Basics of Foundation Design

Electronic Edition, November 2009

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BASICS OF FOUNDATION DESIGN

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P R E F A C E

This copy of the "Red Book" is an update of previous version completed in January 2009 with amendments in March and November of, primarily Chapters 7 and 8. The text is available for free downloading from the author's web site, [**www.Fellenius.net**] and dissemination of copies is encouraged. The author has appreciated receiving comments and questions triggered by the earlier versions of the book and hopes that this revised and expanded text (now consisting of 346 pages as opposed to 275 pages) will bring additional questions and suggestions. Not least welcome are those pointing out typos and mistakes in the text to correct in future updated versions. Note that the web site downloading link includes copies several technical articles that provide a wider treatment of the subject matters.

The "Red Book" presents a background to conventional foundation analysis and design. The origin of the text is two-fold. First, it is a compendium of the contents of courses in foundation design given by the author during his years as Professor at the University of Ottawa, Department of Civil Engineering. Second, it serves as a background document to the software developed by former students and marketed in UniSoft Ltd. in collaboration with the author.

The text is not intended to replace the much more comprehensive 'standard' textbooks, but rather to support and augment these in a few important areas, supplying methods applicable to practical cases handled daily by practicing engineers.

The text concentrates on the static design for stationary foundation conditions, though the topic is not exhaustively treated. However, it does intend to present most of the basic material needed for a practicing engineer involved in routine geotechnical design, as well as provide the tools for an engineering student to approach and solve common geotechnical design problems. Indeed, the author makes the somewhat brazen claim that the text actually goes a good deal beyond what the average geotechnical engineer usually deals with in the course of an ordinary design practice.

The text emphasizes two main aspects of geotechnical analysis, the use of effective stress analysis and the understanding that the vertical distribution of pore pressures in the field is fundamental to the relevance of any foundation design. Indeed, foundation design requires a solid understanding of the in principle simple, but in reality very complex interaction of solid particles with the water and gas present in the pores, as well as an in-depth recognition of the most basic principle in soil mechanics, the *principium* of effective stress.

To avoid the easily introduced errors of using buoyant unit weight, the author recommends to use the straight-forward method of calculating the effective stress from determining separately the total stress and pore pressure distributions, finding the effective stress distribution quite simply as a subtraction between the two. The method is useful for the student and the practicing engineer alike.

The text starts with a brief summary of phase system calculations and how to determine the vertical distribution of stress underneath a loaded area applying the methods of 2:1, Boussinesq, and Westergaard.

The author holds that the piezocone (CPTU) is invaluable for the engineer charged with determining a soil profile and estimating key routine soil parameters at a site. Accordingly, the second chapter gives a background to the soil profiling from CPTU data. This chapter is followed by a summary of methods of routine settlement analysis based on change of effective stress. More in-depth aspects, such as creep and lateral flow are very cursorily introduced or not at all, allowing the text to expand on the influence of adjacent loads, excavations, and groundwater table changes being present or acting simultaneously with the foundation analyzed.

Consolidation analysis is treated sparingly in the book, but for the use and design of acceleration of consolidation by means of vertical drains, which is a very constructive tool for the geotechnical engineers that could be put to much more use than is the current case.

Earth stress – earth pressure – is presented with emphasis on the Coulomb formulae and the effect of sloping retaining walls and sloping ground surface with surcharge and/or limited area surface or line loads per the requirements in current design manuals and codes. Bearing capacity of shallow foundations is introduced and the importance of combining the bearing capacity design analysis with earth stress and horizontal and inclined loading is emphasized. The Limit States Design or Load and Resistance Factor Design for retaining walls and footings is also presented in this context.

The design of piles and pile groups is only very parsimoniously treated in most textbooks. This text, therefore, spends a good deal of effort on presenting the static design of piles considering capacity, negative skin friction, and settlement, emphasizing the interaction of load-transfer and settlement (downdrag), which the author has termed "the Unified Piled Foundation Design", followed by a separate chapter on the analysis of static loading tests. The author holds the firm conviction that the analysis is not completed until the results of the test in terms of load distribution is correlated to an effective stress analysis.

Basics of dynamic testing is presented. The treatment is not directed toward the expert, but is intended to serve as background to the general practicing engineer.

Frequently, many of the difficulties experienced by the student in learning to use the analytical tools and methods of geotechnical engineering, and by the practicing engineer in applying the 'standard' knowledge and procedures, lie with a less than perfect feel for the terminology and concepts involved. To assist in this area, a brief chapter on preferred terminology and an explanation to common foundation terms is also included.

Everyone surely recognizes that the success of a design to a large extent rests on an equally successful construction of the designed project. However, many engineers appear to oblivious that one key prerequisite for success of the construction is a dispute-free interaction between the engineers and the contractors during the construction, as judged from the many acutely inept specs texts common in the field. The author has added a strongly felt commentary on the subject at the end of the book.

A relatively large portion of the space is given to presentation of solved examples and problems for individual practice. The problems are of different degree of complexity, but even when very simple, they intend to be realistic and have some relevance to the practice of engineering design.

Finally, most facts, principles, and recommendations put forward in this book are those of others. Although several pertinent references are included, these are more to indicate to the reader where additional information can be obtained on a particular topic, rather than to give professional credit. However, the author is well aware of his considerable indebtedness to others in the profession from mentors, colleagues, friends, and collaborators throughout his career, too many to mention. The opinions and sometimes strong statements are his own, however, and the author is equally aware that time might suggest a change of these, often, but not always, toward the mellow side.

The author is indebted to Dr. Mauricio Ochoa, PE, for his careful review of the new version after it was first uploaded in January, and for his informing the author about the many typos in need of correction as well as making many most pertinent and much appreciated suggestions for clarifications and add-ons.

Sidney November 2009

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CHAPTER 1

CLASSIFICATION, EFFECTIVE STRESS, and STRESS DISTRIBUTION

1.1 Introduction

Before a foundation design can be embarked on, the associated soil profile must be well established. The soil profile is compiled from three cornerstones of information**:**

- in-situ testing results, particularly continuous tests, such as the CPTU
  and laboratory classification and testing of recovered soil samples
- pore pressure (piezometer) observations
- assessment of the overall site geology

Projects where construction difficulties, disputes, and litigations arise often have one thing in common**:** borehole logs were thought sufficient when determining the soil profile.

The essential part of the foundation design is to devise a foundation type and size that will result in acceptable values of deformation (settlement) and an adequate margin of safety to failure (the degree of utilization of the soil strength). Deformation is ***due to change*** of effective stress and soil strength is ***proportional*** to effective stress. Therefore, all foundation designs must start with determining the effective stress distribution of the soil around and below the foundation unit. That distribution then serves as basis for the design analysis.

Effective stress is the total stress minus the pore pressure (the water pressure in the voids). Determining the effective stress requires that the basic parameters of the soil are known. That is, the pore pressure distribution and the Phase Parameters, such as water content[1] and total density. Unfortunately, far too many soil reports lack adequate information on both pore pressure distribution and phase parameters.

1.2 Phase Parameters

Soil is an "interparticulate medium". A soil mass consists of a heterogeneous collection of solid particles with voids in between. The solids are made up of grains of minerals or organic material. The voids contain water and gas. The water can be clean or include dissolved salts and gas. The gas is similar to ordinary air, sometimes mixed with gas generated from decaying organic matter. The ***solids***, the ***water***, and the ***gas*** are termed the three **phases** of the soil.

To aid a rational analysis of a soil mass, the three phases are "disconnected". Soil analysis makes use of basic definitions and relations of volume, mass, density, water content, saturation, void ratio, etc., as indicated in Fig. 1.1. The definitions are related and knowledge of a few will let the geotechnical engineer derive all the others.

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[1] The term "moisture content" is sometimes used in the same sense as "water content". Most people, even geotechnical engineers, will consider that calling a soil "moist", "damp", or "wet" signifies different conditions of the soils (though undefined). It follows that laymen, read lawyers and judges, will believe and expect that "moisture content" is something different to "water content", perhaps thinking that the former indicates a less than saturated soil. However, there is no difference, It is only that saying "moisture" instead of "water" implies a greater degree of sophistication of the User, and, because the term is not immediately understood by the layman, its use sends the message that the User is in the "know", a specialist of some stature. Don't fall into that trap. Use "water content". Remember, we should strive to use simple terms that laymen can understand. (Quoted from Chapter 10).

The need for phase systems calculation arises, for example, when the engineer wants to establish the effective stress profile at a site and does not know the total density of the soil, only the water content. Or, when determining the dry density and degree of saturation from the initial water content and total density in a Proctor test. Or, when calculating the final void ratio from the measured final water content in an oedometer test. While the water content is usually a measured quantity and, as such, a reliable number, many of the other parameters reported by a laboratory are based on an assumed value of solid density, usually taken as 2,670 kg/m^3 plus the assumption that the tested sample is saturated. The latter assumption is often very wrong and the error can result in significantly incorrect soil parameters.

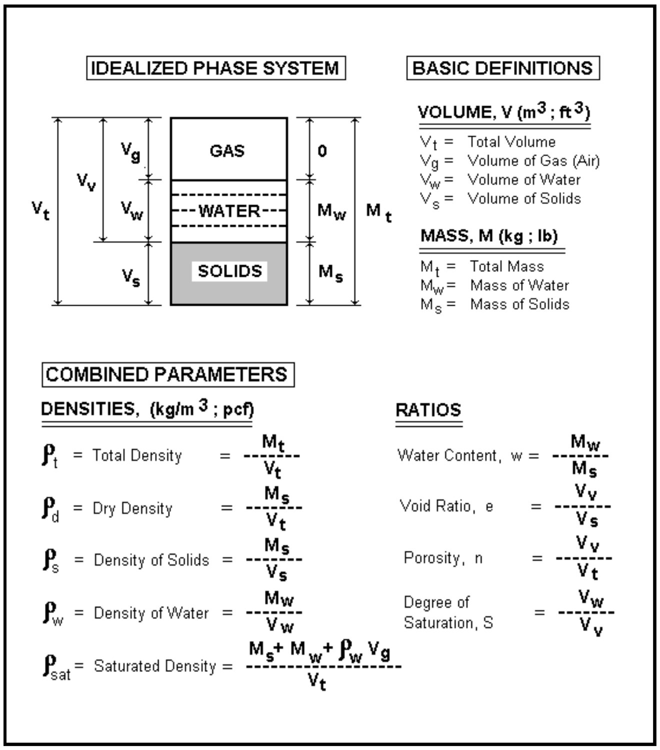

Fig. 1.1 The Phase System definitions

Starting from the definitions shown In Fig. 1.1, a series of useful formulae can be derived, as follows:

(1.1) $$S = \frac{w}{\rho_w} \times \frac{\rho_s \rho_d}{\rho_s - \rho_d} = \frac{w}{e} \times \frac{\rho_s}{\rho_w}$$

(1.2) $$w = S \rho_w \times \frac{\rho_s - \rho_d}{\rho_s \rho_d} = \frac{\rho_t}{\rho_d} - 1$$

(1.3) $$\rho_{SAT} = \frac{M_w + \rho_w V_g + M_s}{V_t} = \rho_d + \rho_w (1 - \frac{\rho_d}{\rho_s}) = \frac{\rho_d}{\rho_s}(\rho_s + e\rho_w) = \rho_s \frac{1+w}{1+e}$$

(1.4) $$\rho_d = \frac{\rho_s}{1+e} = \frac{\rho_t}{1+w} = \frac{\rho_w\, S}{w + \frac{\rho_w}{\rho_s} S}$$

(1.5) $$\rho_t = \frac{\rho_s(1+w)}{1+e} = \rho_d(1+w)$$

(1.6) $$e = \frac{n}{1-n} = \frac{\rho_s}{\rho_d} - 1 = \frac{w}{S} \times \frac{\rho_s}{\rho_w}$$

(1.7) $$n = \frac{e}{1 = e} = 1 - \frac{\rho_d}{\rho_s}$$

When performing phase calculations, the engineer normally knows or assumes the value of the density of the soil solids, ρ_t. Sometimes, the soil can be assumed to be fully saturated (however, presence of gas in fine-grained soils may often result in their not being fully saturated even well below the groundwater table; organic soils are rarely saturated and fills are almost never saturated). Knowing the density of the solids, ρ_t, and one more parameter, such as the water content, all other relations can be calculated using the above formulae (they can also be found in many elementary textbooks, or easily be derived from the basic definitions and relations*).

The density of water is usually 1,000 kg/m^3. However, temperature and, especially, salt content can change this value by more than a few percentage points. For example, places in Syracuse, NY, have groundwater that has a salt content of up to 16 % by weight. Such large salt content cannot be disregarded when determining distribution of pore pressure and effective stress.

While most silica-based clays can be assumed to made up of particles with a solid density of 2,670 kg/m^3 (165 pcf), the solid density of other clay types may be quite different. For example, calcareous clays can have a solid density of 2,800 kg/m^3 (175 pcf). However, at the same time, calcareous soils, in particular coral sands, can have such a large portion of voids that the bulk density is quite low compared to that of silica soils. Indeed, mineral composed of different material can have a very different mechanical response to load. For example, just a few percent of mica in a sand will make the sand weaker and more compressible, all other aspects equal (Gilboy 1928).

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*) The program UniPhase provides a fast and easy means to phase system calculations. The program is available for free downloading as "176 UniPhase.zip" from the author's web site [www.Fellenius.net]. When working in UniPile and UniSettle, or some other geotechnical program where input is total density, the User normally knows the water content and has a good feel for the solid density. The total density value to input is then the calculated by UniPhase. When the User compiles the result of a oedometer test, the water content and the total density values are normally the input and UniPhase is used to determine the degree of saturation and void ratio.

Organic materials usually have a solid density that is much smaller than inorganic material. Therefore, when soils contain organics, their average solid density is usually smaller than for inorganic materials.

Soil grains are composed of minerals and the solid density varies between different minerals. Table 1.1 below lists some values of solid density for minerals that are common in rocks and, therefore, common in soils. (The need for listing the densities in both units could have been avoided by giving the densities in relation to the density of water, which is called "relative density" in modern international terminology and "specific gravity" in old, now abandoned terminology. However, presenting instead the values in both systems of units avoids the conflict of which of the two mentioned terms to use; either the correct term, which many would misunderstand, or the incorrect term, which all understand, but the use of which would suggest ignorance of current terminology convention. Shifting to a home-made term, such as "specific density", which sometimes pops up in the literature, does not make the ignorance smaller).

Table 1.1 Solid Density for Minerals

Mineral Type	**Solid Density** kg/m^3	pcf
Amphibole	≅3,000+	190
Calcite	2,800	180
Quartz	2,670	165
Mica	2,800	175
Pyrite	5,000	310
Illite	2,700	170

Depending on the soil void ratio and degree of saturation, the total density of soils can vary within wide boundaries. Tables 1.2 and 1.3 list some representative values.

Table 1.2 Total saturated density for some typical soils

Soil Type	**Saturated** Total Density Metric (SI) units kg/m^3	English units pcf
Sands; gravels	1,900 - 2,300	118 - 144
Sandy Silts	1,700 - 2,200	105 - 138
Clayey Silts and Silts	1,500 - 1,900	95 - 120
Soft clays	1,300 - 1,800	80 - 112
Firm clays	1,600 - 2,100	100 - 130
Glacial till	2,100 - 2,400	130 - 150
Peat	1,000 - 1,200	62 - 75
Organic silt	1,200 - 1,900	75 - 118
Granular fill	1,900 - 2,200	118 - 140

Table 1.3 Total saturated density for uniform silica sand

"Relative" Density	Total Saturated Density kg/m^3	Water Content %	Void Ratio (**subjective**)
Very dense	2,200	15	0.4
Dense	2,100	19	0.5
Compact	2,050	22	0.6
Loose	2,000	26	0.7
Very loose	1,900	30	0.8

1.3 Soil Classification by Grain Size

All languages describe "clay", "sand", "gravel", etc., which are terms primarily based on grain size. In the very beginning of the 20th century, Atterberg, a Swedish scientist and agriculturalist, proposed a classification system based on specific grain sizes. With minor modifications, the Atterberg system is still used and are the basis of the International Geotechnical Standard, as listed in Table 1.4

Table 1.4 Classification of Grain Size Boundaries (mm)

Clay		<	0.002
Silt			
Fine silt	0.002	<	0.006
Medium silt	0.006	<	0.002
Coarse silt	0.002	<	0.06
Sand			
Fine sand	0.06	<	0.2
Medium sand	0.2	<	0.6
Coarse sand	0.6	<	2.0
Gravel			
Fine gravel	2	<	6
Medium gravel	6	<	20
Coarse gravel	20	<	60
Cobbles	60	<	200
Boulders	200	<	

Soil is made up of grains with a wide range of sizes and is named according to the portion of the specific grain sizes. Several classification systems are in use, e.g., ASTM, AASHTO, and International Geotechnical Society. Table 1.5 indicates the latter, which is also the Canadian standard (CFEM 1992).

The International (and Canadian) naming convention differs in some aspects from the AASHTO and ASTM systems which are dominant in US practice. For example, the boundary between silt and sand in the international standard is at 0.060 mm, whereas the AASHTO and ASTM standards place that boundary at Sieve #200 which has an opening of 0.075 mm. Table 1.5 follows the International standard. For details and examples of classification systems, see Holtz and Kovacs (1981).

Table 1.5 Classification of Grain Size Boundaries (mm)

"Noun" (Clay, Silt, Sand, Gravel)	35		< 100 %
"and" plus noun	20 %	<	35 %
"adjective" (clayey, silty, sandy)	10%	<	20%
"trace" (clay, silt, sand, gravel)	1 %	<	10 %

The grain size distribution for a soil is determined using a standard set of sieves. Conventionally, the results of the sieve analysis are plotted in diagram drawn with the abscissa in logarithmic scale as shown in Fig. 1.2. The three grain size curves, A, B, and C, shown are classified according to Table 1.5 as A: "*Sand trace gravel*". B: Sandy clay some silt, and C: would be named clayey sandy silt some gravel. Samples A and B are alluvial soils and are suitably named. However, Sample C, having 21 %, 44 %, 23 %, and 12 % of clay, silt, sand, and gravel size grains, is from a glacial till for which soil all grain size portions are conventionally named as adjective to the noun “till”, i.e., the sample is a "*clayey sandy silty glacial till*".

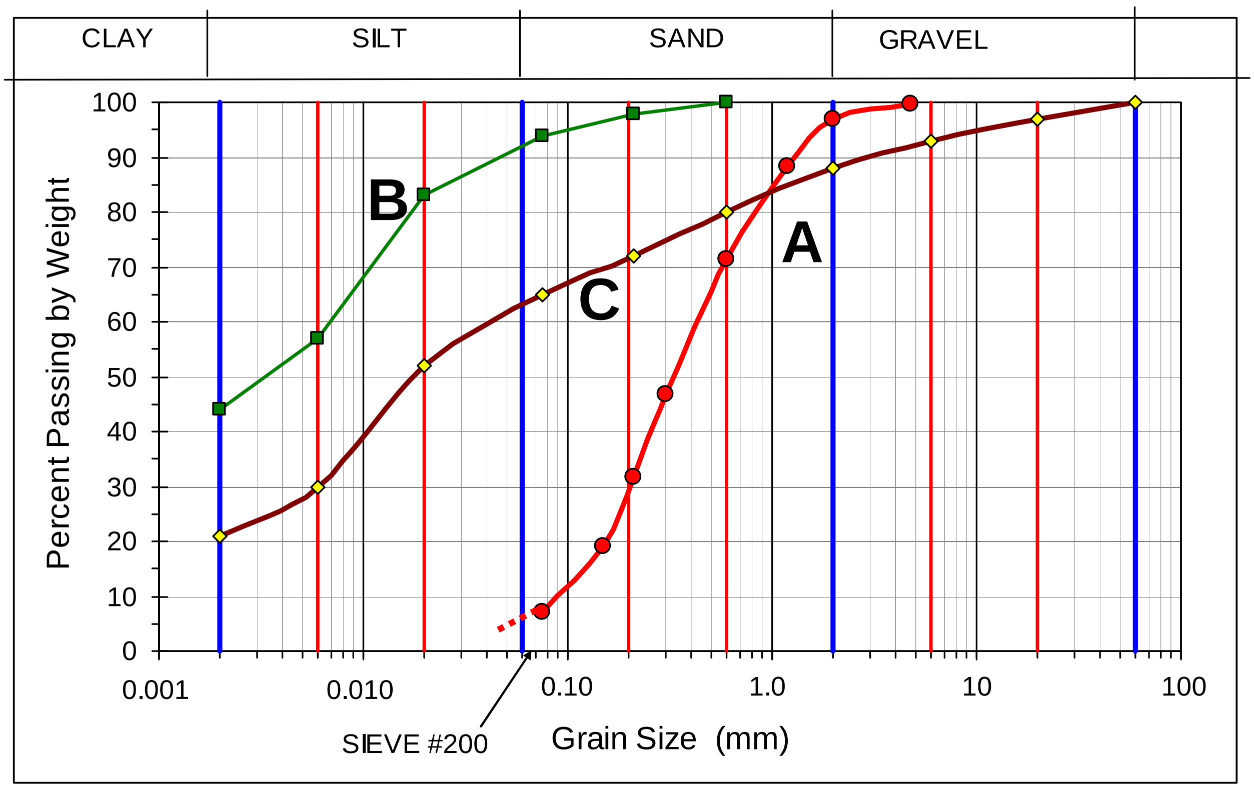

Fig. 1.2 Grain size diagram

Sometimes grain-size analysis results are plotted in a three-axes diagram called "ternary diagram" as illustrated in Fig. 1.3, which allows for a description according to grain size portions to be obtained at a glance.

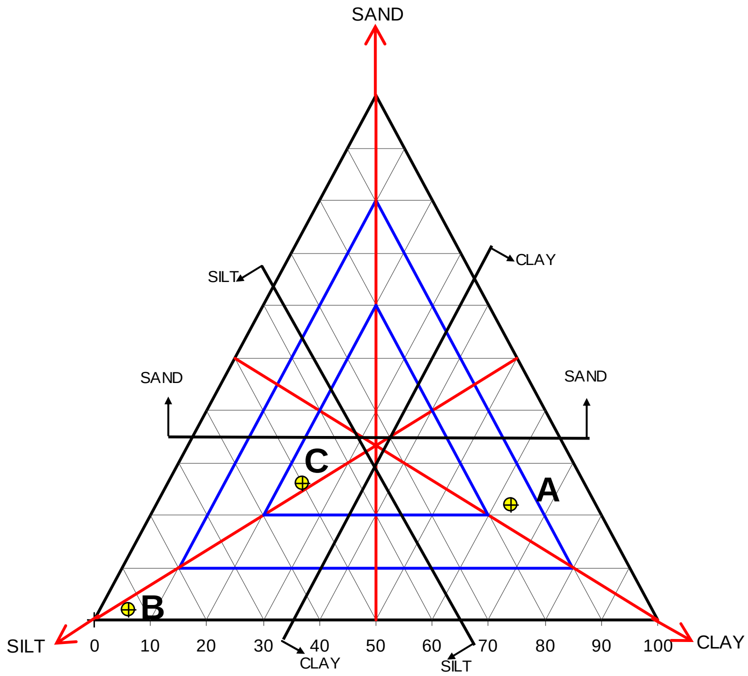

Fig. 1.3 Example of a ternary diagram

1.4. Effective Stress

As mentioned, effective stress is the total stress minus the pore pressure (the water pressure in the voids). Total stress at a certain depth is the easiest of all values to determine as it is the summation of the total unit weight (total density times gravity constant) and height. If the distribution of pore water pressure at the site is hydrostatic, then, the pore pressure at that same point is the height of the water column up to the **groundwater table**, which is defined as the uppermost level of zero pore pressure. (Notice, the soil can be partially saturated also above the groundwater table. Then, because of capillary action, pore pressures in the partially saturated zone above the groundwater table may be negative. In routine calculations, pore pressures are usually assumed to be zero in the zone above the groundwater table).

Notice, however, the pore pressure distribution is not always hydrostatic, far from it actually. Hydrostatic pore water pressure has a vertical pressure gradient that is equal to unity (no vertical flow). Similarly, a site may have a downward gradient from a perched groundwater table, or an upward gradient from an **aquifer** down below (an aquifer is a soil layer containing free-flowing water).

Frequently, the common method of determining the effective stress, $\Delta\sigma'$ contributed by a soil layer is to multiply the buoyant unit weight, γ', of the soil with the layer thickness, Δh, as indicated in Eq. 1.8a.

(1.8a) $$\Delta\sigma' = \gamma'\Delta h$$

The effective stress at a depth, σ'_z is the sum of the contributions from the soil layers, as follows.

(1.8b) $$\sigma'_z = \sum(\gamma'\Delta h)$$

The buoyant unit weight, γ', is often thought to be equal to the total unit weight (γ_t) of the soil minus the unit weight of water (γ_w) which presupposes that there is no vertical gradient of water flow in the soil, $i = 0$, defined below. However, this is only a special case. Because most sites display either an upward flow, maybe even artesian (the head is greater than the depth), or a downward flow, calculations of effective stress must consider the effect of the gradient — the buoyant unit weight is a function of the gradient in the soil as follows.

(1.8c) $$\gamma' = \gamma_t - \gamma_w (1 - i)$$

where
σ' = effective overburden stress
Δh = layer thickness
γ' = buoyant unit weight
γ_t = total (bulk) unit weight
γ_w = unit weight of water
i = upward gradient

The **gradient**, ***i***, is defined as the difference in head between two points divided by the distance the water has to flow between these two points. Upward flow gradient is negative and downward flow gradient is positive. For example, if, for a particular case of artesian condition, the gradient is nearly equal to -1, then, the buoyant weight is nearly zero. Therefore, the effective stress is close to zero, too, and the soil has little or no strength. This is the case of "quick sand", which is not a particular type of sand, but a soil, usually a silty fine sand, subjected to a particular pore pressure condition.

The gradient in a non-hydrostatic condition is often awkward to determine. However, the difficulty can be avoided, because the effective stress is most easily found by calculating the total stress and the pore water pressure separately. The effective stress is then obtained by simple subtraction of the latter from the former.

Note, the difference in terminology—effective *stress* and pore *pressure*—which reflects the fundamental difference between forces in soil as opposed to in water. Stress is directional, that is, stress changes depending on the orientation of the plane of action in the soil. In contrast, pressure is omni-directional, that is, independent of the orientation. Don't use the term "*soil pressure*", it is a misnomer.

The soil stresses, total and effective, and the water pressures are determined, as follows: The **total vertical stress** (symbol σ_z) at a point in the soil profile (also called "total overburden stress") is calculated as the stress exerted by a soil column determined by multiplying the soil total (or bulk) unit weight times the height of the column (or the sum of separate weights when the soil profile is made up of a series of separate soil layers having different unit weights). The symbol for the total unit weight is γ_t (the subscript "t" stands for "total").

(1.9) $$\sigma_z = \gamma_t z \qquad \text{or:} \qquad \sigma_z = \Sigma\, \Delta\sigma_z = \Sigma\, (\gamma_t\, \Delta h)$$

Similarly, the **pore pressure** (symbol u), if measured in a stand-pipe, is equal to the unit weight of water, γ_w, times the height of the water column, h, in the stand-pipe. (If the pore pressure is measured directly, the head of water is equal to the pressure divided by the unit weight of the water, γ_w).

(1.10) $$u = \gamma_w h$$

The height of the column of water (the head) representing the water pressure is usually not the distance to the ground surface nor, even, to the groundwater table. For this reason, the height is usually referred to as the "phreatic height" or the "piezometric height" to separate it from the depth below the groundwater table or depth below the ground surface.