FOUNDATION ENGINEERING

Geotechnical Principles and Practical Applications

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RICHARD L. HANDY

Foundation Engineering

About the Author

Richard L. Handy is a Distinguished Professor Emeritus in the Department of Civil, Construction and Environmental Engineering at Iowa State University. A sought-after teacher, he served as the major professor for over 60 graduate students, many of whom have gone on to make major contributions in geotechnical engineering. A large number of former students and associates recently collaborated to endow a Professorship in his name, and a book of collected papers was issued in his honor.

Dr. Handy may be best known as the inventor of Borehole Shear Tests that perform in-situ measurements of cohesion and friction in soils and rocks. The soil test was used in snow when he and six engineering students were conducting research on an epic voyage of a large ship in the ice-bound Northwest Passage. They also observed the catenary shape of an igloo, which he later adapted to solve a problem that had intrigued Terzaghi, to mathematically define arching action in soils. The analysis revealed that conventional analyses are on the unsafe side and explained a wall failure where there were four fatalities. It received the Thomas A. Middlebrooks Award of the American Society of Civil Engineers.

Dr. Handy also was active in geology. He proposed a variable-wind hypothesis to explain the distribution of wind-blown silt (loess), and showed that the rate of growth of a river meander slows down in time according to a *first-order rate equation*. He then applied the same equation to rates of primary and secondary consolidation in engineering. In recognition of his contributions to geology he was elected a Fellow in the Geological Society of America and the American Association for the Advancement of Science.

Known for his sense of humor, Dr. Handy liked to point out that it is better to have a joke that turns out to be an invention than an invention that turns out to be a joke. His *The Day the House Fell*, published by the American Society of Civil Engineers, Reston, VA, for non-engineers, became a best-seller. His book *FORE and the Future of Practically Everything* published by Moonshine Cove Publishing, Abbeville, SC, adapts first-order rate equations to practically everything, including track world records and baseball home runs.

Dr. Handy also founded and is the Past President of a company that bears his name. The company manufactures and sells geotechnical instruments, with emphasis on in-situ test methods that were created and developed under his direction.

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Contents

Preface

The thread of learning is strengthened through understanding.

Soil is the most abundant construction material, and also the most variable. Early engineering tests of soils involved the resistance to jabbing with a heel or probing with a stick. Probing then developed along two different approaches, hammering and pushing. Both can provide useful information, but the tests do not accurately simulate soil behavior under or near a foundation.

Targeted Tests

A targeted test is one that is directly applicable for design. An example is a pile load test that relates settlement to the applied load. A load test also can be continued to determine an ultimate bearing capacity. A *plate bearing test* can similarly model a shallow foundation, but scaling down makes the results less directly applicable.

A third approach is to obtain and preserve soil samples in their natural state and test them in a laboratory. The problem then becomes how to collect a soil sample without disturbing it, as even the removal of a confining pressure can effect a change.

An Early Targeted Test

The laboratory consolidation test devised by Karl Terzaghi was targeted to measure soil behavior as it may influence foundation settlement. Observations and measurements made during the tests then led to an important spinoff, the concept that pore water pressure subtracts from normal stress and therefore from friction. That now is considered by many to be the entry point for modern soil mechanics.

A Simple Targeted Test

The plastic limit test must be one of the simplest soil tests ever devised, and results are part of most engineering soil classifications. The test uses hand power to roll out, bunch up, and re-roll threads of soil until it dries out and crumbles. The transition moisture content is the plastic limit. It not only depends on a soil clay content but also on its clay mineralogy, and the test was devised long before it became recognized that there is a clay mineralogy.

Two Requirements in Foundation Design

Requirements are as follows: (1) Settlement must be uniform and must not be excessive, and (2) a foundation must not punch down into the ground in a *bearing capacity* failure. If a near-surface soil is not adequate, deep foundations can transfer loads downward to bear on rock or in more competent soil. A complication for deep foundations is that they can derive support from two sources, end-bearing and side friction, and the two contributions are not separated with ordinary top-load tests. They can be isolated by using an expandable *Osterberg cell* to push up from the bottom. Pile behavior and integrity also can be examined with impacts and sound waves.

A New Role for Lateral Soil Pressure

Laboratory triaxial shear tests define relationships between lateral confining pressure and soil strength and bearing capacity. Field tests have led to the discovery that a high lateral pressure imposed on saturated soil can work a temporary change in the soil behavior, and the change can be an important factor affecting foundation settlement. That development is given special attention in the last chapter of this book.

Soil Origins and Clay Mineralogy

One mistake is one too many, but mistakes happen. In foundation engineering a mistake sometimes can be attributed to a disconnect between engineering purpose and site geology. Most soil is hidden away, and geology and soil science, which emphasizes changes caused by weathering, can reveal where and what to look for. For example, expansive clays that cause no end of engineering problems are far more common than can be shown on small-scale engineering soil maps. The geotechnical engineer who is not cognizant of geological relationships and engineering consequences is riding on one wheel.

The Engineer as Teacher

Case history. An architect designed a building with exterior walls of Italian marble, and was in no mood to spend money for deep foundations or anything else that "would not show." He had to be convinced that without deep foundations, the consequences would show.

Introduction

Some Heroes in Geotechnical/Foundation Engineering

Archimedes (287–212 BC) famously discovered "Archimedes Principle" of buoyancy, which affects soil weight and frictional resistance to sliding. He was killed by a Roman soldier who had no appreciation.

Charles-Augustin de Coulomb (1736–1806) was a French military engineer, and while being in charge of building a fort on the island of Martinique he observed that sand grains must have friction or they would not make a respectable pile. He also reasoned that clay must have cohesion or it would not stand unsupported in a steep bank. Those observations led to the "Coulomb equation" for soil shear strength. Over 100 years later, Karl Terzaghi added the influence from pore water pressure that tends to push grains apart.

Coulomb also derived an equation for the lateral force from soil pushing against a retaining wall. The equation, and a later equation proposed by Rankine, puts the maximum soil pressure at the base of a wall but tests conducted by Terzaghi indicate that it is more likely to be zero. That is no small error because raising the height of the center of pressure increases the overturning moment, which makes the Coulomb and Rankine solutions the unsafe side.

Coulomb's Law

After retiring from the Army, Coulomb entered a contest to invent a better marine compass. He did not win the contest but invented the torsion balance that substitutes twisting of fine wires for knife edges. Coulomb then experimented with his instrument to measure tiny forces from electrical charges, electricity being big at the time, and discovered that forces between two electrically charged particles depend on *square* of the separation distance. Coulomb's Law also governs space travel and orbiting distances of satellites.

William John Macquorn Rankine (1820–1872) was a professor at the University of Glasgow. He was most famous for his analysis of the thermodynamics of steam engines, but he also had a simple solution for soil pressures against retaining walls. He defined an *active state* for soil that is acting to retain itself, and a *passive state* for soil that is being pushed. Rankine's and Coulomb's analyses can give the same answers, but both have a limitation.

Christian Otto Mohr (1835–1918) was a German bridge engineer and a professor of mechanics at Stuttgart and Dresden. He devised the "Mohr circle" graphical method for depicting soil stresses, and the “Mohr envelope” defines stress conditions for shear failure. It supports Coulomb’s soil shear strength equation.

Ludwig Prandtl (1875–1953) was a professor at the University of Hanover, most famous for his contributions to aerodynamics. He also developed a theory for the resistance of metal to penetration by a punch based on a curved failure surface called a *log spiral*.

Karl Terzaghi (1883–1963) was from Austria and was educated in mechanical engineering. However, he also was interested in geology and became a professional geologist. He then used an engineering approach for soil problems, for example, by applying Prandtl’s *log spiral* to shallow foundation bearing capacity, a theory and approach that still are widely used. As a professor at Robert College in Turkey, Terzaghi devised the consolidation test and theory for predicting foundation settlement. Those observations led to defining soil shear strength in terms of *effective stress* that takes into account the influence from excess pore water pressure.

Terzaghi also observed that because clay particles must be soft and yielding, contact areas between particles can be expected to vary depending on the contact pressure, which might explain the linear relationship between friction and normal stress. It is the concept that made its way back into mechanical engineering to explain friction. It also can explain the function of a lubricant, to keep surfaces separated.

Geotechnical engineering has grown and continues to grow, and many investigators and practitioners continue to make important contributions. Broad interests, curiosity, imagination, and an interest in working with a complex and somewhat unpredictable natural material are part of the toolkit.

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Karl Terzaghi (1883–1963). Pencil sketch by Tauseef Choudry.

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CHAPTER 1

Defining What Is There

Geology and Foundation Engineering

1.1. The Three Most Common Construction Materials

Concrete has a recipe, steel is made to order and goes by number, and soil and rock are what is there. A first requirement in foundation engineering therefore is to determine and characterize what is there. That requires knowledge or at least familiarity with site geology.

For example, soils of river floodplains are likely to occur as sedimentary layers. A common sequence is clay layers on top of sand layers on top of gravel, as flow velocities decreased during stages of deposition. Soils deposited by winds are more likely to transition horizontally, from sand dunes adjacent to a source to thick, highly erodible deposits of silt that has such an open structure that when saturated with water can collapse under its own weight. With increasing distance from a source the silt is transitional to clay that is particularly troublesome because it is expansive and can lift building foundations in the presence of water.

Procedures used for identifying, boring, probing, sampling, and/or testing vary with different kinds of deposits because of the variability and focus on particular engineering properties. Core samples obtained by pushing a steel tube into the soil are commonly called "undisturbed," but the term is shielded by optimism. A soil that is relieved of existing pressure will respond by simply expanding, so it, to some degree, is disturbed. It also is not possible to accurately reproduce field conditions in a laboratory if, as often is the case, those conditions are not known and are difficult to measure. Many important engineering soil properties are inherited, for example, from having been buried under a thousand meters of glacial ice or a hundred meters or more of soil that has been removed by erosion.

Soils usually are investigated with borings, but there can be no guarantee of what engineering perils may exist between the borings. This limitation is included in every geotechnical report, and usually is written with the assistance of an attorney. Geological awareness can help to make sense out of a situation and can be critical.

Supplementary data can be obtained with geophysical seismic (ground echo) or electrical resistivity tests, and with ground-penetrating radar. Simplest to interpret is the radar that prints out a running log as the instrument is being pulled over the ground, but a limitation is that the depth scale depends on the moisture content, and penetration is limited.

Most important can be observations of soils and rocks exposed by erosion and occurring in outcrops and excavations. Airphotos and drone photos can reveal patterns that are easily overlooked from the ground. Interpretation depends on a sound knowledge and appreciation for geological origins.

1.2. Two Classes of Foundations

Foundations are described as shallow if they bear on near-surface soils or rocks, and deep if they extend down to firmer soil layers or rock. Deep foundations are more likely to be used to support heavy structures such as multistory buildings, and can be effective even if bedrock support is not available. Shallow foundations may be suitable for supporting lighter weight structures, depending on the firmness of the soil.

Support of Deep Foundations

Two sources of support for a deep foundation are end bearing at the base and shearing resistance along the sides, usually referred to as a *skin friction.* As the contributions involve different soil properties and are unlikely to peak out together, they are analyzed and/or measured separately, as side resistance often peaks out and starts to decline before end bearing is fully mobilized. A further complication is that if the ground settles, usually as a consequence of lowering the groundwater table, then skin friction is reversed, so it pushes down instead of up.

Expansive Clays Can Be Expensive Clays

Near-surface soils in many areas of the world often include clay minerals that expand when wet and shrink when dry, affecting pavements and foundations. The problem is intensified because dry weather is preferred for construction, when the clays are dry and deceptively hard but poised and ready to expand. Floors and foundations usually are raised unevenly, so walls develop diagonal cracks, and door and window frames can be distorted so they no longer are rectangular.

Expansive clays are the most costly problem in geotechnical, highway and foundation engineering, with a tally running into billions of dollars annually in the United States alone. But there are remedies and solutions.

End Bearing on Rock

Solid rock can be an ideal support for foundations but basement excavations may be too costly to be practical. Solid rock can lay buried underneath weathered rock and rock fragments and/or geologically younger soil deposits, so these can be penetrated with borings or driven piles that may require end protection with hardened steel tips.

A particularly serious problem can be shallow underground caverns or mine openings that remain undetected until a heavy load is applied. Caverns are created in limestone where infiltrating seepage water that has been rendered slightly acidic by dissolved carbon dioxide and concentrated at a groundwater table. The caverns therefore may be relatively deep and difficult to detect. In geological time as nearby valleys are eroded deeper, the groundwater level is lowered, so caverns become accessible for spelunking. However, vertical channels appropriately called "glory holes" may connect different cavern levels.

Even shallow limestone may hold some surprises if it has been weathered along vertical fractures that become filled with clay. As this is associated with surface weathering and development of a "soil profile," it is discussed later in this chapter. It is the shallow clay pockets, caverns, and mine openings that are most likely to cause problems.

Ground Improvement

Ground improvement means to improve what is there. A simple procedure is to let a pile of soil stand in for a future foundation until settlement stops, then remove the soil and build the structure. This procedure is particularly useful when a series of similar structures such as apartment houses are to be constructed so that after settlement is complete, the soil can be moved on to the next site. Engineering still is required to determine an appropriate preload pressure, measure settlement, and determine if a well system may be required to assist in the removal of water as it is squeezed out of the soil.

Dynamic compaction: Layers of soil can be spread and compacted with rollers or vibrators to create a structural fill. This procedure can dominate cut-and-fill operations for roads and highways, and can be used for foundations. Careful selection of a satisfactory fill soil is required, and standardized test procedures are used to determine appropriate soil moisture content and acceptance criteria for testing and compaction.

Deep dynamic compaction is more likely to be used to process soil in situ in preparation for a future foundation load. It involves using a crane to repeatedly lift and drop a heavy weight to pound the soil into submission. It is best adapted to rural areas.

Chemical soil stabilization can be achieved by mixing soil, Portland cement, or chemical lime prior with soil and compacting it in layers. For deep in situ stabilization, the lime can be introduced into open borings or mixed with the soil in situ in the borings. Lime reacts chemically with expansive clay minerals, so they harden and become non-expansive.

Procedures for ground improvement have received considerable attention in recent years, and are discussed in more detail in the last chapter in this book.

1.3. Residual Soils

Granite mountains are the ultimate source for most sand. Most granite is igneous rock, which means that at one time it was molten, and then slowly solidified at great depth. Therefore, individual crystals are sand-size and larger. Clear grains are quartz, and pink or white grains are feldspars that are more readily weathered to form clay. As feldspars chemically weather to clay, the grains expand, and granite becomes separated into grains of sand.

Travel Is Wearing

Sand is readily moved by gravity, wind, or water. Close to the source, the sand usually has about the same color as granite because it has the same mineralogical composition, about 25 percent quartz and the remainder feldspars. Farther from a

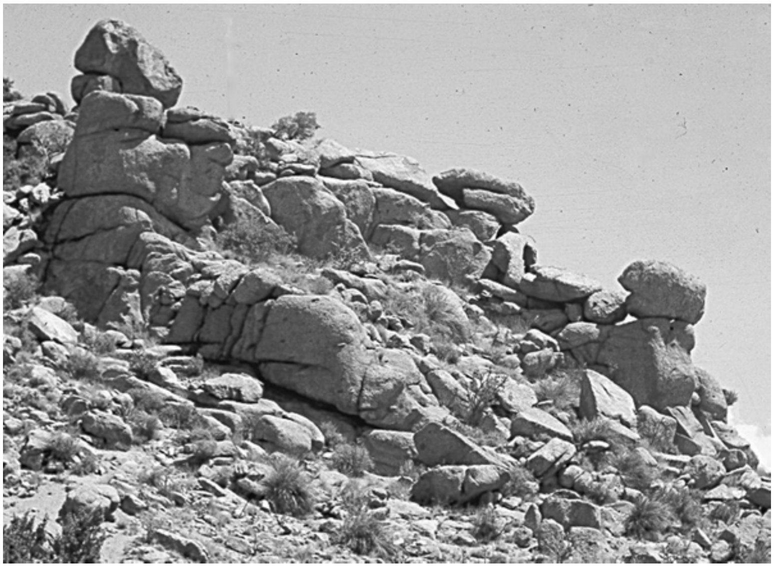

Figure 1.1 Granite is a major component in most mountain ranges and disintegrates along cracks to leave rounded boulders and sand. (Image source: *Geotechnical Engineering: Soil and Foundations Principles and Practice* by Richard L. Handy and Merlin G. Spangler. McGraw-Hill Educations © 2007.)

source, as feldspars weather and are degraded the mineral percentages are reversed, about 75 percent feldspar and the remainder quartz, with a characteristic tan color from grains being coated with iron oxides and clay. An exception is "Ottawa sand" that is a fossil beach sand and is almost pure quartz. One use is to make glass.

Weathering along cracks in granite leaves rounded boulders, as shown in Fig. 1.1. They obviously have not been rounded by rolling along in streams, as commonly assumed. As a general rule, rocks form mountains, which weather and disintegrate into soil that is moved downhill by water and gravity into adjacent valleys where they can be further modified by weathering or moved along by wind and water.

1.4. Soil Layers Created by Weathering

Topsoil "A Horizon"

Topsoil is preferred for gardening but not for engineering, as it contains organic matter that can separate grains and weaken the soil. Topsoil typically is 1–2 ft (0.2–0.5 m) thick unless eroded. At a construction site, topsoil usually is stripped off and saved for later use as a top dressing for lawns. Topsoil may be black from organic matter, and brown or red-brown from iron oxide coatings on soil grains. When developed under trees it can have a thin gray or white layer because of intense weathering from acid soil conditions.

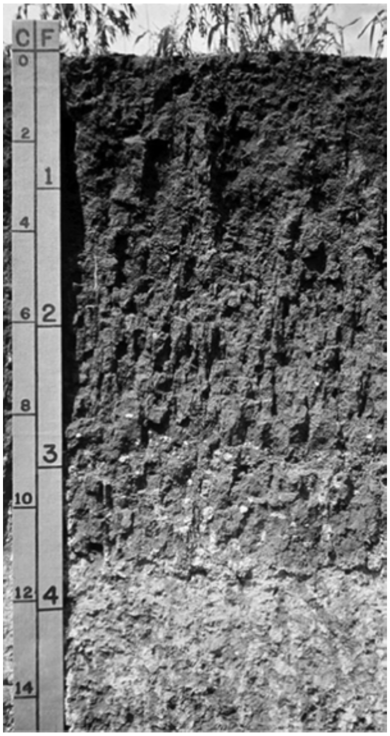

Figure 1.2 A weathered soil profile in expansive clay: Dark, organic *A horizon* topsoil about 8 in. (20 cm) thick on top of brown, clayey *B horizon* subsoil that has a blocky structure indicative of expansive clay. *Olton soil series in western Texas.* (Image source: USDA.)

Subsoil "B Horizon"

Clay that is created by weathering in the overlying A horizon can be carried down with infiltrating rain water to be deposited and concentrated in a relatively thicker subsoil layer called a "B horizon." In temperate climates, B horizons commonly contain concentrated *expansive clay minerals* that shrink when dry and expand when wet. This can cause major problems in engineering.

Shrinkage Cracks and Blocky Structure in Expansive Clays

Vertical shrinkage cracks can define an "active layer" of shrink–swell cycling in expansive clay soils. In a B horizon the cracks can intersect to form a characteristic "subangular blocky" soil structure, as shown in Fig. 1.2. Blocks are coated with thin layers of expansive clay called "clay skins" that prevent bonding, so the soil is avoided for use in foundation engineering.

Case history. Expansive *B horizon* clay soil was recognized and removed from a building site. The pile of soil was not recognized as being expansive and was used as fill soil for another building site, with predictable consequences.

1.5. Vertical Mixing in Expansive Clay

In areas with extended dry seasons, vertical shrinkage cracks can extend a meter or more deep and can define an *active layer* in expansive clay. Cracks are an open invitation for debris and soil that slough off and prevent closing. Repeated open–close cycling then can build up sufficient lateral stress that exceeds the soil unconfined compressive strength, and the soil shears *along inclined planes.*

Shrink–swell cycling, therefore, can eventually mix the A–B horizons into a single thick layer that is expansive and black. The soils have been appropriately referred to as *black cotton soils.* The scientific name is *Vertisol,* for vertical mixing. The soils are bad news for engineering. A clue can be above-ground burials in cemeteries. Various methods can be used to deal with such soils and are discussed in Chap. 4.

1.6. Influence from a Groundwater Table (or Tables)

The level to which water rises in a well defines the groundwater table. It is replenished by seepage so the groundwater level tends to be a weakened expression of hillside surface elevations. Saturation of soil under a groundwater table reduces soil unit weight about one-half; therefore, it can have a major influence on engineering uses as well as contributing to wet basements.

The elevation of a groundwater table obviously is important in engineering, and can be measured from the water level in borings that have been left open for a day or more. The measurements usually are made with a tape that employs an electrical contact.

Groundwater Table and Soil Color

The elevation of a groundwater table can change seasonally depending on rains. Soil below a permanent groundwater level develops a diagnostic gray soil color and is referred to as “unoxidized,” as the gray color is attributed to a lack of oxygen dissolved in the water. Infiltrating rainwater contains dissolved oxygen that can react with iron compounds that stain soil grains to a shade of tan or brown. A seasonally changing groundwater level creates a mottled mixture of gray and brown, sometimes with vertical lines of rust concentrated along former root channels.

A color determination has obvious relevance in engineering as it can indicate seasonal variations in the level of a groundwater table. The examination of soil color should proceed and be recorded soon after the soil has been removed from a boring because it can rapidly change upon exposure to air.

Some guidelines for soil color are listed in Table 1.1. *It will be noted that soil color is not revealed by probing.* A more detailed identification can be made using color charts in the Munsell system, and charts showing only colors commonly found in rocks and soils are available from suppliers.

A Perched Groundwater Table

Downward seepage of water through soil may be impeded by a buried layer of clay to create a “perched” groundwater table that is separated from a deeper and more permanent groundwater level. The clay layer often will represent a former ground surface

Black, dark brown	Organic topsoil or *A horizon*. Avoided in engineering.
Thin, light gray or white	Indicates acidic conditions in soil developed under forest.
Tan or brown	Most common, having been oxidized by exposure to air and therefore above a groundwater table.
Mottled brown and gray	*Fluctuating groundwater table*. Important to recognize in engineering, seasonal changes in buoyant support reduce shearing resistance.
Gray	(a) Most commonly indicates reducing conditions from a lack of oxygen below a permanent groundwater table. (b) May be "fossil" in geologically young glacial soils that have been highly compressed and rendered impermeable by a heavy weight of glacial ice.
Blue or green	Excessive reducing conditions indicating marshy conditions. Can be an important clue to a gas leak. Also can occur in soil after prolonged contact with a bituminous pavement.
White, crusty	*Caliche*: Concentrations of calcium carbonate formed in near-surface soil where the rate of evaporation exceeds the rate of precipitation. Characteristic of near-surface soils in an arid or semiarid climate.

Table 1.1 Some Guidelines for Soil Color

with buried *A* and *B* horizons that are called *paleosols*, for ancient soils. A perched groundwater table can be troublesome, as it can drain into an open excavation.

1.7. Intermittent Recycling

Many soils used in engineering are *sediments*, with properties that are defined by their geological origins. In geological time, sediments become compressed and cemented to form sedimentary rocks. Most common is *shale*, which typically is gray, dense, and thinly layered from having been deeply buried prior to being exposed by geological erosion.

Most shales are deposits from shallow seas that covered areas of continents during past geological time. Rocks that are not thinly layered and are composed of clay are *claystones*. Shale usually is dominant, and often is interlayered with sandstone, limestone, and coal.

Shales of intermediate geological age are less likely to be thinly layered and may contain expansive clay minerals and occasional dinosaur tracks. Thin layering is not a criterion for expansive or non-expansive clay.

1.8. Soil Types and Foundations

The simplest foundations are *slab-on-grade*, concrete slabs that are flat and level. If a foundation slab covers expansive clay, the slab will restrict evaporation, and therefore moisture accumulating under a central area will expand the clay and lift the center part of a structure more than the edges. Expansive clay problems are discussed in Chap. 4. *Shallow foundations* extend down through topsoil, but still can be affected by expansive clays.

Column foundations usually are square but can be round. As discussed later in this chapter they can be hit-or-miss when founded on weathered limestone. *Wall foundations* are linear and more likely to bridge across weak areas. Shallow foundations are commonly used for supporting lightly loaded structures.

Deep foundations initially were straight tree trunks that were stripped of bark and branches. They usually are driven upside-down to take advantage of a natural taper, and still are widely used. Driven piles used to support heavy structures are more likely to be steel or concrete. Steel piles can be pipes, H-beams, or hollow and tapered.

Concrete piles can be driven, or they can be larger in diameter and bored-and-poured. Resistance to lateral forces can be increased by incorporating a "cage" of steel reinforcing that is lowered into the concrete before it sets.

In caving soils that do not hold an open boring, an *augercast pile* is created by twisting a hollow auger that is the full length of a pile into the ground, so soil between the spirals holds the boring open. As the auger is raised, cement grout is pumped down through the center pipe to create a pile from the bottom up. Positive fluid pressure is maintained to prevent caving.

Two classes of deep foundations are end-bearing, which transfer load down to a hard stratum such as bedrock, and *friction* that transfer load to soil that is in contact all along the surface. However, the definition is not exclusive because both mechanisms can contribute, but is highly unlikely that the two resistances will develop and peak out together.

Three consolidation classes of soils: As soil tends to consolidate under its own weight, it typically becomes more supportive with increasing depth. A soil that has been consolidated to equilibrium under existing overburden pressures is said to be *normally consolidated.* Its density and unit weight, therefore, increase with depth.

A soil that has been consolidated under a prior larger overburden pressure is *overconsolidated.* Overconsolidation is advantageous because it can reduce and even prevent significant foundation settlement if the foundation pressure is less than the prior overburden pressure. Some *quasi-elastic* settlement will occur. Overconsolidation can occur with a single emergence–submergence cycle of a groundwater table, so the ideal, normally consolidated soil may be difficult to find in nature.

A soil that is *not* in equilibrium with the existing overburden pressure is said to be *underconsolidated.* This obviously is a potentially unstable condition because if conditions change, the soil may consolidate. In recently deposited soil, the time after deposition may not be sufficient to allow drainage of excess pore water. In that case consolidation is on-going and can be expected to speed up with additional loading. The other common cause for underconsolidation is most likely to be encountered in wind-deposited loess soil, where grains are pulled together by negative (capillary) pressure that can be lost upon saturation with water.

Influence of a Groundwater Table

Even though water can only occupy pore spaces between soil grains, about half of the weight of soil that is under water is supported by buoyancy. As the elevation of a groundwater table depends on the availability of water, it can vary seasonally. However, it is a first-time lowering of a groundwater table that can be most damaging because the soil may be subjected to a load that it has not experienced before. This is most likely to occur in cities, where a surface cover drains carry water away instead of allowing it to penetrate into the ground.

As lowering of a groundwater table removes buoyant support for the soil, even deep foundations such as piles can be affected because if the soil settles