Coastal Foundations and Best Practices

6.1 Introduction

A building's foundation is arguably its most important structural element. Despite its particular location, a foundation must support the building above it and all the loads that are exerted on it. It must adequately transfer loads acting on the structure to the supporting soils and must resist weathering, decay, and corrosion (with little or no maintenance) in order to remain viable for the entire life of the building. The foundation must perform all of these functions while being exposed to the damaging effects and conditions present in a coastal environment. These effects include erosion and scour, breaking waves and moving floodwaters, and the potentially disastrous effects of floodborne debris. Coastal foundations must, therefore, be stronger, better planned and designed, and more solidly constructed than inland foundations.

In inland areas where wind and seismic loads often control the design, the criteria for foundations are well-defined and easily understood by engineers, architects, builders, and building officials. Codes such as the IBC and the IRC (and their predecessors) have for decades provided detailed requirements for foundations and prescriptive foundation designs for many structures. In coastal areas, however, this has not been true.

While wind and seismic criteria have long been established, flood criteria are newer and have appeared only recently in performance-based consensus codes and standards. The flood provisions of ASCE 7 first appeared in the 1995 edition of that standard. Similarly, the consensus standard ASCE 24 was first issued in 1998. Because the origination of flood provisions in performance codes and standards has occurred relatively recently, flood designs have yet to make their way into prescriptive codes and standards. No consensus-based, off-the-shelf, flood-resistant designs that fully address construction in coastal areas currently exist. Documents such as FEMA 259 and FEMA 550 provide prescriptive design guidance for foundations. FEMA 499, Technical Fact Sheets No. 11 (*Foundations in Coastal Areas)*, No. 12 (*Pile Installation*), and No.13 (*Wood Pile-to-Beam Connections*) also provide appropriate guidance.

Some aspects of coastal environments, such as scour and erosion, have not been researched to the point that consensus codes or standards have been developed on these topics. Decisions regarding some coastal issues (e.g., scour and erosion) may need to be based primarily on judgment from local design professionals or published guidance, or on historical data and trends. In the absence of more definitive data, decisions may need to be based solely on local experience.

6.2 Building Codes and Coastal Foundations

Coastal construction is regulated in several IBC sections. IBC Section 1603.1.6 requires that when a home is located within a SFHA, information on local flood conditions and elevations must be specified in the construction documents. When a home is sited in an area subject to high-velocity wave action (i.e., a V Zone), the IBC also requires that the proposed elevation of the lowest horizontal structural member be specified. IBC Section 1612.4 requires that homes in high-velocity wave action zones be designed in accordance with ASCE 24-05, which requires that foundations be constructed to resist all flood forces exerted on them; remain "free of obstructions or attachments that will transfer forces to the structural system or that will restrict or eliminate free passage of high-velocity floodwaters and waves"; and be constructed of flood-resistant materials. ASCE 24-05 requires that structures in areas subject to high-velocity wave action be supported on piles, columns, or shear walls. Shallow mat or raft foundations may be used only when the tops of those foundations are placed below the estimated maximum-eroded ground surface. ASCE 24-05 also specifies freeboard (that is, requires structures to be elevated above the NFIP-mandated requirements). The amount of freeboard depends upon the importance of the building and the orientation of the building's structural elements in relationship to incoming waves. ASCE 24-05 freeboard requirements generally vary between 1 and 2 feet.

IBC Section 1612.5(2) also requires that V Zone construction design documents include a statement that the building is "designed in accordance with ASCE 24" and that the "building or structure to be attached thereto is designed to be anchored to resist flotation, collapse, and lateral movement due to the effects of wind and flood loads acting simultaneously on all building components, and other load requirements of Chapter 16." This provision may require architects or engineers to design the foundation for buildings located within V Zones.

The IRC requirements are similar but somewhat less stringent than those of the IBC. IRC Section R324 requires that homes be elevated and anchored to resist flotation, collapse, and lateral movement; IRC Section R324.3.6 requires that design professionals prepare construction documents stating that the design and construction methods satisfy the flood provisions of the IRC. The freeboard requirements of ASCE 24-05, however, are invoked only when a home is placed within a floodway. As a best practices approach, the freeboard requirements of ASCE 24-05 should be met for all coastal construction (both residential and non-residential).

6.3 Constructing Foundations in Coastal Areas

Building in coastal environments poses unique challenges:

- The effects of storm surge, wave action, and erosion make coastal flooding more damaging than inland flooding.
- Buildings are often required to be elevated higher than they would be in inland sites to avoid flooding and wave action, particularly in areas where storm surge can inflict severe damage on the buildings.
- Foundations are exposed to damaging floodborne debris that results when floodwaters destroy older or weaker buildings and coastal structures.

NOTE

For information on Coastal A Zones, see Chapter 2 of this guide or Chapter 12 of FEMA 55.

- Erosion and scour can undermine foundations, thus causing buildings to fail.
- Basic (design) wind speeds are typically greater in coastal areas than in inland areas and require buildings (and their foundations) to be stronger in order to resist those greater loads.

In coastal environments, code-compliant foundations must be designed and constructed:

- To elevate the building high enough to avoid flooding.
- To be strong enough to resist all loads expected to act on the building and its foundation during a design event.
- To satisfy the minimum requirements of the NFIP and any state or local floodplain management conditions.
- To prevent flotation, collapse, and lateral movement of the building.
- With flood-resistant materials at or below the BFE (or DFE, in areas where the use of freeboard is mandated)
- So that the lowest floor (in A Zones) or the bottoms of the lowest horizontal structural members (in V Zones) are elevated above the BFE/DFE
- To accommodate expected scour and erosion throughout the life of the structure

> **NOTE**
>
> Some coastal areas mapped as A Zones may be subject to damaging waves and erosion. ASCE 24-05 defines Coastal A Zones as areas landward of V Zones or areas landward of an open coast, where breaking-wave heights may exceed 1.5 feet. (The V Zone/A Zone boundary on Flood Insurance Rate Maps denotes areas where design-event breaking-wave heights reach 3 feet. When the wave is 3 feet high or higher, this area is mapped as a V Zone, while areas with waves less than 3 feet high are mapped as A Zones.)

The NFIP allows conventional foundations (that is, shallow, closed foundations equipped with flood-equalizing vents) in Coastal A Zones; however, evaluations conducted after numerous hurricanes confirm that NFIP-allowed conventional foundations often fail when exposed to breaking waves or when undermined by erosion. Because of this, V Zone construction is recommended for Coastal A Zones. As discussed in Chapter 3 of this guide, V Zone construction involves placing structures on deep, open foundations that elevate the lowest horizontal structural member of the building above the BFE or DFE (see Figure 6-1). Figures 6-2 and 6-3 show examples of building failure in an area where Coastal A Zone conditions likely existed.

The inland extent of a Coastal A Zone is the line where a design flood event can create a 1.5-foot-high breaking wave and is identified on newer FIRM panels with a line different from the flood hazard boundary line; this line is called the Limit of Moderate Wave Action (LiMWA). (That boundary is delineated where stillwater depths equal approximately 2 feet.) Breaking waves at that boundary can destroy concrete or masonry foundation walls that lack adequate reinforcement to resist wave loads from those relatively short-breaking waves.

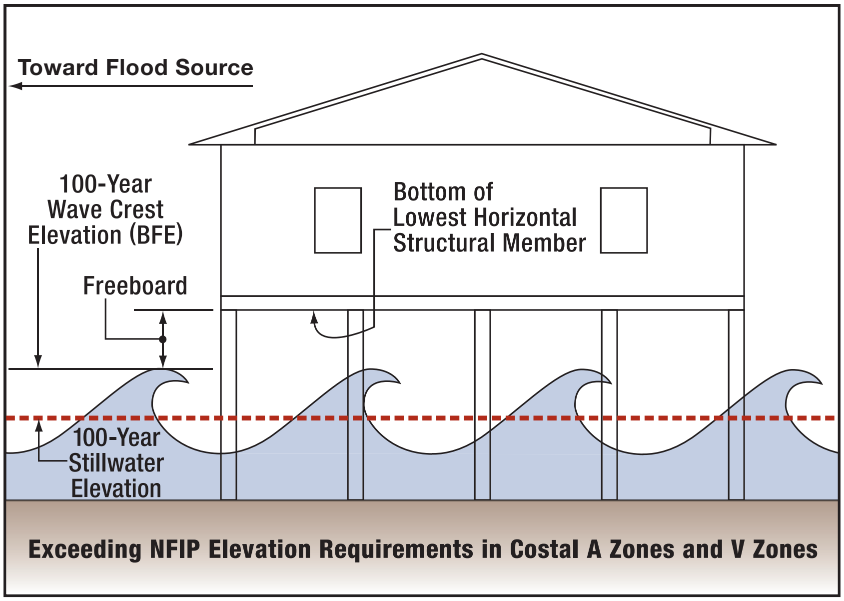

Figure 6-1.
Recommended open-foundation practice for buildings located within the Coastal A Zone and V Zone. (Source: FEMA 55)

Figure 6-2.
NAVARRE BEACH, FLORIDA:
Slab-on-grade foundation failure due to erosion and scour undermining.
(Source: FEMA 489)

Figure 6-3.
NAVARRE BEACH, FLORIDA: Close-up of foundation failure shown in Figure 6-2.
(Source: FEMA 489)

6.4 Elevating Buildings in Coastal Areas

Buildings in coastal areas may be elevated in many ways. Homes can be elevated on fill, constructed with closed foundations (for example, crawlspace foundations, stem wall foundations, or slab-on-grade foundations), or constructed on open foundations (using piers, pilings, or columns). Not all elevation methods, however, are suitable for all coastal areas. In fact, several methods are prohibited in V Zones, while some methods are allowed but not recommended for use within other coastal areas. This section discusses the foundation types used to elevate buildings and the acceptability of each style within a coastal area.

6.4.1 Elevation on Fill

Before building on a site within an SFHA, the site itself can be elevated with fill (see Figure 6-4). Fill can elevate a site above the BFE and thus release the builder from having to comply with certain NFIP construction requirements. Alternatively, fill may be used to partially elevate the site and allow shorter NFIP-compliant foundations to be used. Shorter foundations improve building accessibility and are often desirable for the elderly, handicapped, or others with physical challenges.

Because fill is susceptible to erosion, it is not always the best option to mitigate flood hazards. Its use is prohibited as a means of providing structural support to buildings in V Zones and is not recommended in Coastal A Zones. Fill may not be used as a means of elevating buildings in coastal areas subject to erosion, waves, or fast-moving water.

Figure 6-4.
PLAQUEMINES PARISH, LOUISIANA: Home that had been elevated on fill, during the aftermath of Hurricane Katrina.
(Source: FEMA 549)

6.4.2 Closed Foundations

A closed foundation typically consists of continuous perimeter foundation walls. Because these walls enclose areas within "solid" perimeter walls, this is often referred to as a "closed" foundation. A closed foundation can be a crawlspace foundation, a stem wall foundation (usually filled with compacted soil), or a slab-on-grade (or monolithic) foundation.

> **NOTE**
> Although the NFIP permits closed foundations in A Zones, they are not recommended in Coastal A Zones. The walls of these foundations will be exposed to large forces from waves and fast-moving waters and may exacerbate scour at the building site.

A closed foundation obstructs floodwaters and does not allow water to pass easily through a foundation.Closed foundations also present large surface areas upon which waves and flood forces can act. Because of their vulnerability to breaking waves, the use of closed foundations is prohibited within V Zones and is not recommended within Coastal A Zones.

Properly designed and constructed closed foundations are suitable for SFHAs where the heights of breaking waves are less than 1.5 feet (i.e., non-coastal A Zones). In these instances, the foundation walls must be equipped with openings that allow water to enter the area enclosed by the walls. The openings are necessary to keep unbalanced loads from occurring due to the presence of floodwaters outside the walls (and not inside them). The openings allow water to enter and exit the area behind the foundation. The flow of floodwater into and out of the foundation equalizes water on both sides of the wall. This equalization significantly reduces lateral hydrostatic forces on the walls. FEMA 499, Technical Fact Sheet No. 15, *Foundation Walls*, and FEMA NFIP Technical Bulletin 1: *Openings in Foundation Walls and Walls of Enclosures* (FIA-TB-1), contain information on flood openings for closed foundations.

As with any foundation, closed foundations must adequately support the structure above and transfer loads acting on the elevated building and the foundation to the soil below. In non-coastal environments, wind (or seismic) and gravity loads typically dominate and control foundation design. In coastal environments, flood loads must also be addressed.

Wind loads are transferred through a structure via properly designed and constructed vertical and horizontal load paths. Particular attention should be given where the building attaches to the foundation; the loads created by the wind acting on the roof and walls must be transferred through the building into the foundation and into the ground. For residential construction, connections to resist uplift and shear wall reactions from wind forces are detailed in prescriptive codes and standards such as the IRC, AF&PA's *Wood Frame Construction Manual*, and ICC-600, *Standard for Residential Construction in High-Wind Regions*.

Foundations designed for wind only may lack the strength required to resist flood loads. While wind-resistant foundation designs are prevalent, prescriptive flood- and wind-resistant designs are less available. FEMA 550 is a guidance document which presents many wind- and flood-resistant designs.

For short foundation walls (i.e., those 3 feet high or less) that do not retain backfilled soils, reinforcement may be necessary in order construct a foundation wall. It should be considered that the reinforcing necessary to resist a 1.5-foot-high breaking wave is comparable to that required to resist wind loads of 120 mph. However, taller foundation walls need additional reinforcement to resist breaking-wave loads. For example, 8-foot-high walls may require the placement of vertical reinforcing steel within masonry walls, with a spacing of 16 inches on center. FEMA 550 contains designs for closed foundations that can resist wind loads and flood loads from 1.5-foot-high breaking waves.

6.4.2.1 Crawlspace Foundations

Crawlspace foundations typically consist of perimeter masonry or concrete foundation walls and a system of interior beams and piers that support an elevated floor framing system. In permanent wood foundations, the perimeter walls are framed with preservative-treated wood framing and sheathing. Elevated floors are typically wood-framed, but they may also be constructed of concrete. This section discusses crawlspace foundations on closed foundation walls. (See Subsection 6.4.3.2 for a discussion on open crawlspace foundations.)

In many instances, crawlspaces are used as a location for mechanical equipment (such as ductwork and piping), and the floor framing is typically constructed of wood. If mechanical equipment is installed in the crawlspace, precautions should be taken in order to make sure that the ductwork is located above the BFE in order to maintain NFIP compliance.

Closed-wall crawlspace foundations are usually constructed on relatively shallow, cast-in-place concrete footings, where the depth of the footing is dictated by the local frost depth. Because closed-wall crawlspace foundations are shallow, they are vulnerable to being undermined from erosion and scour and are not recommended for use within Coastal A Zones. Because closed-wall crawlspace foundations are vulnerable to breaking waves, the NFIP prohibits their use within V Zones. Figures 6-5 and 6-6 illustrate the vulnerability of closed-wall crawlspace foundations within a V Zone.

The NFIP requires flood openings in crawlspace foundations constructed within SFHAs. A minimum of two openings (having a total net area of not less than 1 square inch for each square foot of enclosed area subject to flooding) shall be provided. To remain effective, the NFIP requires that the bottoms of flood openings be placed within 1 foot of grade; this limits lateral forces on foundation walls. (FEMA 499 Technical Fact Sheets No. 15, *Foundation Walls*, and No. 27, *Enclosures and Breakaway Walls*, contain guidance on flood openings.)

Figure 6-5.
Building failure caused by undermining of crawlspace foundation during Hurricane Fran. Breaking waves may also have contributed to foundation failure. (Source: FEMA 290)

Figure 6-6.
Failure of crawlspace foundation undermined by scour. (Source: FEMA 290)

Flood openings can rarely, if ever, be used for air ventilation and humidity control. Vents for humidity control are typically most effective at preventing condensation on vulnerable floor framing when they are installed high within the crawlspace; such placement is not effective for protecting foundation walls from damaging flood loads. Vents with combined purposes should be inspected to verify their proper positioning.

NOTE

FEMA 550 has prescriptive designs for crawlspace foundations up to 8 feet high for Exposure C design-wind speeds of up to 150 mph.

A recent trend involves the use of conditioned crawlspaces for temperature and humidity control. To prove effective (and to avoid exacerbating moisture problems), crawlspaces must be completely sealed to prevent migration of exterior humidity into the space. They must also be insulated to control cold areas, where condensation can form. Properly conditioning crawlspaces is a complex undertaking. Because they must be completely sealed for effective conditioning, conditioned crawlspaces should not be used within SFHAs unless the NFIP-required flood vents adequately seal the space while remaining able to open under the pressure exerted by floodwaters. Also, the NFIP requires that any material placed below the BFE (or DFE) be flood-resistant, thus precluding the use of many types of insulation.

6.4.2.2 Stem Wall Foundations

Stem wall foundations are similar to crawlspace foundations. They consist of perimeter foundation walls (typically masonry or concrete), but the interior space that would otherwise form the crawlspace is backfilled with soils that support a floor slab. In the Gulf Coast region, these foundations are often referred to as "chain walls." Figure 6-7 shows a cross section of a typical stem wall foundation.

Anecdotal evidence suggests that during flood events stem wall foundations have performed better than many crawlspace foundations. However, it is important to note that the prescriptive designs set forth in the building codes often limit stem wall height to just a few feet. While higher stem wall foundations can be designed, the cost of suitable fill and proper fill placement often makes their use impractical. The use of stem wall foundations is prohibited within V Zones and is not recommended for use within Coastal A Zones; however, their use is appropriate within A Zones where wave heights are 1.5 feet or less and where footings are deep enough to resist scour and erosion.

Stem wall foundations do not require vents to equalize the pressures exhibited by floodwaters. They do, however, need to be strong enough to resist lateral pressure from retained soils. Because the retained soils can become saturated during a flood event, additional reinforcement is typically needed.

FEMA 550 has prescriptive flood- and wind-resistant designs for stem wall foundations. Designs are provided for two types of walls: cantilevered and laterally supported. In cantilevered walls, reinforcing steel provides sufficient strength to resist lateral forces without relying on the floor slab to laterally support the top of the wall. In laterally supported walls, the top of the wall is tied to the floor slab; the typical result is that less vertical reinforcement is needed in the foundation. Laterally supported walls must be braced to prevent movement or collapse when backfilling.

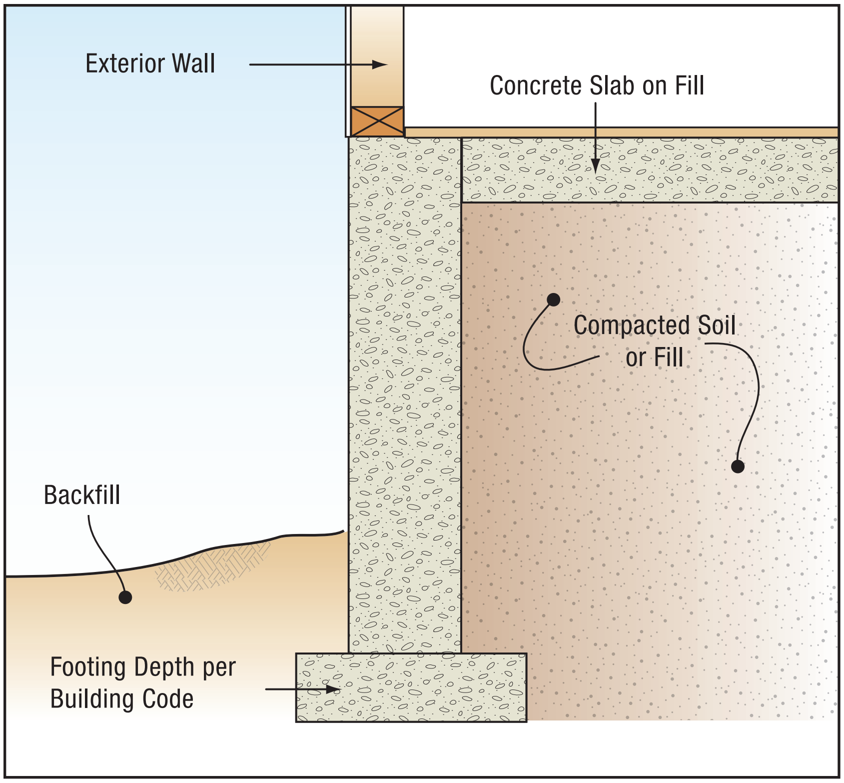

Figure 6-7.
Typical stem wall foundation. (Source: FEMA 543)

6.4.2.3 Slab-on-Grade Foundations

Slab-on-grade foundations are similar to stem wall foundations. Like stem wall foundations, the floor consists of a concrete-grade slab. Unlike stem wall foundations, however, slab-on-grade foundations do not have a true perimeter foundation wall, but instead have thickened portions of the slab that function as footers for the exterior walls and interior bearing walls.

In many areas, slab-on-grade foundations are the most cost-effective type of foundation. In an SFHA, however, their use carries limitations. From a practical standpoint, they can only be used to elevate a building 1 foot or less (higher elevations require large quantities of concrete). Therefore, where flood depths exceed 1 foot, the use of other foundations should be considered. Slab-on-grade foundations can be used in conjunction with properly placed and compacted fill.

Slab-on-grade foundations are shallow foundations that are susceptible to being undermined by scour and erosion. The use of slab-on-grade foundations is prohibited within V Zones and is not recommended for Coastal A Zones. (Note that parking slabs are often permitted below elevated buildings in V Zones, but they are recommended to be frangible; by their design requirements, they are themselves susceptible to undermining and collapse.)

6.4.3 Open Foundations

Open foundations are constructed in such a manner to allow floodwaters to flow freely through them. Open foundations also minimize the total surface area that floodwaters may act upon. When compared to closed foundations for the same size building, an open foundation will have lower-magnitude flood forces acting on the foundation. Open foundations also offer the benefit of being less susceptible to damage from floodborne debris because they provide less contact area for debris to impact than closed foundations.

Simply stated, the portion of the foundation above exterior grade is minimal and allows nearly unrestricted movement of floodwaters beneath the building. Below-grade foundation components can be described as a deep foundation with deeply driven piers or caissons or shallow foundations with footings or grade beams. Terms such as "deep" and "shallow" are relative and are best used to refer to the maximum scour and erosion anticipated during a design event or during the projected life of the building.

Figure 6-8.
FORT MYERS BEACH, FLORIDA: Oceanfront house constructed on an open foundation sustained only minor damage after being exposed to high winds and storm surge. (Source: FEMA 488)

NOTE

While Hurricane Charley created near design-level winds in Florida, the storm surge created by the hurricane was limited. As a result, it was not a design flood event in most impacted areas.

6.4.3.1 Deep, Open Foundations

Buildings founded and supported by driven piles or caissons in deep soil strata generally offer the greatest resistance to coastal hazards. When supported by foundations deep enough to retain sufficient strength to resist flood loads after scour and erosion have removed soils around the foundation, properly constructed buildings can fare well, even when exposed to wind loads. Post-event assessments have revealed success stories, even when buildings have been exposed to conditions greater than those anticipated during a design event. Figures 6-9 and 6-10 illustrate the successful use of deep, open foundations.

Figure 6-9.
FORT MYERS BEACH, FLORIDA: Newly constructed house elevated on an open foundation sustained no storm surge damage when surges several feet deep impacted this site in 2004. (Source: FEMA 488)

Figure 6-10.
DAUPHIN ISLAND, ALABAMA: Successful pile foundation following Hurricane Katrina. The foundation supported the elevated home even after scour and erosion removed several feet of soils.
(Source: FEMA 549)

Unfortunately, post-event assessments of buildings on deep foundations in coastal areas often reveal failures due to poor construction. Many of these failures result from the use of inadequately designed foundations or inadequate connections between the elevated structure and its foundation, as shown in Figures 6-11 and 6-12.

Figure 6-11.
DAUPHIN ISLAND, ALABAMA: Structure near collapse due to insufficient pile embedment.
(Source: FEMA 549)

Figure 6-12.
LONG BEACH, MISSISSIPPI: Structure removed from its foundation when waves exceeded the foundation height and connections between the elevated building and its foundation failed. The building was located within a mapped V Zone.
(Source: FEMA 549)

For successful performance, deep and open foundations must be designed to elevate the building above anticipated floodwaters, transfer all loads applied to the elevated building and the exposed foundation components to the supporting soils, and resist the damaging effects of breaking waves, moving floodwaters, and floodborne debris. FEMA 55 and ASCE 24-05 provide detailed design procedures to calculate the loads associated with these criteria. No prescriptive solutions for open foundations are provided in either the IBC or the IRC.

Pile foundations consist of deep vertical piles installed to support an elevated structure. Because pile foundations are typically set deep within the soil, they are inherently less susceptible to scour and erosion. Piles rely primarily on the friction forces that develop between the pile and the surrounding soils (to resist gravity and uplift forces) and on the compressive strength of the soils (to resist lateral movement and maintain the structure's lateral stability). The soils at the ends of the piles also help resist gravity loads. When the piles rest on their pile tips for load bearing, the designer must show that the soil surrounding the piles provides appropriate lateral stability. Serious consideration should be given by the designer to ensure that the structure is capable of maintaining its lateral stability during a storm event.

Several styles of deep, open foundations exist. Piles are typically treated wood timbers, steel pipes, or pre-cast concrete members. Other materials, such as fiber-reinforced polyester (FRP), are available but are not commonly used in residential construction. For load path continuity, consideration should be given to extending the timber piles to the roof level (in single-story buildings) or to the second level (in multi-level buildings). This provides additional stiffness to the structure that reduces undesirable deflection in the building, increases the ability of a building to resist lateral loads, and may reduce the need to cross-brace the piles.

Crucial aspects of a pile foundation include pile size, installation method, embedment depth, bracing, and connections to the elevated structure (see FEMA, 499 Technical Fact Sheets No. 12, *Pile Installation*, and No. 13, *Wood-Pile-to-Beam Connections*). Inadequate embedment and the use of improperly-sized piles greatly increase the probability of structural collapse. Piles are appropriate for use within all coastal zones when the bearing and lateral capacities are verified by a geotechnical engineer.

The method of installation is a major consideration in the structural integrity of pile foundations. The ideal option is to use a driven-pile method, as it disturbs the supporting soil around the pile the least amount and results in the highest bearing capacity for each pile. Through this method, the pile is held in place with leads while a single-acting or double-acting diesel- or air-powered hammer drives the pile into the ground (see Figure 6-13).

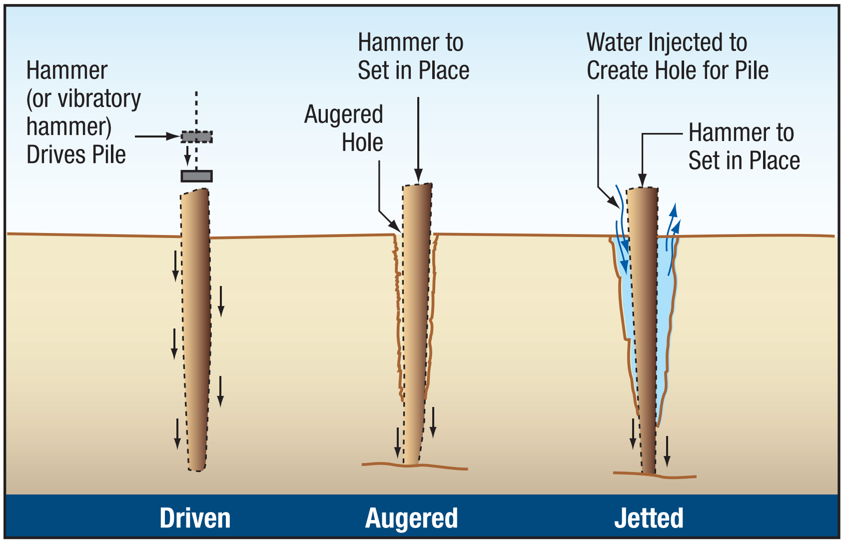

Figure 6-13.
Pile installation methods.
(Source: FEMA 55)

Driven piles may be set with vibratory hammers or with drop hammers, with drop hammers typically proving to be the less expensive choice. A drop hammer consists of a heavy weight raised by a cable (attached to a power-driven winch) which is then dropped onto the pile.

If steel piles are employed, only the driven-pile method should be used. For any pile driving, the authority having jurisdiction or the engineer-of-record may require that a driving log is maintained for each pile. The log will record the number of blows required per foot as driving progresses. This log is a key factor used to determine pile capacity.

Holes for piles may be excavated by an auger if cohesive soils with sufficient clay or silt content are present to prevent cave-in. Augering can be used alone or in conjunction with pile driving. If the hole is "full-sized," the pile is dropped in and the void backfilled. Alternatively, an undersized hole can be drilled and a pile driven into it. When soil conditions are appropriate, the hole will stay open long enough to drop or drive in a pile.

Jetting is another frequently used method of inserting piles into sandy soil. Jetting involves forcing a high-pressure stream of water through a pipe that advances with the pile. The water creates a hole in the sand as the pile is driven until the required depth is reached. Unfortunately, jetting loosens the soil that will support the pile and the tip, resulting in a lower load capacity due to less frictional resistance. Figure 6-13 shows various methods of pile placement.

Wood-Pile-to-Beam Connections

Wood piles are used in many coastal areas for open foundation. These piles are often notched to provide a bearing surface for a beam supporting the house above. When this method is used, the notch should not reduce the pile cross section more than 50 percent (such information is typically provided by a designer on the building plans). A larger pile notch than 50 percent will result in a reduced capacity to carry lateral loads at the connection. Also, for proper support of vertical loads, the beam should bear on the surface of the pile notch.

Chapter 5 discussed the importance of connections within the continuous load path. Post-disaster investigations have observed that the wood-pile-to-beam connection point has been a critical link. If there is a poor connection at the point where the top of the pile connects to the building itself, failure may occur. An engineer should design the connection between a wood pile and the elevated structure (see FEMA 499, Technical Fact Sheet No. 13, *Wood-Pile-to-Beam Connections*). This connection may require pile bracing in order to reduce a pile's unbraced length and maintain a strong connection. Engineers should consider the pile group, the connections, and the floor system (diaphragm) as an entire system. In order to eliminate pile and connection failures, it is important that the floor system and the pile group act as a complete system and not independently.

Pile Bracing

While foundation designs that are free of bracing are preferred, most foundation designs using timber piles rely upon bracing. Possible exceptions include short-pile foundations (i.e., those extending between 4 and 6 feet above grade), foundations supporting small homes with limited vertical surfaces exposed to wind loads, or foundations in areas with low basic wind speeds. When installed properly, bracing increases the stiffness of the pile group that (in some cases) may allow for wider spacing of piles beneath the building or smaller diameter piles to be used. The inclusion of bracing increases the axial capacity of a timber pile due to the reduction in unbraced length. Bracing also reduces lateral displacements of the building by stiffening the foundation.

In wood-framed construction, bracing typically involves diagonal cross-bracing or knee-bracing. Diagonal cross-bracing consists of long, slender steel rods or dimensional lumber installed diagonally between adjacent piles. Knee braces are shorter members installed between piles and the beams they support. Knee braces extend from the upper portion of the pile to the beams and support the pile in such a manner that the unbraced length of the pile is effectively reduced while allowing the floor system to be elevated as high as possible. Due to the strength limitations inherent in wood framing, however, some of the proper connections required to transfer the loads are difficult to obtain with wood framing.

Diagonal cross-bracing is the most effective means of bracing a pile to reduce the unbraced pile length, but this method has vulnerabilities when used in coastal foundation applications. The braces themselves can obstruct moving floodwater and increase a foundation's exposure to impact from waves and debris (see Figure 6-14). Knee-bracing is less vulnerable to flood loads and debris impact but may not provide as much stability and support as diagonal cross-bracing.

Because diagonal braces tend to be slender, these members are susceptible to compression failures; hence, most bracing is considered tension-only bracing. Because wind loads and (to a lesser extent) flood loads

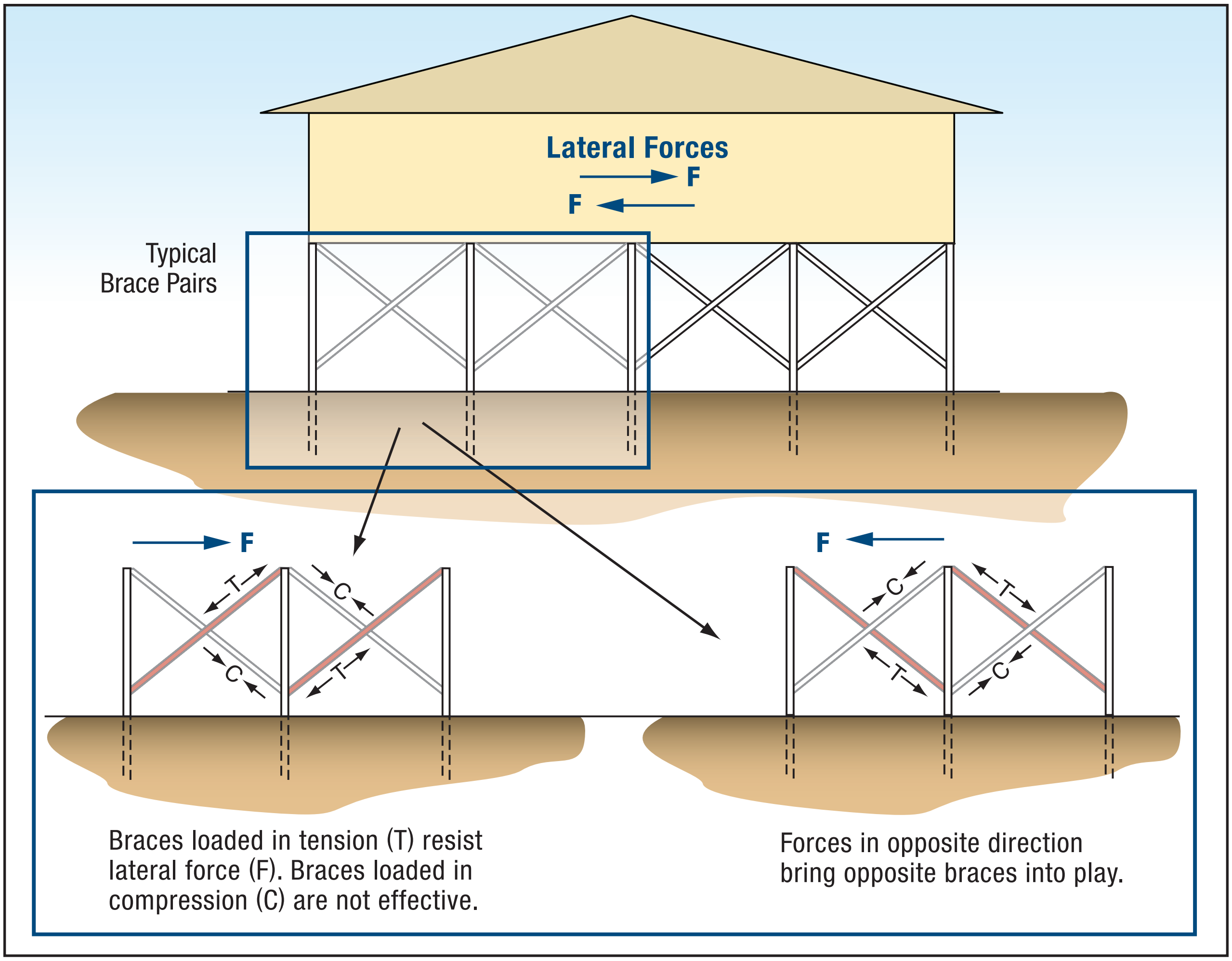

Figure 6-14.
Diagonal bracing schematic. (Source: FEMA 550)

can act in opposite directions, tension-only bracing must be installed in pairs. One set of braces resists loads from one direction while the second set resists loads from the opposite direction.

Figure 6-14 shows how tension-only bracing pairs resist lateral loads on a structure. The orientation of the bracing is an important design consideration and it is important that the bracing is constructed in a manner consistent with the plans. Bracing should be oriented parallel to the anticipated direction of the flow of water to reduce the potential for debris dams.

The placement of the bolted connection of the diagonal cross brace to the pile requires considerable judgment. If the connection is placed too high above grade, the pile length below the connection is not braced and the overall bracing will prove less strong and sturdy. If the connection is placed too close to grade, the bolt hole is more likely to be flooded or infested with termites. Because the bolt hole passes through the untreated part of the pile, flooding and subsequent decay or termite infestation may weaken the pile at a vulnerable location. The bolt hole should, therefore, be treated with a preservative after drilling and before bolt placement. Knots and other imperfections in the pile and bracing should also be considered when selecting the connection points. It is important to review Sections R319, R320, and

R402.1.2 of the IRC to make sure that once timber piles are notched and bolted, the piles are properly field-treated to resist decay and termite infestation.

The use of knee braces (see Figure 6-15) involves installing short diagonal braces between the upper portions of the pilings and the floor system of the elevated structure. The braces increase the stiffness of an elevated pile foundation and can be effective at reducing the lateral forces on a home. While knee braces do not stiffen a foundation as much as diagonal bracing, they do offer some advantages over diagonal braces. For example, knee braces present less obstruction to waves and debris, are shorter than diagonal braces, and are usually designed for both tension and compression loads. Unlike diagonal braces, knee braces do not reduce bending stresses within the piles (in fact, knee braces can actually increase bending stresses) and will not reduce the diameter of the piles required to resist lateral loads.

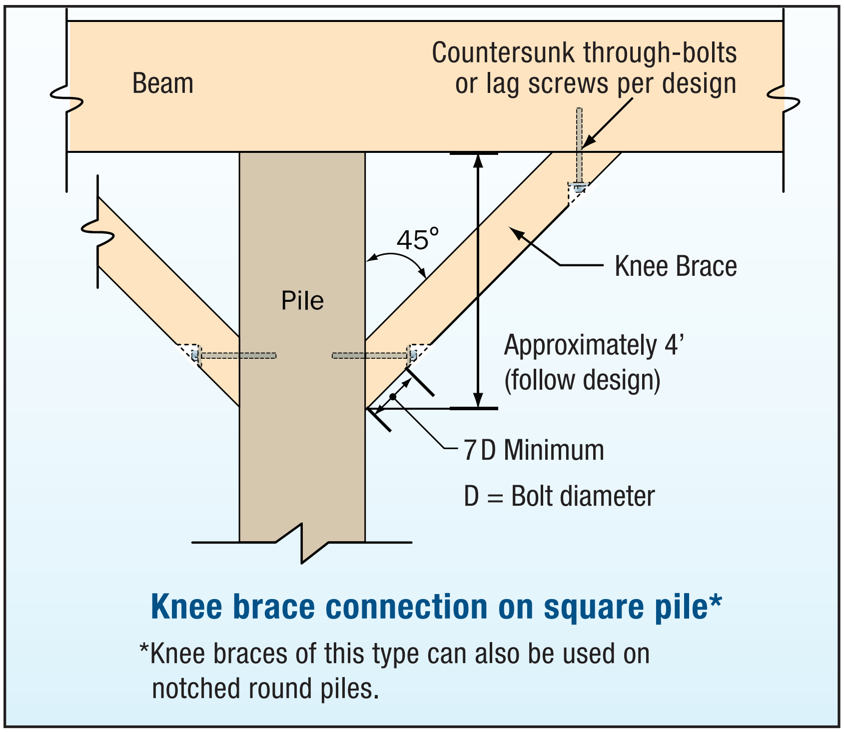

Figure 6-15.
Knee brace connection example.
(Source: FEMA 550)

The entire load path into and through the knee brace must be designed with sufficient capacity. The connections at each end of each knee brace must possess sufficient capacity to handle both tension and compression and to resist vertical loads in the brace. The brace itself must have a sufficient cross-sectional area to resist compression and tensile loads.

Grade Beams in Pile/Column Foundations

The term *grade beam* is used in a variety of ways to describe a number of foundation elements. The most common use in inland construction refers to a spread footing, which allows a foundation to uniformly distribute the load over areas of soil with reduced bearing capacity. However, in coastal areas, the term *grade beam* often refers to a construction technique utilizing a system of concrete pours that help to fix the locations of piles and thus mitigate some flood loads.

Pile foundations (see Figure 6-16) may be designed with grade beams (typically from wood or concrete). Grade beams provide many benefits:

- When incorporated with reinforced concrete or masonry column foundation systems (or with wood piles), grade beams provide lateral stiffness to prevent the need for diagonal cross-bracing or knee-bracing.
- Properly designed and constructed, grade beams facilitate load redistribution and can reduce the potential for collapse during extreme events.
- Grade beams can allow builders to accommodate the inevitable variations that always seem to affect pile placement.

To reduce the effect of scour and erosion on foundations, grade beams must be designed to be self-supporting foundation elements; that is, grade beams must not rely upon the soils beneath them for vertical support. Also, the piles must be designed to carry the weight of grade beams in order to address the condition that results when grade beams are undermined by scour or erosion, in addition to resisting all loads transferred to the piles from the elevated structure and the foundation. For this reason, it is important to ensure that other building elements are not connected to the piles. Slabs used below pile-elevated homes should not be connected to pile foundations or used as grade beams. If the slab is damaged

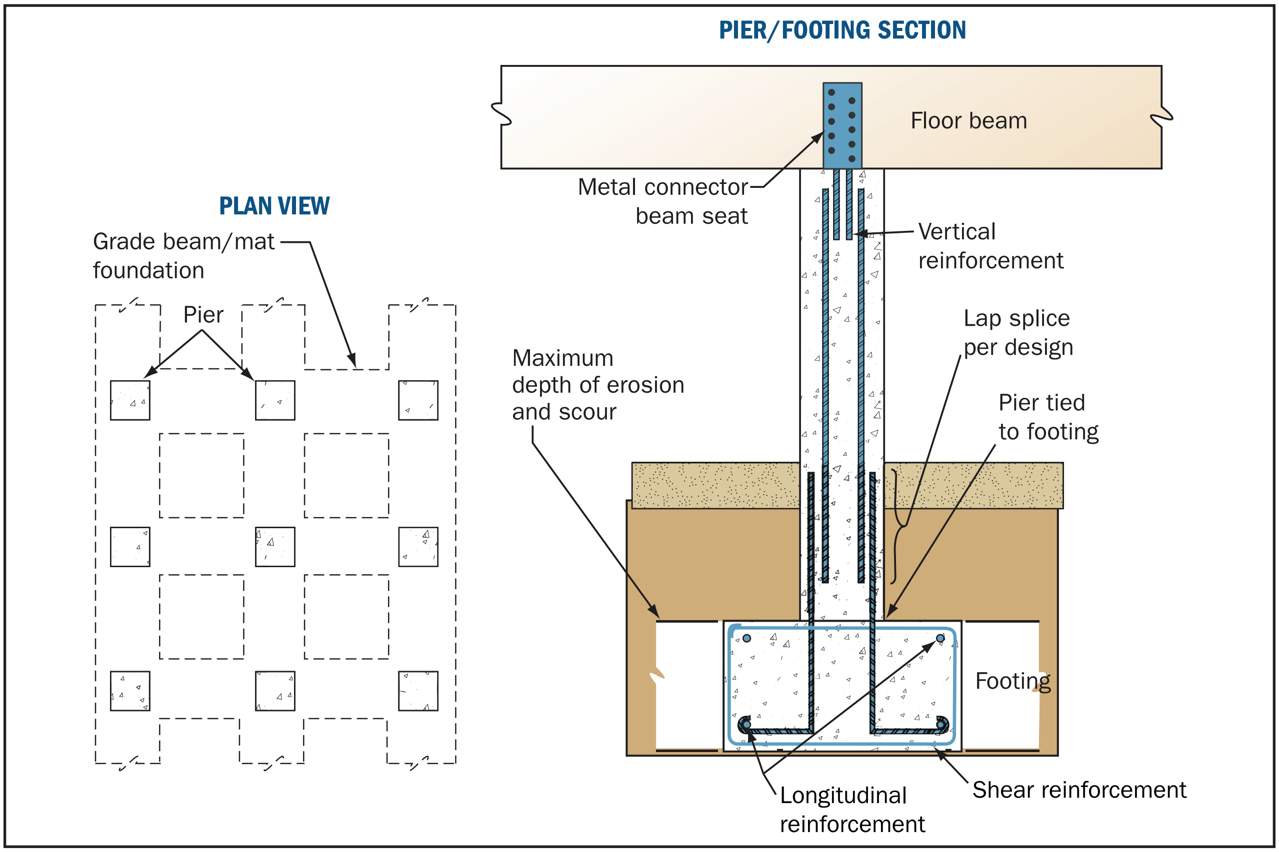

Figure 6-16.
Elevation view (right) of a concrete pile foundation using grade beams. (Source: FEMA 550)

or undermined, the slab may be exposed to flood forces and transfer loads to the foundation. In most cases, the foundation was not designed to resist these higher loads and the foundation may be overloaded, causing it to fail.

Consensus codes and standards generally do not contain prescriptive designs for open foundations; however, criteria are provided for performance-based design. Section 303.4 of SSTD-10 requires that wood-pile foundations, their beams, and connections between the beams and the piles must be designed by a registered engineer or architect. IRC Section R324.2 requires that foundations in V Zones be open (placed on columns or pilings). IRC Section R324.3.3 also requires that foundations in V Zones be designed to resist water loads associated with flooding and precludes the use of shallow (mat or raft) foundations in areas where erosion can undermine foundations. No code or industry standard currently provides prescriptive designs for open foundations. FEMA 550 provides guidance for engineers and architects who design foundations for coastal sites, as well as prescriptive designs for a wide range of buildings and foundation styles.

Breakaway Walls

Within the SFHA, walls may be used to enclose the area below the lowest floor, but these create a condition which must be addressed. The walls or enclosure may consist of latticework, insect screening, or walls specifically designed to fail or "break away" under water or wind loads without causing structural damage to the rest of the structure. It is important that these walls be constructed with flood-resistant materials. They are designed to break free with loads of not less than 10 pounds per square foot—but not more than 20 pounds per square foot—to prevent their loading from imparting additional lateral loads on structural members. These walls are typically constructed of wood studs with an exterior sheathing, but they may be constructed of unreinforced masonry units and designed to fail at the mortar joints.

A key feature of a successful breakaway wall is that the exterior sheathing does not overlap the structure's piling or vertical members. Additionally, it may not overlap the lowest horizontal structural member or above that. These design features ensure that the wall failure does not impact the main structure. Breakaway walls should be certified by a professional engineer or architect and the proper documentation submitted with the building permit. (See FEMA NFIP Technical Bulletin 9: *Design and Construction Guidance for Breakaway Walls Below Elevated Coastal Buildings* (FIA-TB-9), for further information.) See Figure 6-17 for an example of the successful use of a breakaway wall and Figure 6-18, which demonstrates building damages due to incorrect construction of a breakaway wall.

6.4.3.2 Shallow, Open Foundations

Shallow, open foundations generally consist of concrete or masonry piers placed on concrete footers. Their open style makes their use desirable in areas where breaking waves may exist. Because they are founded on shallow soils, however, they remain vulnerable to scour and erosion.

Shallow, open foundations may be allowed, but their use may not be suitable for V Zones (see Figure 6-19). If a shallow, open foundation can be undermined by scour or erosion, the foundation would not satisfy the NFIP requirement of preventing collapse. These foundations are more suitable for use within Coastal A Zones, where the presence of erosion and scour is limited. Shallow, open foundations may be used within Coastal A Zones if the "tops" of their footings can be placed below the maximum scour and

Figure 6-17.
Successful use of a breakaway wall.
(Source: FEMA 489)

Figure 6-18.
Building damages due to the incorrect construction of a breakaway wall.
(Source: FEMA 489)

erosion levels anticipated for the life of the structure. The tops of the footings should be positioned below the maximum anticipated scour or erosion depth because any uncovered area of a footing will be exposed to flood forces. Also, any uncovered area of a footing acts as an obstruction to moving floodwaters and will contribute to localized scour. In all applications (whether inland or coastal), frost-depth requirements must be considered, as they may dictate the depth at which the top of these footings is set. Where expected erosion and scour cannot be accurately quantified, deep and open foundations (such as pilings) should be used.

The performance of shallow, open foundations depends largely upon the style of footing used to support concrete or masonry piers. Discrete pad-style footings rely only upon the weight of the elevated structure and the soil-bearing capacity to resist overturning. When exposed to lateral loads or when undermined by erosion or scour, discrete footings can rotate. Therefore, piers placed on discrete footings are considered to reflect best practices only when wind and flood loads are relatively low. Post-disaster investigations have revealed that a discrete footing may fail when a building is exposed to lateral loads, even when it is not undermined by scour and erosion (see Figures 6-20 and 6-21).

A desired alternative to discrete pad footings is to construct a matrix of grade beams. Piers placed on continuous concrete-grade beams or concrete strip footings provide much greater resistance to lateral loads because the grade beams/footings act as an integral unit and are less prone to rotation.

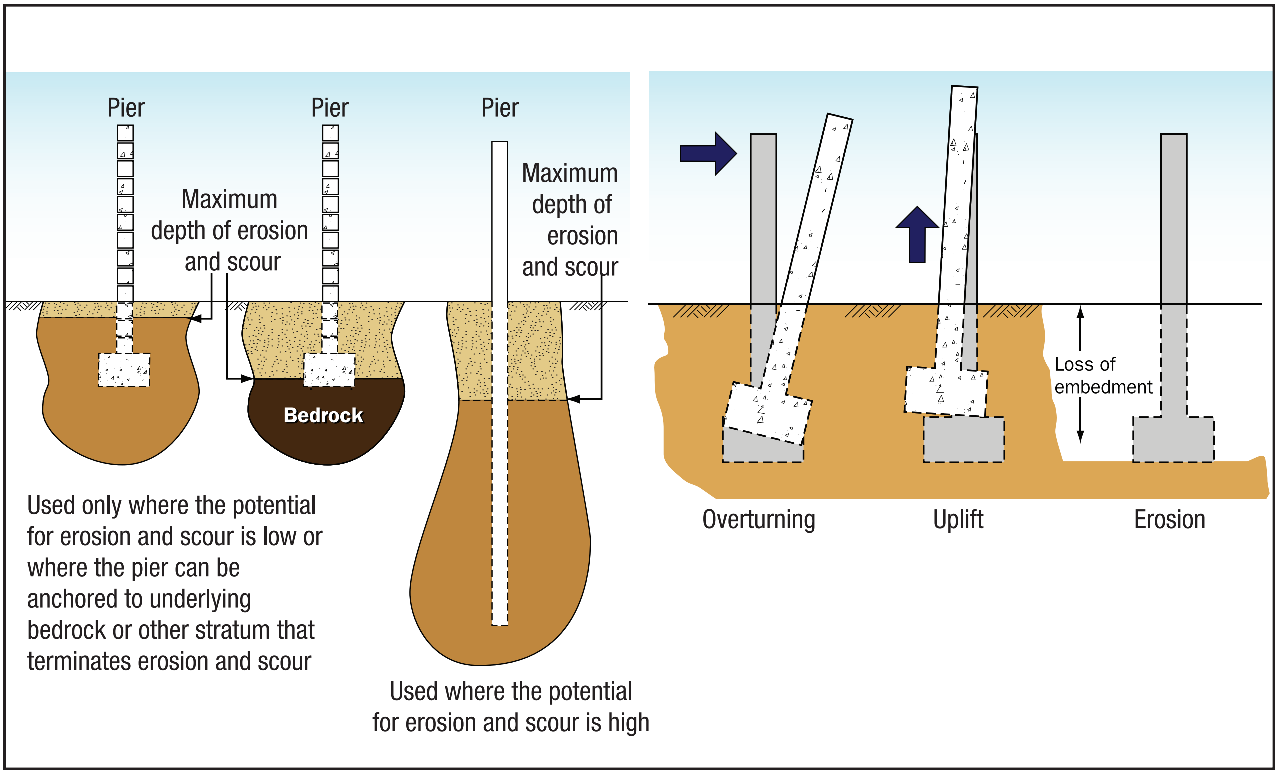

Figure 6-19.
Possible failure modes for masonry piers. (Source: FEMA 550)

Figure 6-20.
PASS CHRISTIAN, MISSISSIPPI: Performance comparison of shallow, open foundations founded on discrete footings (foreground) failed by rotating and overturning, while piers located on more substantial footings—in this case, a concrete mat (background)—survived. (Source: FEMA 549)

Footings and grade beams must be reinforced to resist the bending moments that develop at the base of the piers due to the lateral loads on the foundation and the elevated home (see Figure 6-20). Lateral flood and wind forces result in detailing and connection/reinforcement requirements that are more significant and robust than those commonly used for inland construction. The use of minimal reinforcement or small connectors should be questioned as to their adequacy in coastal applications/foundations (see Figure 6-21).

Although the IRC provides prescriptive solutions that may be used for designing the building above the foundation, the IRC does not provide prescriptive designs for open foundations. FEMA 550 contains guidance for engineers and architects who design foundations for coastal sites. FEMA 550 also offers prescriptive designs for a wide range of buildings and foundation styles. Addendum C of ICC-600 (released in September 2008) includes some prescriptive designs for open foundation. The addendum has prescribed beam designs that can be used in conjunction with FEMA 550 foundation designs.

Figure 6-21.
BELLE FONTAINE POINT, JACKSON COUNTY, MISSISSIPPI: Column connection failure. (Source: FEMA 549)

6.5 Soils Investigation

The foundation design chosen should be based upon the soils that exist at the building site. The IBC and IRC require soil-bearing capacities that are identified in IRC Section R401.4 and IBC Section 1802, respectively. Soil parameters can be determined from the following:

- Soil samples from borings or test pits on the site
- A review of borings from nearby sites
- Information from the local office of the Natural Resources Conservation Service (formerly known as the Soil Conservation Service) and soil surveys published for each county
- The types of foundations that have been installed within the area in the past
- The proposed site history, which would indicate the presence of buried materials (This may require a search of land records showing past ownership focused on how the site may have been used in the past.)

One of the parameters derived from a soil investigation is the bearing capacity, which measures the ability of soils to support gravity loads without soil shear failure or excessive settlement. Commonly measured in pounds per square foot (psf), soil-bearing capacity typically ranges from 1,000 psf for relatively weak soils to more than 10,000 psf for bedrock.

Frequently, designs are initially prepared according to a presumed bearing capacity. It is then the homebuilder's responsibility to verify actual site conditions. The actual soil-bearing capacity should be determined. If soils are found to have higher bearing capacity, the foundation can be constructed as designed or it can be revised to take advantage of these better soils.

The allowable load-bearing values of soils specified in IBC Section 1804 can be used when other data are not available. However, soils can vary significantly in bearing capacity from site to site. A geotechnical engineer should be consulted when unusual or unknown soil conditions are encountered.

The lateral capacity of the soil should not be overlooked. Building failure due to a lack of lateral soil capacity is common during storm events. In addition to verifying the bearing capacity of the soil at the site, the soil's lateral capacity should be consistent with the presumed lateral capacity in the building plans. In the event that the soil lateral capacity does not meet the design capacity of the foundation, the building foundation will need to be modified in order to account for site conditions.