sat} - \gamma_w \quad (3)$$

$$63.2 = \gamma_{dry} + 62.4\, v_v - 62.4$$

$$63.2 = 2.65(62.4)v_s + 62.4(v_v) - 62.4$$

$$125.6 = 165.36\, v_s + 62.4\, v_v.$$

$\gamma_d = 2.65(0.6138)62.4 = 101.50$ pcf

$\gamma_{sat} = 101.5 + 62.4(0.3862) = 125.6$ pcf; $\quad v_v + v_s = 1 \quad (4)$

Solving (3) and (4).

$\gamma_{tot} = 101.5 + 62.4(0.3253) = 121.8$ pcf

$\gamma_{sub} = 125.6 - 62./4 = 63.2$ ok

$$S = \frac{v_w}{v_v} : \frac{0.3253}{0.3862} : 0.842$$

$: 84.27\%$

Solving (3) and (4)

$w_w = 0.20(101.50) = 20.3$; $\quad 125.6 + 165.36\,(1 - v_v) + 62.4\, v_v$

$$v_w = \frac{20.3}{62.4} = 0.3253 \qquad v_v = 0.3862$$

$v_s = 0.6138.$

$$e = \frac{v_v}{v_s} = \frac{0.3862}{0.6138}, \quad e = 0.6292$$

$$n = \frac{v_v}{vt_s} = \frac{0.3862}{1} : 0.3862.$$

Soil 2.

$$e = \frac{v_v}{v_s} \quad 0.72\ v_s = v_v \qquad (1)$$

$$v_v + v_s = 1 \quad v_v = 1 - v_s \qquad (2)$$

Solving (1) and (2).

$$0.72\ v_s = 1 - v_s$$

$$v_s = 0.5814$$

$$v_v = 0.4186$$

$\gamma_{sat} = 96.14 + 62.4(0.4186) : 122.26$ pcf

$$w_s = 2.65(0.5814)(62.4) = 96.14 \rightarrow \gamma_d$$

$\gamma_{sub} = 122.26 - 62.4 = 59.86$ pcf

$$w = \frac{w_w}{w_s}, \quad 0.18 = \frac{w_w}{96.14}, \quad W_w = 17.30$$

$\gamma_{tot} = 96.14 + 62.4(0.2773)$

$$v_w = \frac{17.30}{62.4} = 0.2773$$

$$s = \frac{v_w}{v_v} = \frac{0.2773}{0.4186} = 0.662, \quad 66.27\% = s$$

$$n = \frac{v_v}{v_t} = \frac{0.4186}{1} = 0.4186$$

Soil 3.

$$w = \frac{W_W}{W_S}, \quad 0.20 = \frac{W_W}{W_S}, \quad 0.20\ W_S = W_W \quad (1)$$

$$S = \frac{V_W}{V_V} = 1, \quad V_W = V_V$$

From Eq. (1)

$0.20\ V_S\ (2.65) = V_W$

$0.53\ V_S = V_W$ (2).

$V_W + V_S = 1$ (3) the soil is saturated.

Solving (3) and (2)

$0.53\ V_S = 1 - V_S$

$V_S = 0.6536$

$V_W = 0.3464$

$$e = \frac{0.3464}{0.6536} : 0.5300$$

$$n = \frac{0.3464}{1} = 0.3464.$$

$\gamma_d = 2.65(62.4)(0.6536) = 108.08$

$\gamma_v = 108.08 + 62.4\ (0.3464) = 129.69 = \gamma_{sat.}$

$\gamma_{sub} = 129.69 - 62.4 = 67.29$

Soil 4.

$$w = \frac{W_W}{W_S} = 0.20, \quad 0.20\ W_S = W_W. \qquad (1)$$

$$s = \frac{v_w}{v_v} = 0.5 \quad , \quad v_w = 0.5\ v_v. \qquad (2)$$

From (1).

$v_v + v_s = 1$

$$0.20(2.65)(62.4)(v_s) = 62.4(0.5\ v_v)$$

$$0.20(2.65)(62.4)(1-v_v) = 62.4(0.5\ v_v)$$

$$v_v = 0.5146$$

$$v_w = 0.2573$$

$$v_s = 0.4854$$

$$e = \frac{0.5146}{0.4854} = 1.060$$

$$n = \frac{0.5146}{1} = 0.5146$$

$$\gamma_d = 2.65(62.4)(0.4854) = 80.27 \text{ pcf}$$

$$\gamma_{tot} = 80.27 + 62.4(0.2573) = 96.32 \text{ pcf}$$

$$\gamma_{sat} = 80.27 + 62.4(0.5146) = 112.38 \text{ pcf}$$

$$\gamma_{sub} = 112.38 - 62.4 = 49.98 \text{ pcf}$$

c. **Soil tests**

The following tests are those most commonly used for foundation design work.

d. **Soil classification systems**

In order to have a common language, which can be understood by anyone, it is necessary to classify the soil based on common engineering properties such as grain size distribution, liquid limit and plastic limit. The two main classifi-

Test	Data Obtained	Used For
1. Specific Gravity (Gs)	Ratio between density of soil and density of water	Auxiliary factor to compute other soil properties (n,c) in consolidation studies of clay, degree of saturation of a soil, etc.
2. Atterberg Limits	Liquid Limit (LL) Plastic Limit (PL) Plastic Index (PI)	Classification of soils (cohesive) The LL can give some idea about how expansive the soil is
3. Grain Size Analysis	Grain Size Distribution curve	Classification of soils (size particle bigger than No. 200 sieve)
4. Hydrometer Analysis	Grain Size Distribution curve	Classification of soils (size particle smaller than No. 200 sieve)
5. Water Content	Content of Water in Soil	Auxiliary factor to calculate other Soil Properties
6. Void ratio and porosity	e: void ratio n: porosity	e = important (maybe the most) characteristic which can give idea about the compressibility of the soil n: gives some idea about the degree of soil density
7. Compaction Test	Optimum moisture content and maximum dry density	Used for determining the soil moisture-density relationship of a soil used for building a fill (road,dam)
8. Permeability Test	K: coefficient of permeability	Studying: quantity of leakage through and under dams Rate of consolidation Stability of slopes, embankments Seepage velocity through the soil
9. Consolidation test	: compression index : coefficient of consolidation	to obtain the amount of settlement to obtain the rate of settlement with time
10. Direct Shear Test	Shear resistance ( ) in terms of , c. = c + N + g	Determining the possible bearing capacity of the soil in foundations and earthwork
11. Triaxial compression test	Shear resistance ( ) in terms of , "c"	Making estimates of the probable bearing capacity, stability calculations of

	pore water pressure	earthworks, earth retaining structures and foundations. Analyzing stress-strain relationships of loaded soils
12. Unconfined Compression Test	Shear resistance ( ) in terms of "c"	Measuring the consistency of cohesive soils giving an idea about rupture of embankments, slopes. Determining bearing capacity of the soil
13. Vane shear test	Shear strength of the soil in terms of torsional moments	Obtaining the shearing resistance of the soil when it is not possible to run unconfined compression or tri-axial test
14. California Bearing Ratio (CBR)	CBR which is a comparative measure of the shearing resistance of the soil	Designing asphalt pavement structures
15. Plate Bearing Test	The strength of any elevation in an asphalt pavement	The design and evaluation of asphalt pavements
16. Standard Penetration test (SPT)	N" values	Obtaining the bearing capacity of soils directly
17. Pile load tests	Pile capacity" or ultimate pile load", pile head	To obtain the capacity of a pile to support loads

cation systems currently used are (1) the AASHTO (American Association of State Highway and Transportation Officials) system and (2) The Unified System. The AASHTO classification system is mainly used for disturbed soils, for instance, highway subgrades. It is not used in foundation work. Normally, the unified system (Table 23) is used in foundation design.

In the Unified System, the following symbols are used for identification.

Symbol	Description
G	Gravel
S	Sand
M	Silt
C	Clay
O	Organic silts and clay
P_t	Peat and highly organic soils
H	High plasticity
L	Low plasticity
W	Well graded
P	Poorly graded

Table 2.4 can be used for a better interpretation of the unified system when used in foundation design.

Example 2.2

The following laboratory results were obtained:

percent passing No. 200 sieve : 70%

LL = 35.

PI = 20.

Classify the soil by the unified system: Refer to Table 2.3,