2

FOUNDATIONS

Foundation work in progress for a midrise hotel and apartment building in Boston. The earth surrounding the excavation is retained with steel sheet piling supported by steel walers and tiebacks. Equipment enters and leaves the site via the earth ramp at the bottom of the picture. Although a large backhoe at the right continues to dig around old piles from a previous building on the site, the installation of pressure-injected concrete pile footings is already well underway, with two piledrivers at work in the near and far corners and clusters of completed piles visible in the center of the picture. Concrete pile caps and column reinforcing are under construction in the center of the excavation. *(Courtesy of Franki Foundation Company)*

The function of a *foundation* is to transfer the structural loads reliably from a building into the ground. Every building needs a foundation of some kind: A backyard toolshed will not be damaged by slight shifting of its foundation and may need only wooden skids to spread its load across an area of the ground surface sufficient to support its weight. A wood-framed house needs greater stability than a toolshed, so its foundation reaches through the unstable surface to underlying soil that is free of organic matter and unreachable by winter frost. A larger building of masonry, steel, or concrete weighs many times more than a house, and its foundations pierce the earth until they reach soil or rock that is competent to carry its massive loads; on some sites, this means going 100 feet (30 m) or more below the surface. Because of the variety of soil, rock, and water conditions that are encountered below the surface of the ground and the unique demands that buildings make upon their foundations, foundation design is a highly specialized field combining aspects of geotechnical and civil engineering that can be sketched here only in its broad outlines.

FOUNDATION REQUIREMENTS

A building foundation must support different kinds of loads:

- *Dead load,* the combined weight of all the permanent components of the building, including its own structural frame, floors, roofs, and walls, major permanent electrical and mechanical equipment, and the foundation itself
- *Live loads,* nonpermanent loads caused by the weights of the building's occupants, furnishings, and movable equipment
- *Rain and snow loads*, which act primarily downward on building roofs
- *Wind loads,* which can act laterally (sideways), downward, or upward on a building
- *Seismic loads*, horizontal and vertical forces caused by the motion of the ground relative to the building during an earthquake
- Loads caused by soil and hydrostatic pressure, including *lateral soil pressure loads*, horizontal pressures of earth and groundwater against basement walls; in some instances, *buoyant uplift* forces from underground water, identical to the forces that cause a boat to float; and in others, lateral force *flood loads* that can occur in areas prone to flooding
- In some buildings, *horizontal thrusts* from long-span structural systems such as arches, rigid frames, domes, vaults, or tensile structures

A satisfactory foundation for a building must meet three general requirements:

1. The foundation, including the underlying soil and rock, must be safe against a structural failure that could result in collapse. For example, the foundation for a skyscraper must support the great weight of the building above on a relatively narrow base without danger of overturning.

2. During the life of the building, the foundation must not settle in such a way as to damage the structure or impair its function. (Foundation settlement is discussed more fully in the next section.)

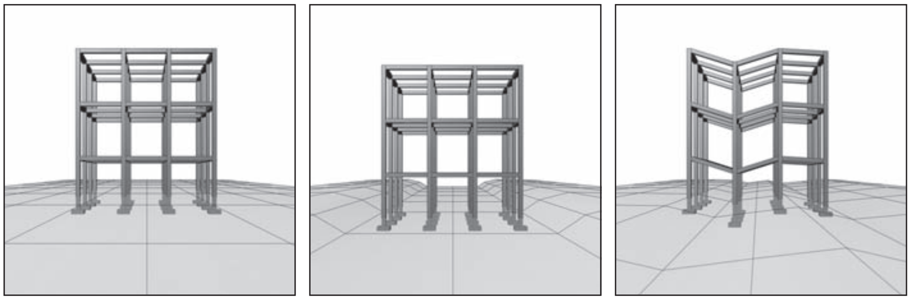
3. The foundation must be feasible, both technically and economically, and practical to build without adverse effects on surrounding property. For example, New York City's tallest buildings tend to cluster on the central and southern portions of Manhattan Island, where the underlying bedrock is closest to the surface and foundations for such buildings are easiest and least expensive to construct.

FOUNDATION SETTLEMENT

All foundations settle to some extent as the earth materials around and beneath them adjust to the loads of the building. Foundations on bedrock settle a negligible amount. Foundations in other types of soil may settle much more. As an extreme example, Mexico City's Palace of Fine Arts has settled more than 15 feet (4.5 m) into the clay soil on which it is founded since it was constructed in the early 1930s. However, building foundation settlement is normally limited to amounts measured in millimeters or fractions of an inch.

Where *foundation settlement* occurs at roughly the same rate throughout all portions of a building, it is

> **We must never trust too hastily to any ground. . . . I have seen a tower at Mestre, a place belonging to the Venetians, which, in a few years after it was built, made its way through the ground it stood upon . . . and buried itself in earth up to the very battlements.**
>
> **Leon Battista Alberti, *Ten Books on Architecture,* 1452.**



(*a*) *Building before settlement occurs* (*b*) *Uniform settlement* (*c*) *Differential settlement*

FIGURE 2.1
Uniform settlement (*b*) is usually of little consequence in a building, but differential settlement (*c*) can cause severe structural damage.

termed *uniform settlement*. Settlement that occurs at differing rates between different portions of a building is termed *differential settlement*. When all parts of a building rest on the same kind of soil, and the loads on the building and the design of its structural system are uniform throughout, differential settlement is normally not a concern. However, where soils, loads, or structural systems differ between parts of a building, different parts of the building structure may settle by substantially different amounts, the frame of the building may become distorted, floors may slope, walls and glass may crack, and doors and windows may not work properly (Figure 2.1). Most foundation failures are attributable to excessive differential settlement. Gross failure of a foundation, in which the soil fails completely to support the building, is extremely rare.

EARTH MATERIALS

Classifying Earth Materials

For the purposes of foundation design, *earth materials* are classified according to particle size, the presence of organic content, and, in the case of finer grained soils, sensitivity to moisture content:

- *Rock* is a continuous mass of solid mineral material, such as granite or limestone, which can only be removed by drilling and blasting. Rock is never completely monolithic, but is crossed by a system of joints (cracks) that vary in quantity and extent and that divide the rock into irregular blocks. Despite these joints, rock is generally the strongest and most stable material on which a building can be founded.
- *Soil* is a general term referring to any earth material that is particulate.
- If an individual particle of soil is too large to lift by hand or requires two hands to lift, it is a *boulder*.
- If it takes the whole hand to lift a particle, it is called a *cobble*.
- If a particle can be lifted easily between thumb and forefinger, the soil is *gravel*. In the Unified Soil Classification System (Figure 2.2), gravels are classified as having more than half their particles larger than 0.19 inch (4.75 mm) in diameter but none larger than 3 inches (76 mm).
- If individual soil particles can be seen but are too small to be picked up individually, the soil is *sand*. Sand particles range in size from about 0.19 to 0.003 inch (4.75–0.075 mm). Both sand and gravel are referred to as *coarse-grained soils*.
- Individual *silt* particles are too small to be seen with the unaided eye and range in size from 0.003 to 0.0002 inch (0.075–0.005 mm). Like coarse-grained soil particles, silt particles are roughly spherical, or equidimensional, in shape.
- *Clay* particles are plate-shaped rather than spherical (Figure 2.3) and smaller than silt particles, less than 0.0002 inch (0.005 mm) in size. Both sands and silts are also referred to as *fine-grained soils*.
- Peat, topsoil, and other *organic soils* are not suitable for the support of building foundations. Because of their high organic matter content, they are spongy, they compress easily, and their properties can change over time due to changing water content or biological activity within the soil.

Properties of Soils

The ability of a coarse-grained soil (gravel or sand) to support the weight of a building depends primarily on the strength of the individual soil particles and the friction between them. Imagine holding a handful of spherical, smooth ball bearings: If you squeeze the bearings, they easily slide past one another in your hand. There is little friction between them. However, if you squeeze a handful of crushed stone, whose particles have rough, angular facets, the frictional forces between the particles are large, and there will be little movement between them. This resistance to sliding, or *shear resistance*, of the crushed stone is also directly proportional to the confining force pushing the particles together. Thus, sand confined by surrounding soil within the earth can support a heavy building, whereas a conical pile of sand deposited loosely on the surface of the ground can support very little, because there is little or no shear resistance between the unconfined particles. Soils that behave in this manner are termed *frictional* or *cohesionless*.

			Group Symbol	Descriptive Names of Soil within This Group
Coarse-Grained Soils	Gravels	Clean Gravels	GW	Well-graded gravel or well-graded gravel with sand, little or no fines
			GP	Poorly graded gravel or poorly graded gravel with sand, little or no fines
		Gravels with Fines	GM	Silty gravel, silty gravel with sand
			GC	Clayey gravel, clayey gravel with sand
	Sands	Clean Sands	SW	Well-graded sand or well-graded sand with gravel, little or no fines
			SP	Poorly graded sand or poorly graded sand with gravel, little or no fines
		Sands with Fines	SM	Silty sand, silty sand with gravel
			SC	Clayey sand, clayey sand with gravel
Fine-Grained Soils	Silts and Clays	Liquid Limit < 50	ML	Silt or silt-sand-gravel mixtures, low plasticity
			CL	Lean clay or clay-sand-gravel mixtures, low plasticity
			OL	Organic clay or silt (clay or silt with significant organic content), or organic clay- or silt-sand-gravel mixtures, low plasticity
		Liquid Limit = 50	MH	Elastic silt, silt-sand-gravel mixtures
			CH	Fat clay or clay-sand-gravel mixtures, high plasticity
			OH	Organic clay or silt (clay or silt with significant organic content), or organic clay- or silt-sand-gravel mixtures, high plasticity
Highly Orgzanic Soils			PT	Peat, muck, and other highly organic soils

FIGURE 2.2
The Unified Soil Classification System, from ASTM D 2487. The group symbols are a universal set of abbreviations for soil types, as seen for example, in Figure 2.8.

In fine-grained soils, particles are smaller, particle surface area is larger in relation to size and weight, and the spaces between particles, or *soil pores*, are smaller. As a consequence, surface forces also affect the properties of these soils. The properties of silts are more sensitive to the amount of water in the soil than are those of coarse-grained soils. With sufficient moisture content, capillary forces can reduce friction between particles and change the state of silt from solid to liquid.

Clay particles, being extremely small and flatter in shape, have surface-area-to-volume ratios hundreds or thousands of times greater than even those of silt. Electrostatic repulsive and attractive forces play an important role in clay soil's properites, as do variations in the arrangement, or *fabric*, of the particles in sheets or other structures that are more

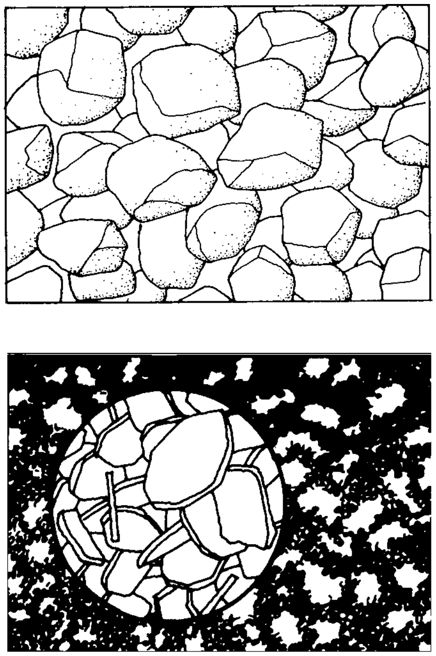


FIGURE 2.3
Silt particles (*top*) are approximately equidimensional granules, while clay particles (*bottom*) are platelike and much smaller than silt. (A circular area of clay particles has been magnified to make the structure easier to see.)


EXCAVATION IN FRICTIONAL SOIL

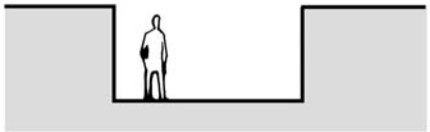

EXCAVATION IN HIGHLY COHESIVE SOIL

FIGURE 2.4
Excavations in frictional and highly cohesive soils.

complex than the simple close-packing typical of spherical particles in coarse-grained soils and silts. As a result, clays are generally *cohesive*; that is, even in the absence of confining force, they retain measurable shear strength. Put simply, cohesive soils tend to stick together. It is often possible to dig vertical-walled excavations in clay soil (Figure 2.4). There is sufficient shear strength in the unconfined soil to prevent the soil wall from sliding into the excavation. In contrast, a cohesionless soil such as sand must be excavated at a much more shallow angle to avoid the collapse of the excavation wall. Cohesive soils also tend to be hard when dry and moldable, or *plastic*, when moist. Some silts also exhibit cohesive properties, though generally to a lesser extent than clays.

Soils for Building Foundations

Generally, soil groups listed toward the top of Figure 2.2 are more desirable for supporting building foundations than those listed further down. The higher-listed soils tend to have better *soil engineering properties*, that is, they tend to have greater loadbearing capacity, to be more stable, and to react less to changes in moisture content. Rock is generally the best material on which to found a building. When rock is too deep to be reached economically, the designer must choose from the strata of different soils that lie closer to the surface and design a foundation to perform satisfactorily in the selected soil.

Figure 2.5 gives some conservative values of *loadbearing capacity* for various types of soil. These values give only an approximate idea of the relative strengths of different soils; the strength of any particular soil is also dependent on factors such as the presence or absence of water, the depth at which the soil lies beneath the surface, and, to some extent, the manner in which the foundation acts upon it. In practice, the designer may also choose to reduce the pressure of the foundations on the soil to well below these values in order to reduce the potential for building settlement.

The *stability* of a soil is its ability to retain its structural properties under the varying conditions that may occur during the lifetime of the building. In general, rock, gravels, and sands tend to be the most stable soils, clays the least stable, and silts somewhere in between. Many clays change size under changing subsurface moisture conditions, swelling considerably as they absorb water and shrinking as they dry. In the presence of highly expansive clay soils, a foundation may need to be designed

TABLE 1804.2
ALLOWABLE FOUNDATION AND LATERAL PRESSURE

CLASS OF MATERIALS	ALLOWABLE FOUNDATION PRESSURE (psf)[d]	LATERAL BEARING (psf/f below natural grade)[d]	LATERAL SLIDING	
			Coefficient of friction[a]	Resistance (psf)[b]
1. Crystalline bedrock	12,000	1,200	0.70	—
2. Sedimentary and foliated rock	4,000	400	0.35	—
3. Sandy gravel and/or gravel (GW and GP)	3,000	200	0.35	—
4. Sand, silty sand, clayey sand, silty gravel and clayey gravel (SW, SP, SM, SC, GM and GC)	2,000	150	0.25	—
5. Clay, sandy clay, silty clay, clayey silt, silt and sandy silt (CL, ML, MH and CH)	1,500[c]	100	—	130

For SI: 1 pound per square foot = 0.0479 kPa, 1 pound per square foot per foot = 0.157 kPa/m.
a. Coefficient to be multiplied by the dead load.
b. Lateral sliding resistance value to be multiplied by the contact area, as limited by Section 1804.3.
c. Where the building official determines that in-place soils with an allowable bearing capacity of less than 1,500 psf are likely to be present at the site, the allowable bearing capacity shall be determined by a soils investigation.
d. An increase of one-third is permitted when using the alternate load combinations in Section 1605.3.2 that include wind or earthquake loads.

FIGURE 2.5
Presumptive surface bearing values of various soil types, from the 2006 IBC. Classes 3, 4, and 5 refer to the soil group symbols in Figure 2.2. *(Portions of this publication reproduce tables from the* 2006 International Building Code, *International Code Council, Inc., Washington, D.C. Reproduced with Permission. All rights reserved)*

with underlying void spaces into which the clay can expand to prevent structural damage to the foundation itself. When wet clay is put under pressure, water can be slowly squeezed out of it, with a corresponding gradual reduction in volume. In this circumstance, long-term settlement of a foundation bearing on such soil is a risk that must be considered. Taken together, these properties make many clays the least predictable soils for supporting buildings. (In Figure 2.2, the fine-grained soil groups indicated as having a liquid limit greater than 50 are generally the ones most affected by water content, exhibiting higher plasticity (moldability) and greater expansion when wet and lower strength when dry.

In regions of significant earthquake risk, stability of soils during seismic events is also a concern. Sands and silts with high water content are particularly susceptible to *liquefaction*, that is, a temporary change from solid to liquid state during cyclic shaking. Soil liquefaction can lead to loss of support for a building foundation or excessive pressure on foundation walls.

The drainage characteristics of a soil are important in predicting how water will flow on and under building sites and around building substructures. Where a coarse-grained soil is composed of particles mostly of the same size, it has the greatest possible volume of void space between particles, and water will pass through it most readily. Where coarse-grained soils are composed of particles with a diverse range of sizes, the volume of void space between particles is reduced, and such soils drain water less efficiently. Coarse-grained soils consisting of particles of all sizes are termed *well graded* or *poorly sorted*, those with a smaller range of particle sizes are termed *poorly graded* or *well sorted*, and those with particles mostly of one size are termed *uniformly graded* (Figure 2.6).

Because of their smaller particle size, fine-grained soils also tend to drain water less efficiently: Water passes slowly through very fine sands and silts and almost not at all through many clays. A building site with clayey or silty soils near the surface drains poorly and is likely to be muddy and covered with puddles during rainy periods, whereas a gravelly site is likely to remain dry. Underground, water passes quickly through strata of gravel and sand but tends to accumulate above layers of clay and fine silt. An excellent way to keep a basement dry is to surround it with a layer of uniformly graded gravel or crushed stone. Water passing through the soil toward the building cannot reach the basement without first falling to the bottom of this porous layer, from where it can be drawn off in perforated pipes before it accumulates (Figures 2.60–2.62). It does little good to place perforated drainage pipes directly in clay or silt because water cannot flow through the impervious soil toward the pipes.

Rarely is the soil beneath a building site composed of a single type. Beneath most buildings, soils of various types are arranged in superimposed layers (*strata*) that were formed by various past geologic processes. Frequently, soils in any one layer are themselves also mixtures of different soil groups, bearing descriptions such as *well-graded gravel with silty clay and sand, poorly graded sand with clay, lean clay with gravel*, and so on. Determining the suitability of any particular site's soils for support of a building foundation, then, depends on the behaviors of the various soils types and how they interact with each other and with the building foundation.

Subsurface Exploration and Soils Testing

Prior to designing a foundation for any building larger than a single-family house (and even for some single-family

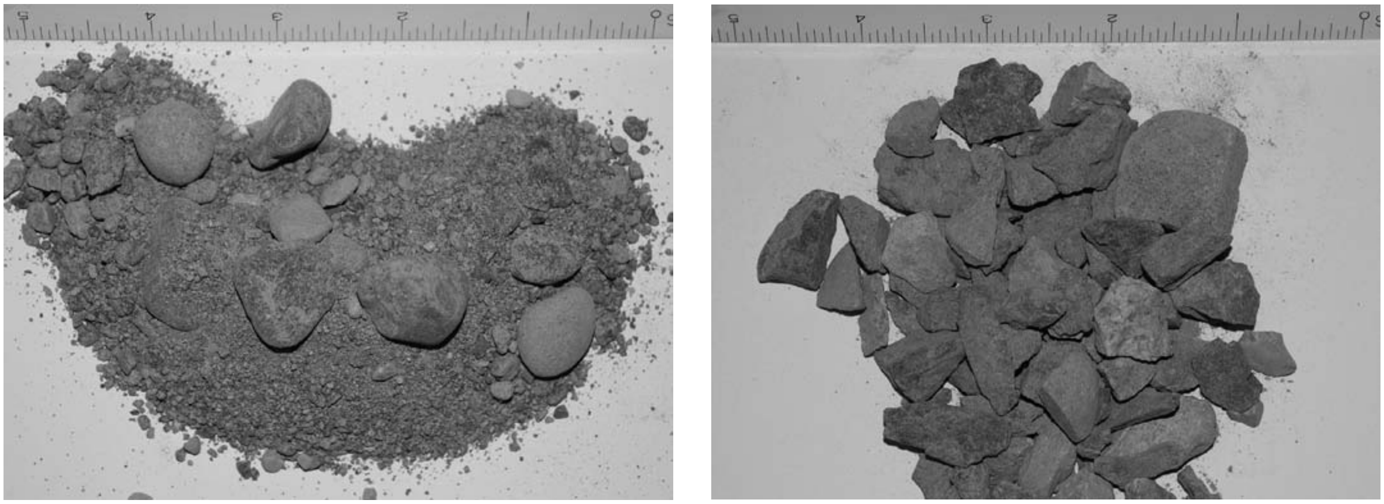


FIGURE 2.6

Two gravel samples, illustrating differences in range of particle sizes or *grading*. The left-hand sample, with a diverse range of particle sizes, comes from a well-graded sandy gravel. On the right is a sample of a uniformly graded gravel in which there is little variation in size among particles. *(Photos by Joseph Iano)* houses), it is necessary to determine the soil and water conditions beneath the site. This can be done by digging *test pits* or by making *test borings*. Test pits are useful when the foundation is not expected to extend deeper than roughly about 16 feet (3 m), the maximum practical reach of small excavating machines. The strata of the soil can be observed in the pit, and soil samples can be taken for laboratory testing. The level of the *water table* (the elevation at which the soil is saturated and the pressure of the groundwater is atmospheric) will be readily apparent in coarse-grained soils if it falls within the depth of the pit because water will seep through the walls of the pit up to the level of the water table. On the other hand, if a test pit is excavated below the water table in clay, free water will not seep into the pit because the clay is relatively impermeable. In this case, the level of the water table must be determined by means of an observation well or special devices that are installed to measure water pressure. If desired, a *load test* can be performed on the soil in the bottom of a test pit to determine the stress the soil can safely carry and the amount of settlement that should be anticipated under load.

If a pit is not dug, borings with standard penetration tests can give an indication of the bearing capacity of the soil by the number of blows of a standard driving hammer required to advance a sampling tube into the soil by a fixed amount. Laboratory-quality soil samples can also be recovered for testing. Test boring (Figure 2.7) extends the possible range of exploration much deeper into the earth than test pits and returns information on the thickness and locations of the soil strata and the depth of the water table. Usually, a number of holes are drilled across the site; the information from the holes is coordinated and interpolated in the preparation of drawings that document the subsurface conditions for the use of the engineer who will design the foundation (Figure 2.8).

Laboratory testing of soil samples is important for foundation design. By passing a dried sample of coarse-grained soil through a set of sieves with graduated mesh sizes, the particle size distribution in the soil can be determined. Further tests on fine-grained soils assist in their identification and provide information on their engineering properties. Important among

FIGURE 2.7
A truck-mounted drilling rig capable of core drilling to 1500 feet (450 m).
(Courtesy of Acker Drilling Company, Inc.)

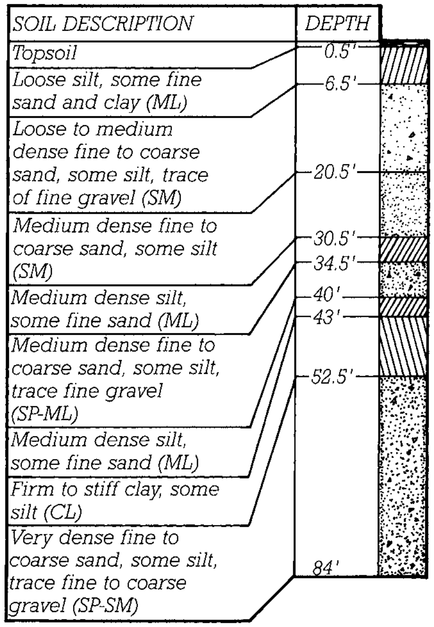


FIGURE 2.8
A typical log from a soil test boring indicating the type of soil in each stratum and the depth in feet at which it was found. The abbreviations in parentheses refer to the Unified Soil Classification System, and are explained in Figure 2.2.

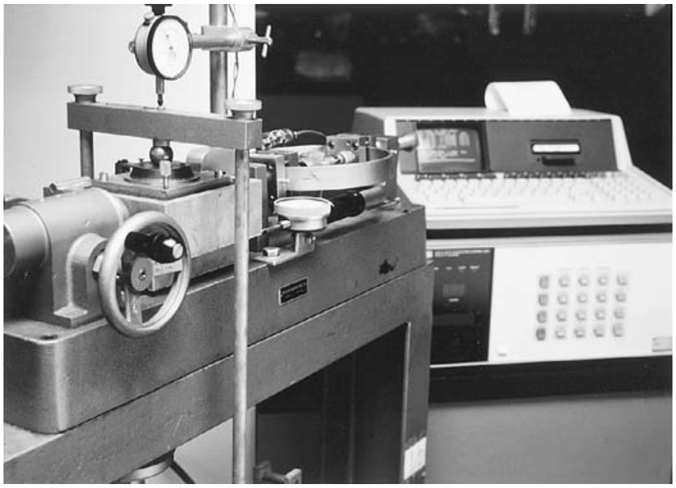
these are tests that establish the *liquid limit,* the water content at which the soil passes from a plastic state to a liquid state, and the *plastic limit,* the water content at which the soil loses its plasticity and begins to behave as a solid. Additional tests can determine the water content of the soil, its permeability to water, its shrinkage when dried, its shear and compressive strengths, the amount by which the soil can be expected to consolidate under the load, and the rate at which consolidation will take place (Figure 2.9). The last two qualities are helpful in predicting the rate and magnitude of foundation settlement in a building.

The information gained through subsurface exploration and soil testing is summarized in a written *geotechnical report*. This report includes the results of both the field tests and the laboratory tests, recommended types of foundations for the site, recommended depths and bearing stresses for the foundations, and an estimate of the expected rate of foundation settlement. This information can be used directly by foundation and structural engineers in the design of the excavations, dewatering and slope support systems, foundations, and substructure. It is also used by contractors in the planning and execution of sitework.


(*a*) (*b*)

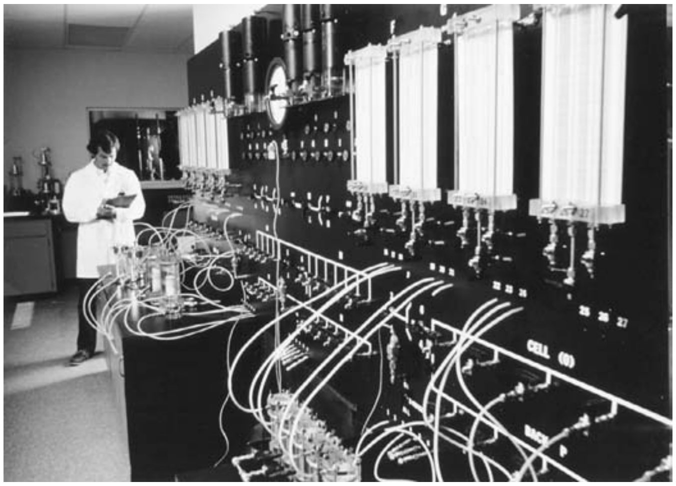
FIGURE 2.9
Some laboratory soil testing procedures. (*a*) To the right, the hardness of split spoon samples is checked with a penetrometer to be sure that they come from the same stratum of soil. To the left, a soil sample from a Shelby sampling tube is cut into sections for testing. (*b*) A section of undisturbed soil from a Shelby tube is trimmed to examine the stratification of silt and clay layers. (*c*) A cylindrical sample of soil is set up for a triaxial load test, the principal method for determining the shear strength of soil. The sample will be loaded axially by the piston in the top of the apparatus and also circumferentially by water pressure in the transparent cylinder. (*d*) A direct shear test, used to measure the shear strength of cohesionless soils. A rectangular prism of soil is placed in a split box and sheared by applying pressure in opposite directions to the two halves of the box. (*e*) One-dimensional consolidation tests in progress on fine-grained soils to determine their compressibility and expected rate of settlement. Each sample is compressed over an extended period of time to allow water to flow out of the sample. (*f*) A panel for running 30 simultaneous constant-head permeability tests to determine the rate at which a fluid, usually water, moves through a soil. (*g*) A Proctor compaction test, in which successive layers of soil are compacted with a specified tamping force. The test is repeated for the same soil with varying moisture content, and a curve is plotted of density achieved versus moisture content of the soil to identify the optimum moisture content for compacting the soil in the field. Not shown here are some common testing procedures for grain size analysis, liquid limit, plastic limit, specific gravity, and unconfined compression. *(Courtesy of Ardaman and Associates, Inc., Orlando, Florida)*

(*c*)



(*d*)

(*e*)



(*f*)

(*g*)

CONSIDERATIONS OF SUSTAINABILITY IN SITE WORK, EXCAVATIONS, AND FOUNDATIONS

Building sites should be selected and developed so as to protect and conserve natural habitats and resources, to promote biodiversity, to preserve quality open space, and to minimize pollution and unnecessary energy consumption.

Site Selection

Buying and renovating an existing building rather than building a new one saves a great deal of building material and energy. If the existing building has been scheduled for demolition, its renovation also avoids the disposal of an enormous quantity of material in a landfill.

Building in an urban area with existing infrastructure, rather than in undeveloped land unconnected to other community resources, protects open space, natural habitats, and natural resources.

Building on a damaged or polluted site, and designing the building so that it helps to restore the site, benefits the environment rather than degrades it.

Avoiding construction on prime agricultural land prevents the permanent loss of this productive use of the land.

Avoiding construction on undeveloped land that is environmentally sensitive protects the wildlife and natural habitats such land supports. This includes floodplains, land that provides habitat for endangered or threatened species, wetlands, mature forest lands and prairies, and land adjacent to natural bodies of water.

Avoiding construction on public parkland or land adjacent to bodies of water that support recreational use prevents the permanent loss of public resources.

Selecting a building that is well connected to existing networks of public transportation, and to pedestrian and bicycle paths, pays environmental dividends every day for the life of the building by saving fuel, reducing air pollution from automobiles, and minimizing commute times.

Site Design

Minimizing the building footprint and protecting and enhancing portions of the site with natural vegetation protects habitat and helps maintain biodiversity.

Appropriate landscape design and the use of captured rainwater, recycled wastewater, or other nonpotable sources of water for landscape irrigation minimize wasteful water consumption.

Minimizing impervious ground surface (such as for vehicle parking) and providing a surface drainage system that conducts water to areas on the site where it can be absorbed into the ground works to replenish natural aquifers, avoid overloading of storm sewer systems, and reduce water pollution.

Grading the site to appropriate slopes and planting vegetation that holds the soil in place will prevent erosion.

EXCAVATION

At least some *excavation* is required for every building. Organic topsoil is subject to decomposition and to shrinking and swelling with changes in moisture content. It is excellent for growing lawns and landscape plants but unsuitable for supporting buildings. Often, it is scraped away from the building area and stockpiled to one side for redistribution over the site after construction of the building is complete. After the topsoil has been removed, further digging is necessary to place the footings out of reach of water and wind erosion. In colder climates, foundations must be placed below the level to which the ground freezes in winter, the *frost line*, or they must be insulated in such a way that the soil beneath them cannot freeze. Otherwise, a foundation can be lifted and damaged by soil that expands slightly as it freezes. Or, under certain soil and temperature conditions, upward migration of water vapor from the pores in the soil can result in the formation of *ice lenses*, thick layers of frozen water crystals than can lift foundations by even larger amounts.

Excavation is required on many sites to place the footings at a depth where soil of the appropriate bearing capacity is available. Excavation is frequently undertaken so that one or more levels of basement space can be added to a building, whether for additional habitable rooms, for parking, or for mechanical equipment and storage. Where footings must be placed deep to get below the frost line or reach competent soil, a basement is often bargain-rate space, adding little to the overall cost of the building.

In particulate soils, a variety of excavating machines can be used to loosen and lift the soil from the ground: bulldozers, shovel dozers, backhoes, bucket loaders, scrapers, trenching machines, and power shovels of every type. If the soil must be moved more than a short distance, dump trucks come into use.

In rock, excavation is slower and many times more costly. Weak or highly fractured rock can sometimes be broken up with power shovels, tractor-mounted rippers, pneumatic hammers, or drop balls such as those used in building demolition. Blasting, in which explosives are placed

Deep Foundations

Caissons

A *caisson,* or *drilled pier* (Figure 2.37), is similar to a column footing in that it spreads the load from a column over a large enough area of soil that the allowable stress in the soil is not exceeded. It differs from a column footing in that it extends through strata of unsatisfactory soil beneath the substructure of a building until it reaches a more suitable stratum. A caisson is constructed by drilling or hand-digging a hole, belling (flaring) the hole out at the bottom as necessary to achieve the required bearing area, and filling the hole with concrete. Large *auger drills* (Figures 2.38 and 2.39) are used for drilling caissons; hand excavation is used only if the soil is too full of boulders for the drill. A temporary cylindrical steel casing is usually lowered around the drill as it progresses to support the soil around the hole. When a firm bearing stratum is reached, the bell, if required, is created at the bottom of the shaft either by hand excavation or by a special *belling bucket* on the drill (Figure 2.40). The bearing surface of the soil at the bottom of the hole is then inspected to be sure it is of the anticipated quality, and the hole is filled with concrete, withdrawing the casing as the concrete rises. Reinforcing is seldom used in the concrete except near the top of the caisson, where it joins the columns of the superstructure.

Caissons are large, heavy-duty foundation components. Their shaft

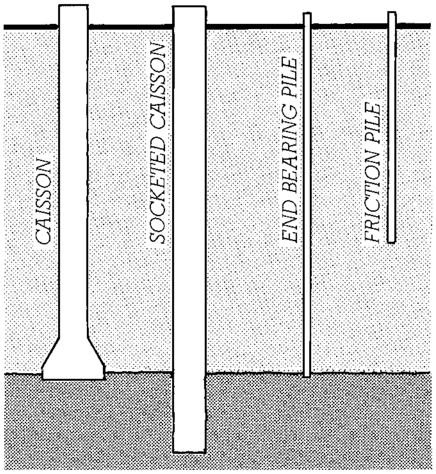


Figure 2.37
Deep foundations. Caissons are concrete cylinders poured into drilled holes. They reach through weaker soil (light shading) to bear on competent soil beneath. The end bearing caisson at the left is belled as shown when additional bearing capacity is required. The socketed caisson is drilled into a hard stratum and transfers its load primarily by friction between the soil or rock and the sides of the caisson. Piles are driven into the earth. End bearing piles act in the same way as caissons. The friction pile derives its load-carrying capacity from friction between the soil and the sides of the pile.

Figure 2.38
A 6-foot- (1828-mm)-diameter auger on a telescoping 70-foot (21-m) bar brings up a load of soil from a caisson hole. The auger will be rotated rapidly to spin off the soil before being reinserted in the hole. *(Courtesy of Calweld Inc.)*

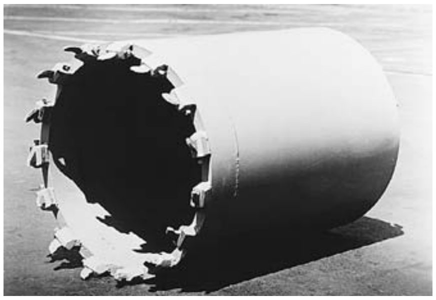


FIGURE 2.39
For cutting through hard material, the caisson drill is equipped with a carbide-toothed coring bucket. *(Courtesy of Calweld Inc.)*

diameters range from 18 inches (460 mm) up to 8 feet (2.4 m) or more. *Belled caissons* are practical only where the bell can be excavated in a cohesive soil (such as clay) that can retain its shape until concrete is poured. Where groundwater is present, the temporary steel casing can prevent flooding of the caisson hole during its construction. But where the bearing stratum is permeable, water may be able to fill the hole from below and caisson construction may not be practical.

A *socketed caisson* (Figure 2.37) is drilled into rock at the bottom rather than belled. Its bearing capacity comes not only from its end bearing, but from the frictional forces between the sides of the caisson and the rock as well. Figure 2.41 shows the installation of a rock caisson or drilled-in caisson, a special type of socketed caisson with a steel H-section core.

FIGURE 2.40
The bell is formed at the bottom of the caisson shaft by a belling bucket with retractable cutters. The example shown here is for an 8-foot- (2.44-m)-diameter shaft and makes a bell 21 feet (6.40 m) in diameter. *(Courtesy of Calweld Inc.)*

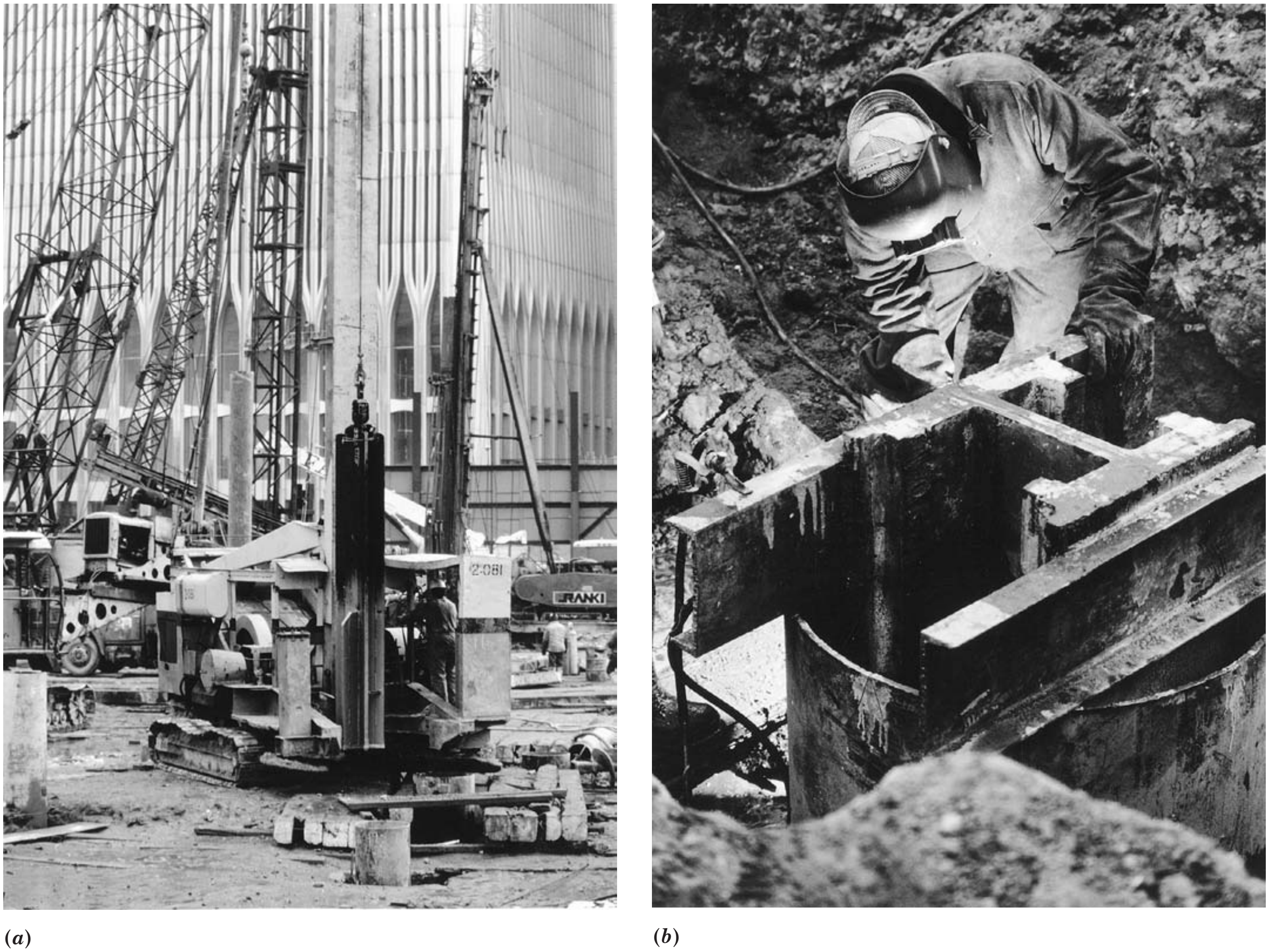

(*a*) (*b*)

FIGURE 2.41

Installing a rock caisson. (*a*) The shaft of the caisson has been drilled through softer soil to the rock beneath and cased with a steel pipe. A churn drill is being lowered into the casing to begin advancing the hole into the rock. (*b*) When the hole has penetrated the required distance into the rock stratum, a heavy steel H-section is lowered into the hole and suspended on steel channels across the mouth of the casing. The space between the casing and the H-section is then filled with concrete, producing a caisson with a very high load-carrying capacity because of the composite structural action of the steel and the concrete. *(Courtesy of Franki Foundation Company)*

Piles

A *pile* (Figure 2.37) is distinguished from a caisson by being forcibly driven into the earth rather than drilled and poured. It may be used where noncohesive soils, subsurface water conditions, or excessive depth of bearing strata make caissons impractical. The simplest kind of pile is a *timber pile*, a tree trunk with its branches and bark removed; it is held small end down in a *piledriver* and beaten into the earth with repeated blows of a heavy mechanical hammer. If a pile is driven until its tip encounters firm resistance from a suitable bearing stratum such as rock, dense sands, or gravels, it is an *end bearing pile*. If it is driven only into softer material, without encountering a firm bearing layer, it may still develop a considerable load-carrying capacity through frictional resistance between the sides of the pile and the soil through which it is driven; in this case, it is known as a *friction pile*. (Some piles rely on a combination of end bearing and friction for their strength.) Piles are usually driven closely together in clusters that contain 2 to 25 piles each. The piles in each cluster are later joined at the top by a reinforced concrete *pile cap*, which distributes the load of the column or wall above among the piles (Figures 2.42 and 2.43).

If . . . solid ground cannot be found, but the place proves to be nothing but a heap of loose earth to the very bottom, or a marsh, then it must be dug up and cleared out and set with piles made of charred alder or olive wood or oak, and these must be driven down by machinery, very closely together. . . .

Marcus Vitruvius Pollio, Roman Architect, *The Ten Books on Architecture,* 1st century B.C.

End bearing piles work essentially the same as caissons and are used on sites where a firm bearing stratum can be reached by the piles, sometimes at depths of 150 feet (45 m) or more. Each pile is driven "to refusal," the point at which little additional penetration is made with continuing blows of the hammer, indicating that the pile is firmly embedded in the bearing layer. Friction piles work best in silty, clayey, and sandy soils. They are driven either to a predetermined depth or until a certain level of resistance to hammer blows is encountered, rather than to refusal as with end bearing piles. Clusters of friction piles have the effect of distributing a concentrated load from the structure above into a large volume of soil around and below the cluster, at stresses that lie safely within the capability of the soil (Figure 2.44).

The loadbearing capacities of piles are calculated in advance based on soil test results and the properties of the piles and piledriver. To verify

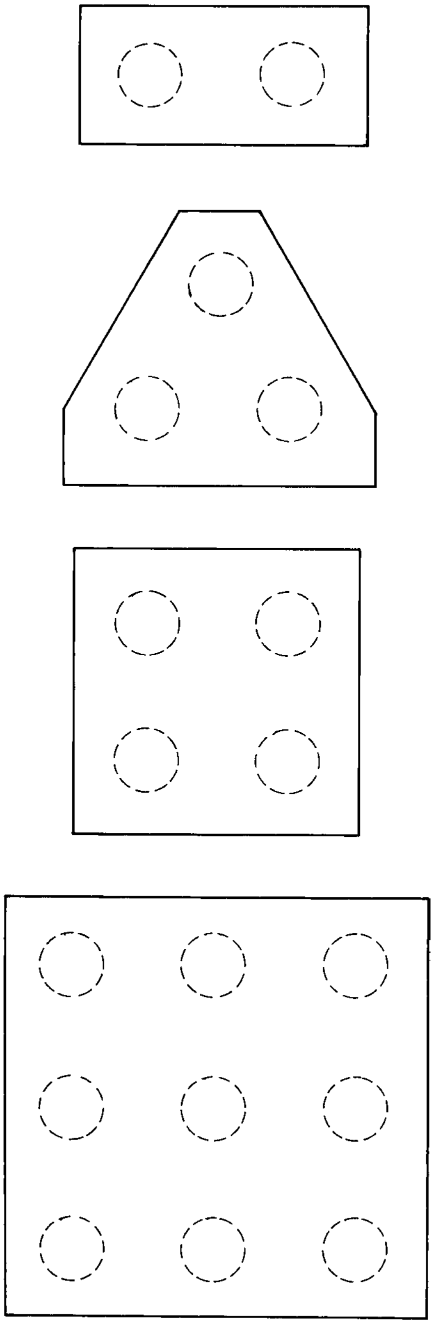


Figure 2.42
Clusters of two, three, four, and nine piles with their concrete caps, viewed from above. The caps are reinforced to transmit column loads equally into all the piles in the cluster, but the reinforcing steel has been omitted here for the sake of clarity.

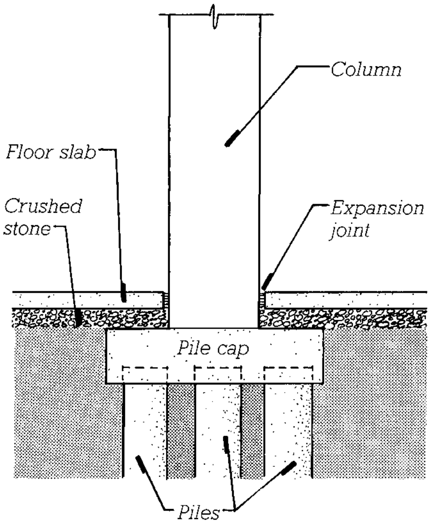


Figure 2.43
An elevation view of a pile cap, column, and floor slab.

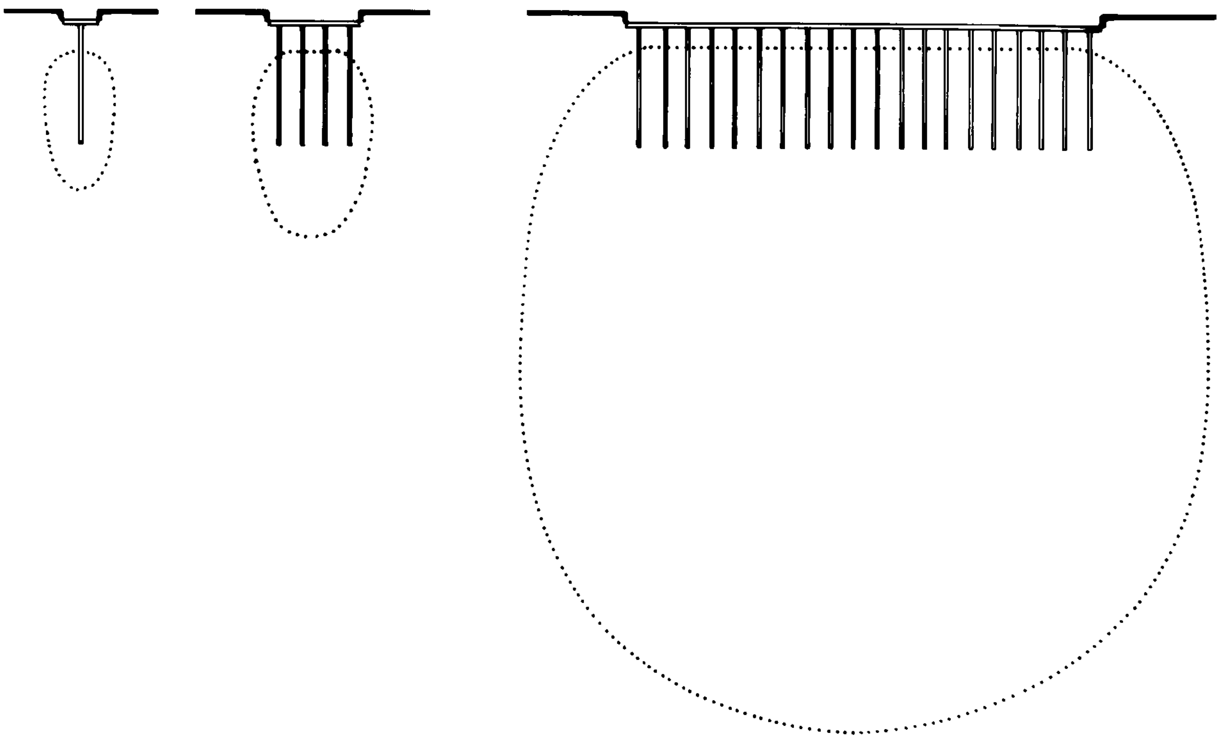


FIGURE 2.44
A single friction pile (left) transmits its load into the earth as an equal shear pressure along the bulb profile indicated by the dotted line. As the size of the pile cluster increases, the piles act together to create a single larger bulb of higher pressure that reaches deeper into the ground. A building with many closely spaced clusters of piles (right) creates a very large, deep bulb. Care must be taken to ensure that large-pressure bulbs do not overstress the soil or cause excessive settlement of the foundation. The settlement of a large group of friction piles in clay, for example, will be considerably greater than that of a single isolated pile.

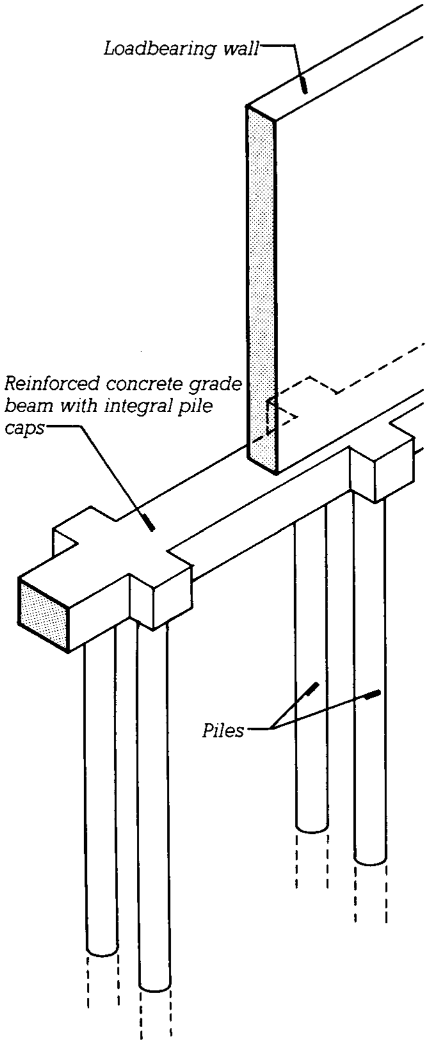


FIGURE 2.45
In order to support a loadbearing wall, pile caps are joined by a grade beam. The reinforcing in the grade beam is similar to that in any ordinary continuous concrete beam and has been omitted for clarity. In some cases, a concrete loadbearing wall can be reinforced to act as its own grade beam.

the correctness of the calculation, test piles are often driven and loaded on the building site before foundation work begins.

Where piles are used to support loadbearing walls, reinforced concrete *grade beams* are constructed between the pile caps to transmit the wall loads to the piles (Figure 2.45). Grade beams are also used with caisson foundations for the same purpose.

Pile Driving

Pile hammers are massive weights lifted by the energy of steam, compressed air, compressed hydraulic fluid, or a diesel explosion, then dropped against a block that is in firm contact with the top of the pile. Single-acting hammers fall by gravity alone, while double-acting hammers are forced downward by reverse application of the energy source that lifts the hammer. The hammer travels on tall vertical rails called *leads* (pronounced "leeds") at the front of a piledriver (Figure 2.46). It is first hoisted up the leads to the top of each pile as driving commences, then follows the pile down as it penetrates the earth. The piledriver mechanism includes lifting machinery to raise each pile into position before driving.

Figure 2.46

A piledriver hammers a precast concrete pile into the ground. The pile is supported by the vertical structure (leads) of the piledriver and driven by a heavy piston mechanism that follows it down the leads as it penetrates deeper into the soil. (© *David van Mill, Netherlands*)

In certain types of soil, piles can be driven more efficiently by vibration than by hammer blows alone, using a vibratory hammer mechanism. Where vibrations from hammering could be a risk to nearby existing structures, some lightweight pile systems can also be installed by rotary drilling or hydraulic pressing.

Pile Materials

Piles may be made of timber, steel, concrete, and various combinations of these materials (Figure 2.47). Timber piles have been used since Roman times, when they were driven by large mechanical hammers hoisted by muscle power. Their main advantage is that they are economical for lightly loaded foundations. On the minus side, they cannot be spliced during driving and are, therefore, limited to the length of available tree trunks, approximately 65 feet (20 m). Unless pressure treated with a wood preservative or completely submerged below the water table, they will decay (the lack of free oxygen in the water prohibits organic growth). Relatively small hammers must be used in driving timber piles to avoid splitting them. Capacities of individual timber piles lie in the range of 10 to 55 tons (9000 to 50,000 kg).

Two forms of steel piles are used, H-piles and pipe piles. *H-piles* are special hot-rolled, wide-flange sections, 8 to 14 inches (200 to 355 mm) deep, which are approximately square in cross section. They are used mostly in end bearing applications. H-piles displace relatively little soil during driving. This minimizes the upward displacement of adjacent soil, called *heaving*, that sometimes occurs when many piles are driven close together. Heaving can be a particular problem on urban sites, where it can lift adjacent buildings.

H-piles can be brought to the site in any convenient lengths, welded together as driving progresses to form any necessary length of pile, and cut off with an oxyacetylene torch when the required depth is reached. The cutoff ends can then be welded onto other piles to avoid waste. Corrosion can be a problem in some soils, however, and unlike closed pipe piles and hollow precast concrete piles, H-piles cannot be inspected after driving to be sure they are straight and undamaged. Allowable loads on H-piles run from 30 to 225 tons (27,000 to 204,000 kg).

Steel *pipe piles* have diameters of 8 to 16 inches (200 to 400 mm). They may be driven with the lower end either open or closed with a heavy steel plate. An open pile is easier to drive than a closed one, but its interior must be cleaned of soil and inspected before being filled with concrete, whereas a closed pile can be inspected and concreted immediately after driving. Pipe piles are stiff and can carry loads from 40 to 300 tons (36,000 to 270,000 kg). They displace relatively large amounts of soil during driving, which can lead to upward heaving of nearby soil and buildings. The larger sizes of pipe piles require a very heavy hammer for driving.

Minipiles, also called *pin piles* or *micropiles*, are a lightweight form of steel piles made from steel bar or pipe 2 to 12 inches (50 to 300 mm) in diameter. Minipiles are inserted into holes drilled in the soil and grouted in place. When installed within existing buildings, they may also be forced into the soil by hydraulic jacks pushing downward on the pile and upward on the building structure. Since no hammering is required, they are a good choice for repair or improvement of existing foundations where vibrations

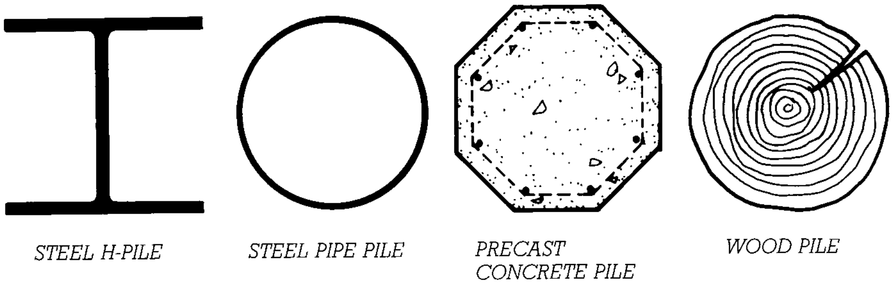


FIGURE 2.47
Cross sections of common types of piles. Precast concrete piles may be square or round instead of the octagonal section shown here and may be hollow in the larger sizes.

from the hammering of conventional piles could damage the existing structure or disrupt ongoing activities within the building (Figure 2.54). Where vertical space is limited, such as when working in the basement of an existing building, minipiles can be installed in individual sections as short as 3 feet (1 m) that are threaded end-to-end as driving progresses. Minipiles can reach depths as great as 200 feet (60 m) and have working capacities as great as 200 to 300 tons (180,000 to 270,000 kg).

Precast concrete piles are square, octagonal, or round in section, and in large sizes often have open cores to allow inspection (Figures 2.47–2.49). Most are prestressed, but some for smaller buildings are merely reinforced (for an explanation of prestressing, see pages 544–548). Typical cross-sectional dimensions range from 10 to 16 inches (250 to 400 mm) and bearing capacities from 45 to 500 tons (40,000 to 450,000 kg). Advantages of precast piles include high load capacity, an absence of corrosion or decay problems, and, in most situations, a relative economy of cost. Precast piles must be handled carefully to avoid bending and cracking before installation. Splices between lengths of precast piling can be made effectively with mechanical fastening devices that are cast into the ends of the sections.

A *sitecast concrete pile* is made by driving a hollow steel shell into the ground and filling it with concrete. The shell is sometimes corrugated to increase its stiffness; if the

FIGURE 2.48
Precast, prestressed concrete piles. Lifting loops are cast into the sides of the piles as crane attachments for hoisting them into a vertical position.
(Courtesy of Lone Star/San-Vel Concrete)

FIGURE 2.49
A driven cluster of six precast concrete piles, ready for cutting off and capping.
(Photo by Alvin Ericson)

corrugations are circumferential, a heavy steel *mandrel* (a stiff, tight-fitting liner) is inserted in the shell during driving to protect the shell from collapse, then withdrawn before concreting. Some shells with longitudinal corrugations are stiff enough that they do not require mandrels. Some types of mandrel-driven piles are limited in length, and the larger diameters of sitecast piles (up to 16 inches, or 400 mm) can cause ground heaving. Load capacities range from 45 to 150 tons (40,000 to 136,000 kg). The primary reason to use sitecast concrete piles is their economy.

There is a variety of proprietary sitecast concrete pile systems, each with various advantages and disadvantages (Figure 2.50). *Concrete pressure-injected footings* (Figure 2.51) share characteristics of piles, piers, and footings. They are highly resistant to uplift forces, a property that is useful for tall, slender buildings in which there is a potential for overturning of the building, and for tensile anchors for tent and pneumatic structures. *Rammed aggregate piers* and *stone columns* are similar to pressure-injected footings, but are constructed of crushed rock that has been densely compacted into holes created by drilling or the action of proprietary vibrating probes.

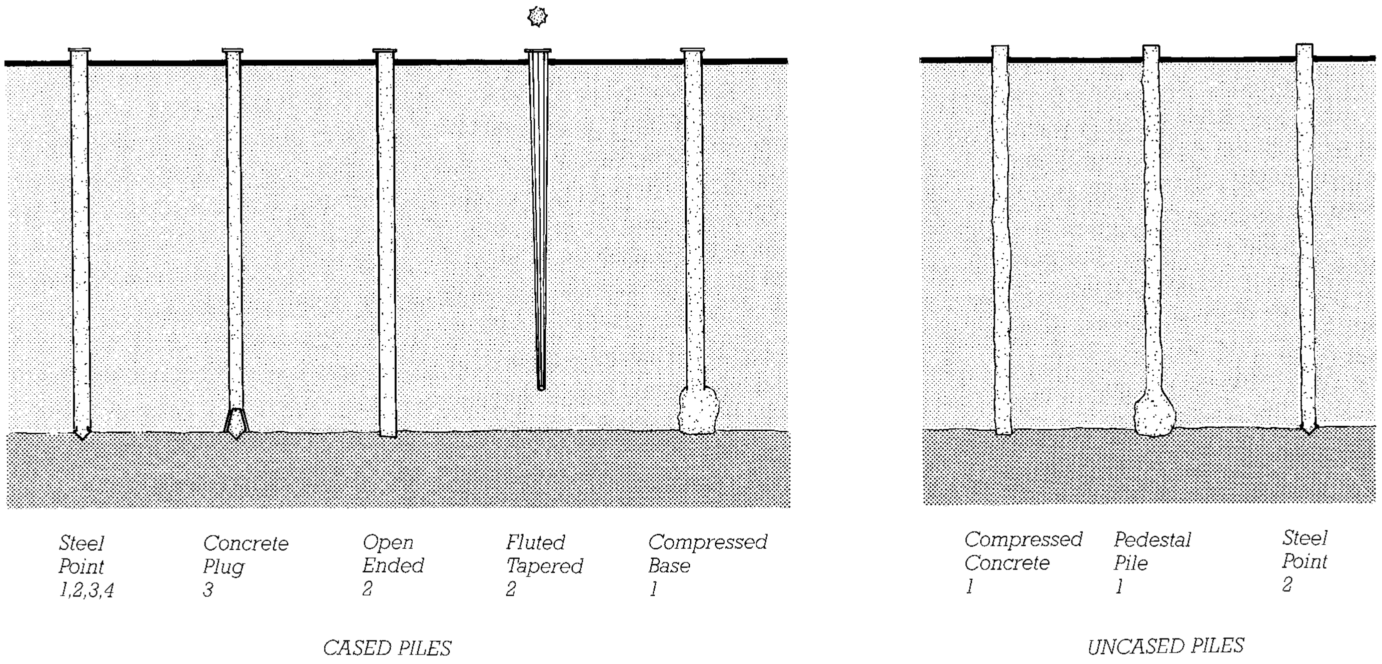
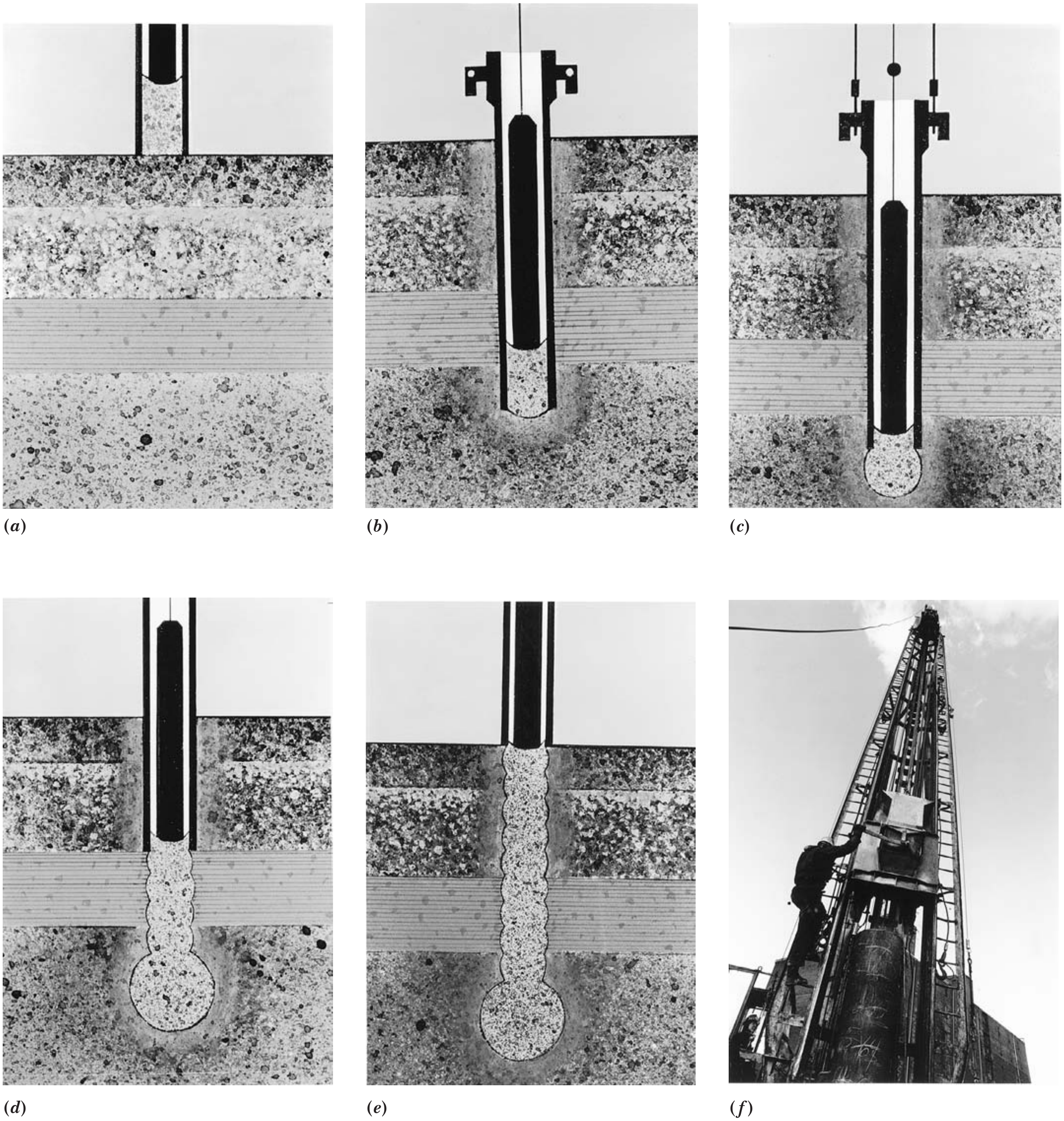


FIGURE 2.50
Some proprietary types of sitecast concrete piles. All are cast into steel casings that have been driven into the ground; the uncased piles are made by withdrawing the casing as the concrete is poured and saving it for subsequent reuse. The numbers refer to the methods of driving that may be used with each: 1. Mandrel driven. 2. Driven from the top of the tube. 3. Driven from the bottom of the tube to avoid buckling it. 4. Jetted. Jetting is accomplished by advancing a high-pressure water nozzle ahead of the pile to wash the soil back alongside the pile to the surface. Jetting has a tendency to disrupt the soil around the pile, so it is not a favored method of driving under most circumstances.



(*a*) (*b*) (*c*)

(*d*) (*e*) (*f*)

FIGURE 2.51

Steps in the construction of a proprietary pressure-injected, bottom-driven concrete pile footing. (*a*) A charge of a very low-moisture concrete mix is inserted into the bottom of the steel drive tube at the surface of the ground and compacted into a sealing plug with repeated blows of a drop hammer. (*b*) As the drop hammer drives the sealing plug into the ground, the drive tube is pulled along by the friction between the plug and the tube. (*c*) When the desired depth is reached, the tube is held and a bulb of concrete is formed by adding small charges of concrete and driving the concrete out into the soil with the drop hammer. The bulb provides an increased bearing area for the pile and strengthens the bearing stratum by compaction. (*d*, *e*) The shaft is formed of additional compacted concrete as the tube is withdrawn. (*f*) Charges of concrete are dropped into the tube from a special bucket supported on the leads of the driving equipment. *(Courtesy of Franki Foundation Company)*

Seismic Base Isolation

In areas where strong earthquakes are common, buildings are sometimes placed on *base isolators*. When significant ground movement occurs, the base isolators flex or yield to absorb a significant portion of this movement; as a result, the building and its substructure move significantly less than they would otherwise, reducing the forces acting on the structure and lessening the potential for damage. A frequently used type of base isolator is a multilayered sandwich of rubber and steel plates (Figure 2.52). The rubber layers deform in shear to allow the rectangular isolator to become a parallelogram in cross section in response to relative motion between the ground and the building. A lead core deforms enough to allow this motion to occur, provides damping action, and keeps the layers of the sandwich aligned.

UNDERPINNING

Underpinning is the process of strengthening and stabilizing the foundations of an existing building. It may be required for any of several reasons: The existing foundations may never have been adequate to carry their loads, leading to excessive settlement of the building over time. A change in building use or additions to the building may overload the existing foundations. New construction near a building may disturb the soil around its foundations or require that its foundations be carried deeper. Whatever the cause, underpinning is a highly specialized task that is seldom the same for any two buildings. Three different alternatives are available when foundation

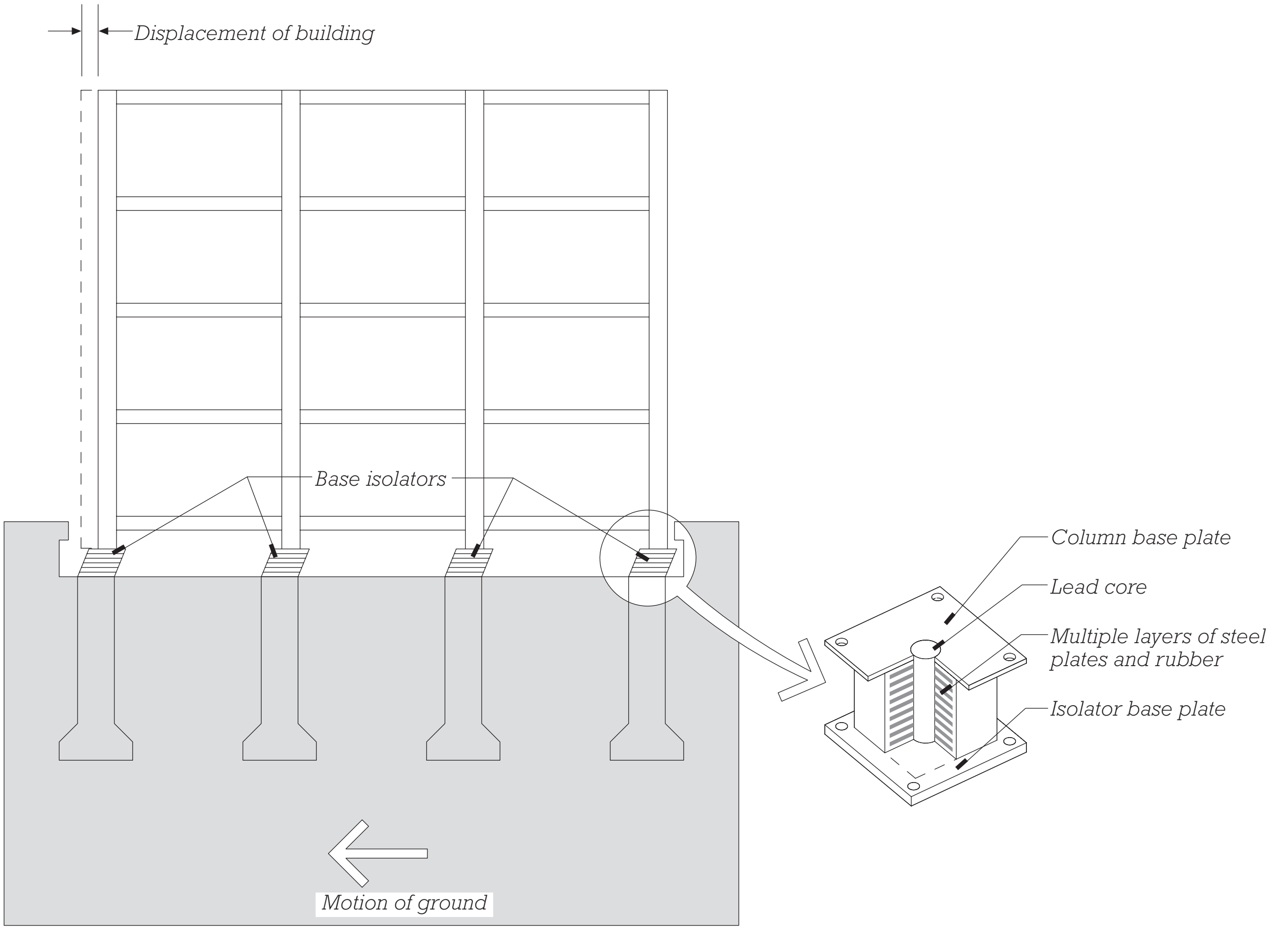


FIGURE 2.52
Base isolation.

capacity needs to be increased: The foundations may be enlarged; new, deep foundations can be inserted under shallow ones to carry the load to a deeper, stronger stratum of soil; or the soil itself can be strengthened by grouting or by chemical treatment. Figures 2.53 and 2.54 illustrate in diagrammatic form some selected concepts of underpinning.

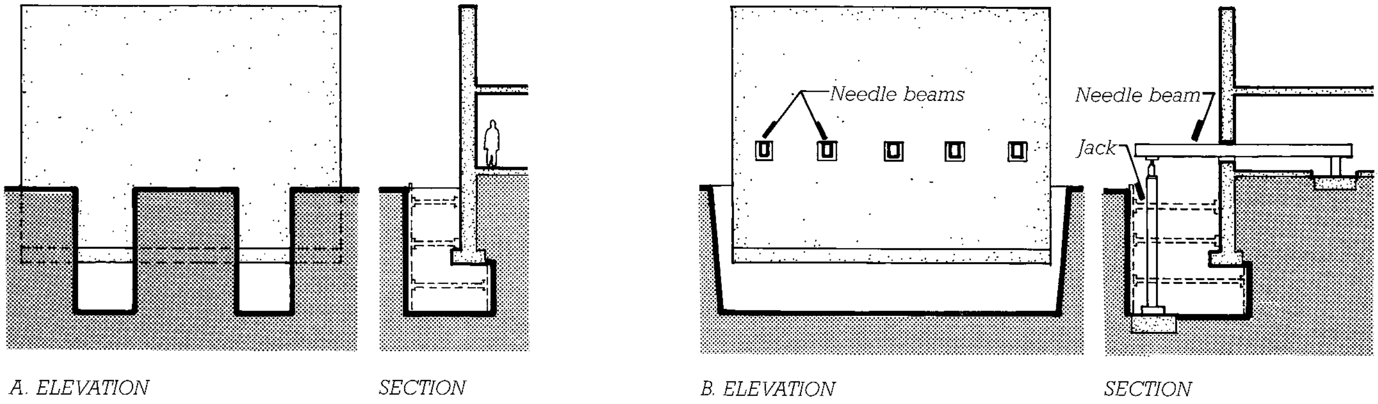


FIGURE 2.53
Two methods of supporting a building while carrying out underpinning work beneath its foundation, each shown in both elevation and section. (*a*) Trenches are dug beneath the existing foundation at intervals, leaving the majority of the foundation supported by the soil. When portions of the new foundations have been completed in the trenches, using one of the types of underpinning shown in Figure 2.54, another set of trenches is dug between them and the remainder of the foundations is completed. (*b*) The foundations of an entire wall can be exposed at once by needling, in which the wall is supported temporarily on needle beams threaded through holes cut in the wall. After underpinning has been accomplished, the jacks and needle beams are removed and the trench is backfilled.

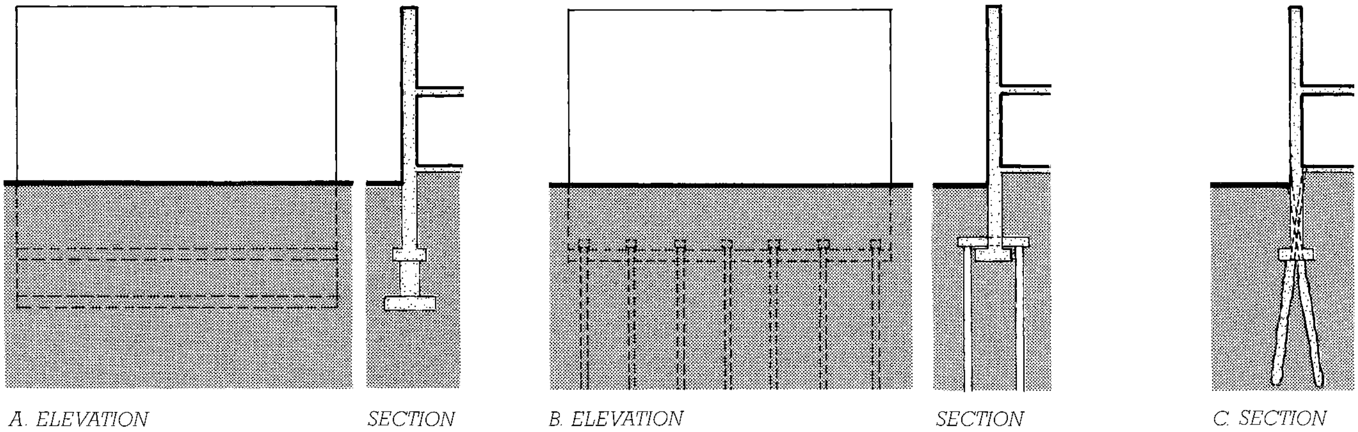


FIGURE 2.54
Three types of underpinning. (*a*) A new foundation wall and footing are constructed beneath the existing foundation. (*b*) New piles or caissons are constructed on either side of the existing foundation. (*c*) Minipiles are inserted through the existing foundation. Minipiles do not generally require excavation or temporary support of the building.

RETAINING WALLS

A *retaining wall* holds soil back to create an abrupt change in the elevation of the ground. A retaining wall must resist the pressure of the earth that bears against it on the uphill side. Retaining walls may be made of masonry, preservative-treated wood, coated or galvanized steel, precast concrete, or, most commonly, sitecast concrete.

The structural design of a retaining wall must take into account such factors as the height of the wall, the character of the soil behind the wall, the presence or absence of groundwater behind the wall, any structures whose foundations apply pressure to the soil behind the wall, and the character of the soil beneath the base of the wall, which must support the footing that keeps the wall in place. The rate of structural failure in retaining walls is high relative to the rate of failure in other types of structures. Failure may occur through fracture of the wall, overturning of the wall due to soil failure, lateral sliding of the wall, or undermining of the wall by flowing groundwater (Figure 2.55). Careful engineering design and site supervision are crucial to the success of a retaining wall.

There are many ways of building retaining walls. For walls less than 3 feet (900 mm) in height, simple, unreinforced walls of various types are often appropriate (Figure 2.56). For taller walls, and ones subjected to unusual loadings or groundwater, the type most frequently employed today is the cantilevered concrete

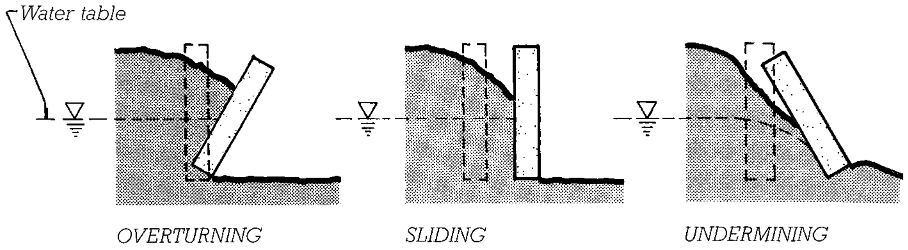


FIGURE 2.55
Three failure mechanisms in retaining walls. The high water table shown in these illustrations creates pressure against the walls that contributes to their failure. The undermining failure is directly attributable to groundwater running beneath the base of the wall, carrying soil with it.

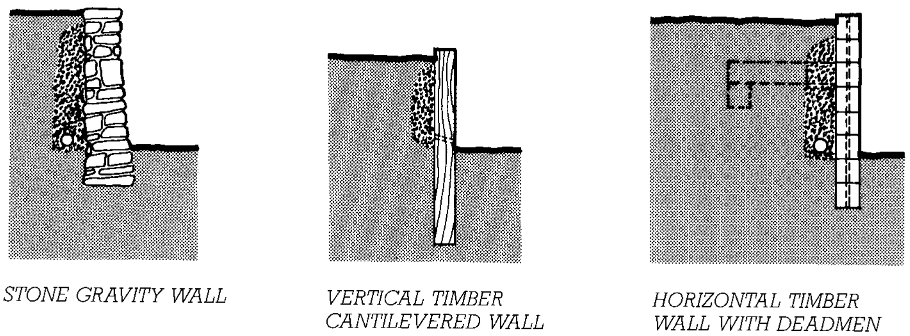


FIGURE 2.56
Three types of simple retaining walls, usually used for heights not exceeding 3 feet (900 mm). The deadmen in the horizontal timber wall are timbers embedded in the soil behind the wall and connected to it with timbers inserted into the wall at right angles. The timbers, which should be pressure treated with a wood preservative, are held together with very large spikes or with steel reinforcing bars driven into drilled holes. The crushed-stone drainage trench behind each wall is important as a means of relieving water pressure against the wall to prevent wall failure. With proper engineering design, any of these types of construction can also be used for taller retaining walls.

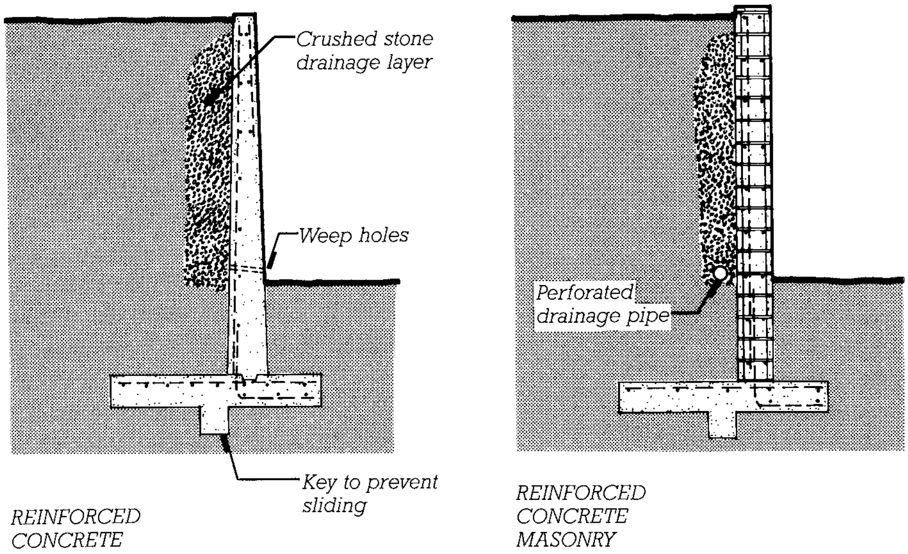


Figure 2.57
Cantilevered retaining walls of concrete and concrete masonry. The footing is shaped to resist sliding and overturning, and drainage behind the wall reduces the likelihood of undermining. The pattern of steel reinforcing (broken lines) is designed to resist the tensile forces in the wall.

Figure 2.58
A segmental retaining wall consisting of specially made concrete blocks designed to interlock and prevent sliding. The wall leans back against the soil it retains; this reduces the amount of soil the wall must retain and makes it more stable against the lateral push of the soil. *(Courtesy of VERSA-LOK Retaining Wall Systems)*

retaining wall, two examples of which are shown in Figure 2.57. The shape and reinforcing of a cantilevered wall can be custom designed to suit almost any situation. Proprietary systems of interlocking concrete blocks are also used to construct sloping *segmental retaining walls* that need no steel reinforcing (Figure 2.58).

Earth reinforcing (Figure 2.59) is an economical alternative to conventional retaining walls in many situations. Soil is compacted in thin layers, each containing strips or meshes of galvanized steel, polymer fibers, or glass fibers, which stabilize the soil in much the same manner as the roots of plants. *Gabions* are another form of earth retention in which corrosion-resistant wire baskets are filled with cobble- or boulder-sized rocks and then stacked to form retaining walls, slope protection, and similar structures.

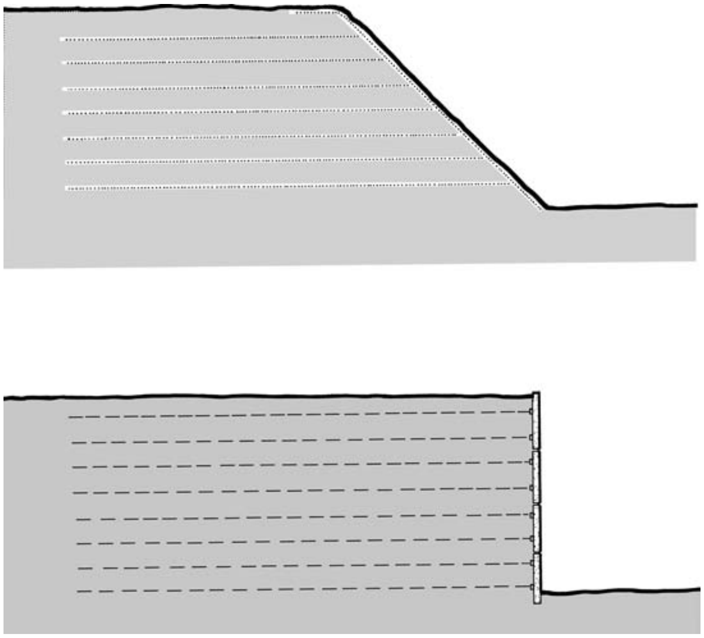


FIGURE 2.59
Two examples of earth reinforcing. The embankment in the top section was placed by alternating thin layers of earth with layers of synthetic mesh fabric. The retaining wall in the lower section is made of precast concrete panels fastened to long galvanized steel straps that run back into the soil.

GEOTEXTILES

Geotextiles are flexible fabrics made of chemically inert plastics that are highly resistant to deterioration in the soil. They are used for a variety of purposes relating to site development and the foundations of buildings. As described in the accompanying text, in *earth reinforcement* or *soil reinforcement*, a plastic mesh fabric or grid is used to support an earth embankment or retaining wall. The same type of mesh may be utilized in layers to stabilize engineered fill beneath a shallow footing (Figure A), or to stabilize marginal soils under driveways, roads, and airport runways, acting very much as the roots of plants do in preventing the movement of soil particles.

Another geotextile that is introduced later in this chapter is drainage matting, an open matrix of plastic filaments with a feltlike filter fabric laminated onto one side to keep soil particles from entering the matrix. In addition to providing free drainage around foundation walls, drainage matting is often used beneath the soil in the bottoms of planter boxes and under heavy paving tiles on rooftop terraces, where it maintains free passage for the drainage of water above a waterproof membrane.

Synthetic filter fabrics are wrapped over and around subterranean crushed stone drainage layers such as the one frequently used around a foundation drain. In this position, they keep the stone and pipe from gradually becoming clogged with fine soil particles carried by the groundwater. Similar fabrics are used at grade during construction, acting as temporary barriers to filter soil out of water that runs off a construction site, thus preventing contamination of lakes, streams, or stormwater systems.

Special geotextiles are manufactured to stake down on freshly cut slopes to prevent soil erosion and encourage revegetation; some of these are designed to decay and disappear into the soil as plants take over the function of slope stabilization. Another type of geotextile is used for weed control in landscaped beds, where it allows rainwater to penetrate the soil but blocks sunlight, preventing weeds from sprouting.