CHAPTER 4

Design of Foundations

4.1 General

A foundation supports and anchors the superstructure of a building and transfers all loads (including those from flood, wind, or seismic events) imposed on it directly to the ground. Foundations distribute the loads to the earth over an adequate area so that loads do not exceed the bearing capacity of the soil and so that lateral movement or settlement is minimized. In cold climates, the bottom of the foundation must be below the frost line to prevent freeze-thaw damage and frost heave of the footing.

A foundation in residential construction may consist of a footing, wall, slab, pier, pile, or a combination of these elements. This chapter addresses the following foundation types—

- Crawl space.
- Basement.
- Slab-on-grade with stem wall.
- Monolithic slab.
- Piles.
- Piers.
- Alternative methods.

As discussed in chapter 1, the most common residential foundation materials are cast-in-place concrete and concrete masonry (that is, concrete block). Preservative-treated wood, precast concrete, and other materials may also be used. The concrete slab-on-grade is a prevalent foundation type in the South and Southwest; basements are the most common type in the East and Midwest. Crawl spaces are common in the Northwest and Southeast. Pile foundations designed to function after being exposed to scour and erosion are commonly used in coastal flood zones to elevate structures above flood levels. Piles also are used in weak or expansive soils to reach a stable stratum and on steeply sloped sites. Figure 4.1 depicts different foundation types; a brief description follows.

A *crawl space* is a building foundation that uses a perimeter foundation wall to create an underfloor space that is not habitable; the interior crawl space elevation may or may not be below the exterior finish grade. In mapped flood plains, a crawl space that has the interior grade below the exterior grade on all sides is considered a basement. A *basement* typically is defined as a portion of a building that is partly or completely below the exterior grade and that may be used as habitable space, as storage space, or for parking. The primary difference between a basement and a crawl space is height (basements usually are taller). The floors of basements usually are finished, and the interiors frequently are finished. The wall height is sometimes determined by the depth of the footing required for frost protection.

A *slab-on-grade with an independent stem wall* is a concrete floor supported by the soil independently of the rest of the building. The stem wall supports the building loads and in turn is supported directly by the soil or a footing. A *monolithic* or *thickened-edge slab* is a ground-supported slab-on-grade with an integral footing (that is, a thickened edge); it is normally used in warmer regions that have little or no frost depth but is also used in colder climates when adequate frost protection is provided (see section 4.7).

When necessary, *piles* are used to transmit the load to a deeper soil stratum with a higher bearing capacity to prevent failure from undercutting of the foundation by scour from flood water flow at high velocities and to elevate the building above required flood elevations. Piles also are used to isolate the structure from expansive soil movements.

Pier and beam foundations can provide an economical alternative to crawl space perimeter wall construction. A common practice is to use a brick curtain wall between piers for appearance and bracing.

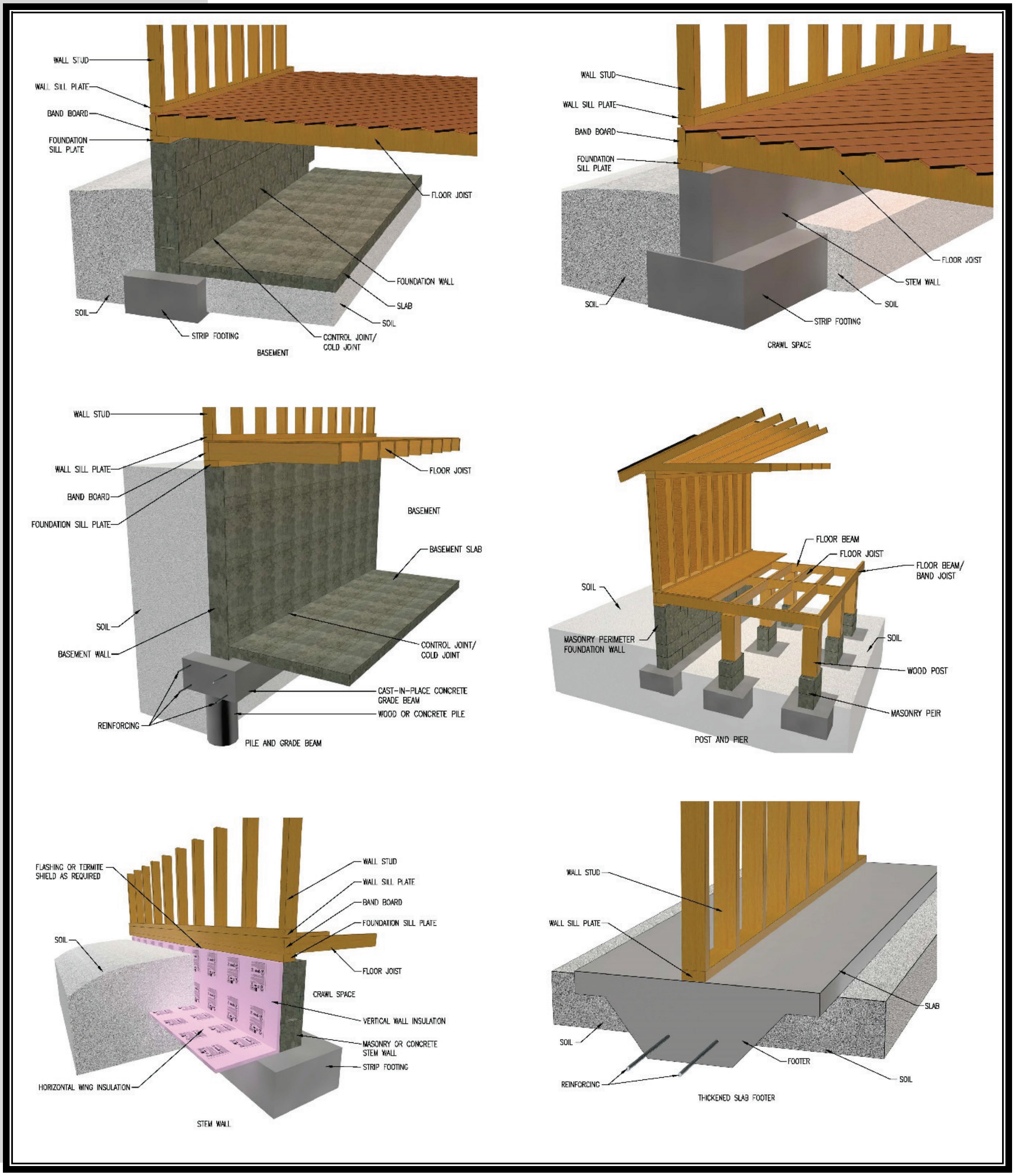
The design procedures and information in this chapter cover the following topics.

- Foundation materials and properties.
- Soil-bearing capacity and footing size.
- Concrete or gravel footings.
- Concrete and masonry foundation walls.
- Preservative-treated wood walls.
- Insulating concrete foundations.
- Concrete slabs on grade.
- Pile foundations.
- Frost protection.

Concrete design procedures generally follow the strength design method contained in the American Concrete Institute's ACI 318 (ACI, 2011) although certain aspects of the procedures may be considered conservative relative to conventional residential foundation applications. For this reason, this guide provides supplemental design guidance when practical and technically justified. ACI 332 (ACI, 2010), which contains design provisions and guidance specific to residential construction, is referenced in the International Residential Code (IRC) as an alternative to the conventional foundation requirements of the code or the design procedures of ACI 318. Masonry design procedures follow the allowable stress design (ASD) method of The Masonry Society's TMS 402 (TMS, 2011). Wood design procedures are used to design the connections between the foundation system and the structure above and follow the ASD method for wood construction (see chapter 7 for connection design information). In addition, the designer is referred to the applicable design standards for symbol definitions and additional guidance because the intent of this chapter is to provide supplemental instruction in the efficient design of residential foundations.

To maintain consistency, this guide uses the load and resistance factor design (LRFD) load combinations that were used in chapter 3, which are also those specified in the American Society of Civil Engineers' ASCE 7. There may be some minor variations in those required in ACI 318 for strength design of concrete. The purpose of this guide is to provide designs that are at least consistent with current residential building code and construction practice. With respect to the design of concrete in residential foundations, the guide seeks to provide reasonable safety margins that meet or exceed the minimums required for other, more crucial requirements of a home—namely, the safety of lives. The designer is responsible for ensuring that the design meets the building code requirements and will be approved by the building official.

FIGURE 4.1 *Types of Foundations*



4.2 Material Properties

A residential designer using concrete and masonry materials must have a basic understanding of such materials, including variations in the materials' composition and structural properties. In addition, a designer must take into consideration soils, which are also considered a foundation material (Section 4.3 provides information on soil bearing). A brief discussion of the properties of concrete and masonry follows.

4.2.1 Concrete

The concrete compressive strength (f_c') used in residential construction is typically either 2,500 or 3,000 pounds per square inch (psi), although other values may be specified. For example, 4,000 psi concrete may be used for improved weathering resistance in particularly severe climates or unusual applications. The concrete compressive strength may be verified in accordance with the American Society for Testing and Materials' ASTM C39 (ASTM, 2012c). Given that the rate of increase in concrete strength diminishes with time, the specified compressive strength usually is associated with the strength attained after 28 days of curing time, when the concrete attains about 85 percent of its fully cured compressive strength.

Concrete is a mixture of cement, water, and sand, gravel, crushed rock, or other aggregates. Sometimes one or more admixtures are added to change certain characteristics of the concrete, such as workability, durability, and time of hardening. The proportions of the components determine the concrete mix's compressive strength and durability.

Type

Portland cement is classified into several types, in accordance with ASTM C150 (ASTM, 2012b). Residential foundation walls typically are constructed with *Type I* cement, which is a general-purpose Portland cement used for the vast majority of construction projects. Other types of cement are appropriate in accommodating conditions related to heat of hydration in massive pours and sulfate resistance. In some regions, sulfates in soils have caused durability problems with concrete. The designer should check into local conditions and practices.

Weight

The weight of concrete varies depending on the type of aggregates used in the concrete mix. Concrete typically is classified as lightweight or normal weight. The density of unreinforced normal weight concrete ranges between 144 and 156 pounds per cubic foot (pcf) and typically is assumed to be 150 pcf. Residential foundations usually are constructed with normal weight concrete.

Slump

Slump is the measure of concrete consistency; the higher the slump, the wetter the concrete and the easier it flows. Slump is measured in accordance with ASTM C143 (ASTM, 2012d) by inverting a standard 12-inch-high metal cone, filling it with concrete, and then removing the cone; the amount the concrete that settles in units of inches is the slump. Most foundations, slabs, and walls consolidated by hand methods have a slump between 4 and 6 inches. One problem associated with a high-slump concrete is segregation of the aggregate, which leads to cracking and scaling. Therefore, a slump of greater than 6 inches should be avoided. Adding water lowers the strength while improving workability, so the total amount of water in the concrete should be carefully monitored and controlled. Admixtures used during extremely cold or hot weather placement (or for other reasons) may change the slump.

Weather Resistance

Concrete is largely weather resistant. When concrete may be subjected to freezing and thawing during construction, however, or when concrete is located in regions prone to extended periods of freezing, additional measures must be taken. Those requirements can be found in the IRC (ICC, 2012), and include air entrainment and increased minimum compressive strength requirements.

Admixtures

Admixtures are materials added to the concrete mix to improve workability and durability and to retard or accelerate curing. Some of the most common admixtures are described below.

- *Water reducers* improve the workability of concrete without reducing its strength.
- *Retarders* are used in hot weather to allow more time for placing and finishing concrete. Retarders may also reduce the early strength of concrete.
- *Accelerators* reduce the setting time, allowing less time for placing and finishing concrete. Accelerators may also increase the early strength of concrete.
- *Air entrainers* are used for concrete that will be exposed to freeze-thaw conditions and deicing salts. Less water is needed and segregation of aggregate is reduced when air entrainers are added.

Reinforcement

Concrete has high compressive strength but low tensile strength; therefore, reinforcing steel often is embedded in the concrete to provide additional tensile strength and ductility. In the rare event that the capacity is exceeded, the reinforcing steel begins to yield, thereby preventing an abrupt failure that may otherwise occur with plain, unreinforced concrete. For this reason, a larger safety margin is used in the design of plain concrete construction than in reinforced concrete construction.

Steel reinforcement is available in grade 40 or grade 60; the grade number refers to the minimum tensile yield strength (f_y) of the steel (i.e., grade 40 is a minimum 40 thousand pounds per square inch [ksi] steel and grade 60 is a minimum 60 ksi steel). Either grade may be used for residential construction; however, most steel reinforcement in the U.S. market today is grade 60. The concrete mix, or slump, must be adjusted by adding the appropriate amount of water to allow the concrete to flow easily around the reinforcement bars, particularly when the bars are closely spaced or are crowded at points of overlap. Close rebar spacing rarely is required in residential construction, however, and should be avoided in design if at all possible.

The most common steel reinforcement or rebar sizes in residential construction are No. 3, No. 4, and No. 5, which correspond to diameters of 3/8 inch, 1/2 inch, and 5/8 inch, respectively. The bar designations indicate the bar size in 1/8-inch increments. These three sizes of rebar are easily manipulated at the jobsite by using manual bending and cutting devices. Table 4.1 shows useful relationships between the rebar number, diameter, and cross-sectional area for reinforced concrete and masonry design.

Fiber reinforcement is being used in some concrete slab installation. The fiber could be steel, natural, or synthetic. It helps (1) improve resistance to freeze-thaw, (2) increase resistance to some spalling of the surface, (3) control cracking, and (4) improve the concrete's shatter resistance. Fibers generally do not increase the structural strength of the concrete slab and do not replace normal reinforcing bars used for tensile strength.

TABLE 4.1 Rebar Size, Diameter, and Cross-Sectional Areas

Size	Diameter (inches)	Area (square inches)
No. 3	3/8	0.11
No. 4	1/2	0.20
No. 5	5/8	0.31
No. 6	3/4	0.44
No. 7	7/8	0.60
No. 8	1	0.79

4.2.2 Concrete Masonry Units

Concrete masonry units (CMUs), commonly referred to as concrete blocks, are composed of Portland cement, aggregate, and water. In some situations, CMUs may also include admixtures. Low-slump concrete is molded and cured to produce strong blocks or units. Residential foundation walls typically are constructed with units 7 5/8 inches (nominal 8 inches) high by 15 5/8 inches (nominal 16 inches) long, providing a 3/8-inch allowance for the width of mortar joints. Nominal 8- and 12-inch-thick CMUs are readily available for use in residential construction.

Type

ASTM C90 (ASTM, 2013) requires that the minimum average design strength (f'_m) of standard CMUs be 1,900 psi, with no individual unit having a compressive strength of less than 1,700 psi. Higher strengths also may be specified if required by design. The ASTM classification includes two types. Type II is a non-moisture-controlled unit and is the type typically used for residential foundation walls.

Weight

CMUs are available with different densities by altering the type(s) of aggregate used in their manufacture. CMUs typically are referred to as lightweight, medium weight, or normal weight, with respective unit weights or densities of less than 105 pcf, between 105 and 125 pcf, and more than 125 pcf. Residential foundation walls typically are constructed with low- to medium-weight units because of the low compressive strength required. Lower density units are generally more porous, however, and must be properly protected to resist moisture intrusion. A common practice in residential basement foundation wall construction is to provide a cement-based parge coating and a brush- or spray-applied bituminous coating on the belowground portions of the wall. Section R406 in the IRC provides the prescriptive requirements for parging and damp-proofing or waterproofing foundation walls that retain earth and enclose interior spaces. The parge coating is not required for concrete foundation wall construction.

Hollow or Solid

CMUs are classified as hollow or solid in accordance with ASTM C90. The net concrete cross-sectional area of most CMUs ranges from 50 to 70 percent, depending on unit width, face-shell and web thicknesses, and core configuration. *Hollow* units are defined as those in which the net concrete cross-sectional area is less than 75 percent of the gross cross-sectional area. *Solid* units are not necessarily solid but are defined as those in which the net concrete cross-sectional area is 75 percent of the gross cross-sectional area or greater.

Mortar

Masonry mortar is used to join CMUs into a structural wall; it also retards air and moisture infiltration. The most common way to lay block is in a running bond pattern, in which the vertical head joints between blocks are offset by half the block length from one course to the next. Mortar is composed of water, cement, lime, and clean, well-graded sand, and water and is typically classified into *types M, S, N, O,* and *K,* in accordance with ASTM C270 (ASTM, 2012a). Residential foundation walls typically are constructed with *type M* or *type S* mortar, both of which are generally recommended for load-bearing interior and exterior walls, including above- and below-grade applications.

Grout

Grout is a slurry consisting of cementitious material, aggregate, and water. When needed, grout commonly is placed in the hollow cores of CMUs to provide a wall with added strength. In reinforced load-bearing masonry wall construction, grout is usually placed only in those hollow cores containing steel reinforcement. The grout bonds the masonry units and steel so that they act as a composite unit to resist imposed loads. Grout may also be used in unreinforced concrete masonry walls for added strength. The IRC requires grouted cells at foundation sill and sole plate anchor bolt locations, regardless of whether the masonry wall is otherwise reinforced.

4.3 Soil-Bearing Capacity and Footing Size

Soil-bearing investigations rarely are required for residential construction except when a history of local problems provides evidence of known risks (for example, organic deposits, landfills, expansive soils, and seismic risk). Soil-bearing tests on stronger-than-average soils can, however, justify using smaller footings or eliminating footings entirely if the foundation wall provides sufficient bearing surface. Table 4.2 provides a conservative relationship between soil type and load-bearing value. A similar table is published in the building codes (table R401.4.1 in the IRC). These presumptive soil-bearing values, however, should be used only when the building codes do not require geotechnical investigation reports (section R401.4, IRC).

TABLE 4.2 Presumptive Soil-Bearing Values by Soil Description

Presumptive Load-Bearing Value (psf)	Soil Description
1,500	Clay, sandy clay, silty clay, clayey silt, silt, and sandy silt
2,000	Sand, silty sand, clayey sand, silty gravel, and clayey gravel
3,000	Gravel and sandy gravel
4,000	Sedimentary and foliated rock
12,000	Crystalline bedrock

psf = pounds per square foot.

Source: ICC (2012).

When a soil-bearing investigation is desired to determine more accurate and economical footing requirements, the designer commonly turns to ASTM D1586, *Standard Penetration Test (SPT) and Split-Barrel Sampling of Soils* (ASTM, 2011). This test relies on a 2-inch-diameter device driven into the ground with a 140-pound hammer dropped from a distance of 30 inches. The number of hammer drops or blows needed to create a 1-foot penetration (blow count) yields values that can be roughly correlated to soil-bearing values, as shown in Table 4.3. The instrumentation and cost of conducting the SPT usually are not warranted for typical residential applications. Nonetheless, the SPT method provides information on deeper soil strata and thus can offer valuable guidance for foundation design and building location, particularly when subsurface conditions threaten to be problematic. The values in Table 4.3 are associated with the blow count from the SPT method. Many engineers can provide reasonable estimates of soil bearing by using smaller penetrometers at lower cost, although such devices and methods may require an independent calibration to determine presumptive soil-bearing values and may not be able to detect deep subsurface problems. Calibrations may be provided by the manufacturer or, alternatively, developed by the engineer.

In addition to ASTM D1586, the Dynamic Cone Penetrometer (DCP) test (Burnham and Johnson, 1993), has gained widespread use as a more economical alternative with equivalent accuracy. In this handheld test, a metal cone is driven into the ground by repeatedly striking it with a 17.6-pound (8-kilogram) weight, dropped from a distance of 2.26 feet (575 millimeters). Penetration of the cone is measured after each blow; the blow count per 1 3/4-inch penetration is approximately equivalent to the SPT blow count provided in table 4.3.

The designer should exercise judgment when selecting the final design value and be prepared to make adjustments (increases or decreases) in interpreting and applying the results to a specific design. The values in tables 4.2 and 4.3 generally are associated with a safety factor of 3 (Naval Facilities Engineering Command, 1986) and are considered appropriate for noncontinuous or independent spread footings supporting columns or piers (that is, point loads). Use of a safety factor could be considered for smaller structures with continuous spread footings, such as houses, or structures for which ultimate (LRFD) values are used for design loads. The presumptive values in Table 4.3—or as modified as described previously—are intended to be used with the ASD load combinations in chapter 3. If LRFD (strength) design load combinations are used, then the presumptive values should be additionally adjusted (that is, divided by the maximum load factor in the load combination considered, usually a factor of 1.6 for live or snow loads).

Table 4.3 ***Presumptive Soil-Bearing Values (psf) Based on Standard Penetrometer Blow Count***

In Situ Consistency, N[1]		Loose[2] (5 to 10 blows per foot)	Firm (10 to 25 blows per foot)	Compact (25 to 50 blows per foot)
Noncohesive Soils	Gravel	4,000 (10)	8,000 (25)	11,000 (50)
	Sand	2,500 (6)	5,000 (20)	6,000 (35)
	Fine sand	1,000 (5)	3,000 (12)	5,000 (30)
	Silt	500 (5)	2,000 (15)	4,000 (35)
In Situ Consistency, N[1]:		**Soft[3] (3 to 5 blows per foot)**	**Medium (about 10 blows per foot)**	**Stiff (more than 20 blows per foot)**
Cohesive Soils	Clay, sand, gravel mixtures	2,000 (3)	5,000 (10)	8,000 (20)
	Sandy or silty clay	1,000 (4)	3,000 (8)	6,000 (20)
	Clay	500 (5)	2,000 (10)	4,000 (25)

Source: Naval Facilities Engineering Command, 1986.

psf = pounds per square foot.

[1]N denotes the standard penetrometer blow count in blows per foot, in accordance with ASTM D1586; shown in parentheses.
[2]Compaction should be considered in these conditions, particularly when the blow count is five blows per foot or less.
[3]Pile and grade beam foundations should be considered in these conditions, particularly when the blow count is five blows per foot or less.

The required width or area of a spread footing is determined by dividing the building load on the footing by the soil-bearing capacity from table 4.2 or table 4.3, as shown below. Building design loads, including dead and live loads, should be determined in accordance with chapter 3 by using ASD load combinations.

$$Area_{independent\ spread\ footing} = \frac{Load\ in\ lbs}{Soil-bearing\ capacity\ in\ psf}$$

$$Width_{continuous\ footing} = \frac{Load,\ lb\ per\ linear\ foot\ (plf)}{Soil-bearing\ capacity\ in\ psf}$$

4.4 Footings

The objectives of footing design are—

- To provide a level surface for construction of the foundation wall.
- To provide adequate transfer and distribution of building loads to the underlying soil.
- To provide adequate strength, in addition to the foundation wall, to prevent differential settlement of the building in weak or uncertain soil conditions by bridging those poor soil conditions.
- To place the building foundation at a sufficient depth to avoid frost heave or thaw weakening in frost-susceptible soils and to avoid organic surface soil layers.
- To provide adequate anchorage or mass (when needed in addition to the foundation wall) to resist potential uplift, sliding, and overturning forces resulting from high winds or severe seismic events.

This section presents design methods for concrete and gravel footings. The designer must first establish the required footing width in accordance with section 4.3. Further, if soil conditions are stable or the foundation wall can adequately resist potential differential settlement, the footing may be completely eliminated.

By far, the most common footing in residential construction is a continuous concrete spread footing; however, concrete and gravel footings are both recognized in prescriptive footing size tables in residential building codes for most typical conditions (ICC, 2012). In contrast, special conditions give rise to engineering concerns that must be addressed to ensure the adequacy of any foundation design. Special conditions include—

- Steeply sloped sites requiring a stepped footing.
- High wind conditions.
- Inland or coastal flooding conditions.
- High-hazard seismic conditions.
- Poor soil conditions.