

Chapter 7

FOUNDATION DESIGN REQUIREMENTS

7.1 GENERAL

7.1.1 Scope. This chapter includes only those foundation requirements that are specifically related to seismic resistant construction. It assumes compliance with all other basic requirements which include, but are not limited to, requirements for the extent of the foundation investigation, fills to be present or to be placed in the area of the structure, slope stability, subsurface drainage, settlement control, and soil bearing and lateral soil pressure recommendations for loads acting without seismic forces.

7.1.2 References. The following document shall be used as specified in this chapter.

ACI 318 *Building Code Requirements for Structural Concrete*, American Concrete Institute, 2002.

AISC-Seismic *Seismic Provisions For Structural Steel Buildings*, American Institute of Steel Construction May 21, 2002

7.1.3 Definitions.

Basement: Any story below the lowest story above grade.

Component: See Sec. 1.1.4.

Design earthquake ground motion: See Sec. 1.1.4.

Design strength: See Sec. 4.1.3.

Longitudinal reinforcement ratio: Area of the longitudinal reinforcement divided by the cross-sectional area of the concrete.

Nominal strength: See Sec. 4.1.3.

Owner: See Sec. 1.1.4.

Pile: Deep foundation components including piers, caissons, and piles.

Pile cap: Foundation elements to which piles are connected, including grade beams and mats.

Reinforced concrete: See Sec. 9.1.3.

Required strength: See Sec. 4.1.3.

Seismic Design Category: See Sec. 1.1.4.

Seismic forces: See Sec. 1.1.4.

Site Class: See Sec. 3.1.3.

Structure: See Sec. 1.1.4.

Wall: See Sec. 4.1.3.

7.1.4 Notation

A_{ch} Cross sectional-area of a component measured to the outside of the special lateral reinforcement.

A_g Gross cross sectional-area of a component.

f'_c Specified compressive strength of concrete used in design.

f_{yh}	Specified yield stress of the special lateral reinforcement.
h_c	The core dimension of a component measured to the outside of the special lateral reinforcement.
P	Axial load on pile calculated in accordance with Sec. 4.2.2.
S_{DS}	See Sec. 3.1.4.
s	Spacing of transverse reinforcement measured along the length of an element.

7.2 GENERAL DESIGN REQUIREMENTS

The resisting capacities of the foundations, subjected to the load combinations prescribed elsewhere in these *Provisions*, shall meet the requirements of this chapter.

7.2.1 Foundation components. The strength and detailing of foundation components under seismic loading conditions, including foundation elements and attachments of the foundation elements to the superstructure, shall comply with the requirements of Chapters 8, 9, 10, 11, or 12, unless otherwise specified in this chapter. The strength of foundation components shall not be less than that required for load combinations that do not include seismic load effects.

7.2.2 Soil capacities. The capacity of the foundation soil in bearing or the capacity of the interface between pile, pier, or caisson and the soil shall be sufficient to support the structure with all prescribed loads, without seismic forces, taking due account of the settlement that the structure can withstand. For the load combinations including seismic load effects as specified in Sec. 4.2.2, the soil capacities must be sufficient to resist loads at acceptable strains considering both the short duration of loading and the dynamic properties of the soil.

7.2.3. Foundation load-deformation characteristics. Where permitted for the linear analysis procedures in Chapter 5, the load-deformation characteristics of the foundation-soil system (foundation stiffness) shall be modeled in accordance with the requirements of this section. The linear load-deformation behavior of foundations shall be represented by an equivalent linear stiffness using soil properties that are compatible with the soil strain levels associated with the design earthquake motion. The strain-compatible shear modulus, G , and the associated strain-compatible shear wave velocity, v_s , needed for the evaluation of equivalent linear stiffness shall be determined using the criteria in Sec. 5.6.2.1.1 or based on a site-specific study. Parametric variations of not less than 50% increase and decrease in stiffness shall be incorporated in dynamic analyses unless smaller variations can be justified based on field measurements of dynamic soil properties or direct measurements of dynamic foundation stiffness.

7.3 SEISMIC DESIGN CATEGORY B

Any construction meeting the requirements of Sec. 7.1 and 7.2 is permitted to be used for structures assigned to Seismic Design Category B.

7.4 SEISMIC DESIGN CATEGORY C

Foundations for structures assigned to Seismic Design Category C shall comply with Sec. 7.3 and the additional requirements of this section.

7.4.1 Investigation. An investigation shall be conducted and a written report shall be provided that shall include, in addition to the requirements of Sec. 7.1 and the evaluations required in Sec. 7.2.2, the results of an investigation to determine the potential hazards due to slope instability, liquefaction, differential settlement, and surface displacement due to faulting or lateral spreading, all as a result of earthquakes. The report shall contain recommendations for appropriate foundation designs or other measures to mitigate the effects of the above hazards. Where deemed appropriate by the authority having jurisdiction, a report is not required when prior evaluations of nearby sites with similar soil conditions provide sufficient direction relative to the proposed construction.

7.4.2 Pole-type structures. Construction employing posts or poles as columns embedded in earth or embedded in concrete footings in the earth are permitted to be used to resist both axial and lateral loads. The depth of embedment required for posts or poles to resist seismic forces shall be determined by means of the design criteria established in the foundation investigation report.

7.4.3 Foundation ties. Individual pile caps, drilled piers, or caissons shall be interconnected by ties. All ties shall be capable of carrying, in tension or compression, a force equal to the product of the larger pile cap or column load times S_{DS} divided by 10 unless it can be demonstrated that equivalent restraint can be provided by reinforced concrete beams within slabs on grade or reinforced concrete slabs on grade or confinement by competent rock, hard cohesive soils, very dense granular soils, or other approved means.

7.4.4 Special pile requirements. The following special requirements for piles, piers, or caissons are in addition to all other requirements in the code administered by the authority having jurisdiction.

All concrete piles and concrete filled pipe piles shall be connected to the pile cap by embedding the pile reinforcement in the pile cap for a distance equal to the development length as specified in ACI 318 as modified by Chapter 9 of these *Provisions*. The pile cap connection can be made by the use of field-placed dowel(s) anchored in the concrete pile. For deformed bars, the development length is the full development length for compression or tension, in the case of uplift, without reduction in length for excess area.

Ends of rectangular hoops, spirals, and ties shall be terminated with seismic hooks as defined in Sec. 21.1 of ACI 318 turned into the confined concrete core. The ends of circular spirals and hoops shall be terminated with 90-degree hooks turned into the confined concrete core.

For resistance to uplift forces, anchorage of steel pipe (or round HSS), concrete filled steel pipe, or H piles to the pile cap shall be made by means other than concrete bond to the bare steel section.

Exception: Anchorage of concrete filled steel pipe piles is permitted to be accomplished using deformed bars developed into the concrete portion of the pile.

Where a minimum length for reinforcement or the extent of closely spaced confinement reinforcement is specified at the top of the pile, provisions shall be made so that those specified lengths or extents are maintained after pile cut-off.

7.4.4.1 Uncased concrete piles. The longitudinal reinforcement ratio for uncased cast-in-place concrete drilled or augered piles, piers, or caissons shall not be less than 0.0025 throughout the largest region defined as follows: the top one-third of the pile length, the top 10 ft (3 m) below the ground, or the flexural length of the pile. The flexural length shall be taken as the length from the top of the pile to the lowest point where the calculated flexural demand exceeds 0.4 times the concrete section cracking moment. The longitudinal reinforcing shall extend beyond the flexural length of the pile by the tension development length. Longitudinal reinforcement shall consist of at least four bars and shall be confined with closed ties or equivalent spirals with a diameter of not less than 3/8 in. (9.5 mm) and spaced not more than 16 times the diameter of the smallest longitudinal bar. Within three pile diameters of the bottom of the pile cap, transverse confinement reinforcing shall be spaced not more than the lesser of eight times the diameter of the smallest longitudinal bar or 6 in. (150 mm).

7.4.4.2 Metal-cased concrete piles. Reinforcement requirements are the same as for uncased concrete piles.

Exception: Spiral welded metal casing of a thickness not less than No. 14 gauge may be considered to provide concrete confinement equivalent to the closed ties or equivalent spirals required in an uncased concrete pile, provided that the metal casing is adequately protected against possible deleterious action due to soil constituents, changing water levels, or other factors indicated by boring records of site conditions.

7.4.4.3 Concrete-filled pipe. The longitudinal reinforcement ratio at the top of the pile shall not be less than 0.01 and such reinforcement shall extend into the pile at least two times the length required for embedment into the pile cap.

7.4.4.4 Precast (non-prestressed) concrete piles. The longitudinal reinforcement ratio for precast concrete piles shall not be less than 0.01. Longitudinal reinforcement shall be full length and shall be confined with closed ties or equivalent spirals with a diameter of not less than 3/8 in. (9.5mm) and spaced not more than the lesser of 16 times the diameter of the smallest longitudinal bar or 8 in. (200 mm). Within three pile diameters of the bottom of the pile cap, transverse confinement reinforcing shall be spaced not more than the lesser of eight times the diameter of the smallest longitudinal bar or 6 in. (152 mm).

7.4.4.5 Precast-prestressed piles. Transverse reinforcement shall consist of circular hoops or spirals. For the upper 20 ft (6 m) of the pile, the volumetric ratio of transverse reinforcement shall not be less than the larger of 0.007 or that required by Eq. 7.4-1 as follows:

$$\rho_s = 0.12 \frac{f'_c}{f_{yh}} \quad (7.4-1)$$

Where:

ρ_s = volumetric ratio of transverse reinforcement (volume of transverse reinforcement divided by volume of enclosed core),

f'_c = specified compressive strength of concrete, psi (Mpa), and

f_{yh} = yield strength of transverse reinforcement, which shall not be taken greater than 85,000 psi (586 MPa).

Below the 20 ft (6 m) point, the amount of transverse reinforcement shall not be less than one-half that required by Eq. 7.4-1.

7.5 SEISMIC DESIGN CATEGORIES D, E, AND F

Foundations for structures assigned to Seismic Design Category D, E, or F shall comply with Sec. 7.4 and the additional requirements of this section. Concrete foundation components shall be designed and constructed in accordance with Sec. 21.8 of ACI 318, except as modified by the requirements of this section.

Exception: Detached one- and two-family dwellings of light-frame construction not exceeding two stories in height above grade need only comply with the requirements for Sec.7.4 and Sec. 7.5.3.

7.5.1 Investigation. In addition to requirements of Sec. 7.4.1, the investigation and report shall include the determination of lateral pressures on basement and retaining walls due to earthquake motions.

7.5.2 Liquefaction potential and soil strength loss. The geotechnical report shall describe the likelihood and potential consequences of liquefaction and soil strength loss (including estimates of differential settlement, lateral movement, lateral loads on foundations, reduction in foundation soil-bearing capacity, increases in lateral pressures on retaining walls, and flotation of embedded structures) and shall discuss mitigation measures. Such measures shall be given consideration in the design of the structure and can include, but are not limited to, ground stabilization, selection of appropriate foundation type and depths, selection of appropriate structural systems to accommodate anticipated displacements and forces, or any combination of these measures.

The potential for liquefaction and soil strength loss shall be evaluated for site peak ground accelerations, magnitudes, and source characteristics consistent with the design earthquake ground motions. Peak ground acceleration is permitted to be determined based on a site-specific study taking into account soil

amplification effects or, in the absence of such a study, peak ground accelerations shall be assumed equal to $S_{DS}/2.5$.

7.5.3 Foundation ties. Individual spread footings founded on soil assigned to Site Class E or F shall be interconnected by ties designed in accordance with Sec. 7.4.3.

7.5.4 Special pile and grade beam requirements. Piling shall be designed and constructed to withstand the maximum curvatures resulting from earthquake ground motions and structural response. Curvatures shall include the effects of free-field soil strains (without the structure), modified for soil-pile interaction, coupled with pile deformations induced by lateral pile resistance to structure seismic forces. Concrete piles in Site Class E or F shall be designed and detailed in accordance with Sec. 21.4.4.1, 21.4.4.2, and 21.4.4.3 of ACI 318 within seven pile diameters of the pile cap and of the interfaces between strata that are hard or stiff and strata that are liquefiable or are composed of soft to medium-stiff clay.

Section 21.10.3.3 of ACI 318 need not apply where grade beams have the required strength to resist the forces from the load combinations of Section 4.2.2.2. Section 21.10.4.4(a) of ACI 318 need not apply to concrete piles.

Design of anchorage of piles into the pile cap shall consider the combined effect of axial forces due to uplift and bending moments due to fixity to the pile cap. For piles required to resist uplift forces or provide rotational restraint, anchorage into the pile cap shall be capable of developing the following:

1. In the case of uplift, the least of: the nominal tensile strength of the longitudinal reinforcement in a concrete pile, the nominal tensile strength of a steel pile, the nominal uplift strength of the soil-pile interface times 1.3, or the axial tension force calculated in accordance with Sec. 4.2.2.2. The nominal uplift strength of the soil-pile interface shall be taken as the ultimate frictional or adhesive force that can be developed between the soil and the pile.
2. In the case of rotational restraint, the lesser of: the load effects (axial forces, shear forces, and moments) calculated in accordance with Sec. 4.2.2.2, or development of the nominal axial, bending, and shear strength of the pile.

Splices of pile segments shall be capable of developing the lesser of: the nominal strength of the pile section, or the axial forces, shear forces, and moments calculated in accordance with Sec. 4.2.2.2.

Pile moments, shears, and lateral deflections used for design shall be established considering the interaction of the pile and soil. Where the ratio of the depth of embedment of the pile to the pile diameter or width is less than or equal to 6, the pile may be assumed to be flexurally rigid with respect to the soil.

Where the center-to-center spacing of piles in the direction of the lateral force is less than eight pile diameters, the effects of such spacing on the lateral response of the piles shall be included. Where the center-to-center spacing of piles is less than three pile diameters, the effects of such spacing on the vertical response of the piles shall be included.

Batter piles shall be capable of resisting forces and moments calculated in accordance with Sec. 4.2.2.2.

Where vertical and batter piles act jointly to resist foundation forces as a group, these forces shall be distributed to the individual piles in accordance with their relative horizontal and vertical rigidities and the geometric distribution of the piles within the group. The connection between batter piles and grade beams or pile caps shall be capable of developing the nominal strength of the pile acting as a short column.

7.5.4.1 Uncased concrete piles. The longitudinal reinforcement ratio for uncased cast-in-place concrete drilled or augered piles, piers, or caissons shall not be less than 0.005 throughout the largest region defined as follows: the top one-half of the pile length, the top 10 ft (3 m) below the ground, or the flexural length of the pile. The flexural length shall be taken as the length of pile to a point where 0.4 times the concrete section cracking moment exceeds the calculated flexural demand at that point.

Longitudinal reinforcement shall consist of at least four bars and shall be confined with closed ties or equivalent spirals at a spacing of not more than the least of: 12 times the diameter of the smallest longitudinal bar, one-half the diameter of the section, or 12 in. (300 mm). Ties shall have a diameter of not less than 3/8 in. (9.5 mm) where the pile diameter is less than or equal to 20 in. (500 mm) and not less than 1/2 in. (12.7 mm) for piles of larger diameter. Within three pile diameters of the bottom of the pile cap, transverse confinement reinforcing shall satisfy Sec. 21.4.4.1, 21.4.4.2, and 21.4.4.3 of ACI 318. Where the assigned Site Class is A, B, C, or D and the soil is not subject to liquefaction, it shall be permitted to use a transverse spiral reinforcing ratio of not less than one-half of that required in Sec. 21.4.4.1(a) of ACI 318.

7.5.4.2 Metal-cased concrete piles. Reinforcement requirements are the same as for uncased concrete piles.

Exception: Spiral welded metal-casing of a thickness not less than No. 14 gauge may be considered to provide concrete confinement equivalent to the closed ties or equivalent spirals required in an uncased concrete pile, provided that the metal casing is adequately protected against possible deleterious action due to soil constituents, changing water levels, or other factors indicated by boring records of site conditions.

7.5.4.3 Precast (non-prestressed) concrete piles. Within three pile diameters of the bottom of the pile cap, transverse confinement reinforcing shall satisfy Sec. 21.4.4.1, 21.4.4.2, and 21.4.4.3 of ACI 318. Where the assigned Site Class is A, B, C, or D and the soil is not subject to liquefaction, it shall be permitted to use a transverse spiral reinforcing ratio of not less than one-half of that required in Sec. 21.4.4.1(a) of ACI 318.

7.5.4.4 Precast-prestressed piles. The requirements of ACI 318 need not apply, unless specifically referenced.

Where the total pile length in the soil is 35 ft (11 m) or less, transverse confinement reinforcement shall be provided throughout the length of the pile. Where the pile length exceeds 35 ft (11 m), transverse confinement reinforcement shall be provided throughout the largest region defined as follows: the top 35 ft (11 m) below the ground, or the distance from the underside of the pile cap to the first point of zero curvature plus three times the least pile dimension. The transverse confinement reinforcement shall be spiral or hoop reinforcement with a center-to-center spacing not greater than the least of: one-fifth of the least pile dimension, six times the diameter of the longitudinal tendons, or 8 in. (200 mm).

Where the transverse confinement reinforcement consists of spirals or circular hoops, the volumetric ratio of transverse reinforcement shall not be less than that required by Eq. 7.5-1 and 7.5-2, but need not exceed 0.021.

$$\rho_s = 0.25 \left(\frac{f'_c}{f_{yh}} \right) \left(\frac{A_g}{A_{ch}} - 1 \right) \left(0.5 + \frac{1.4P}{f'_c A_g} \right) \quad (7.5-1)$$

$$\rho_s = 0.12 \left(\frac{f'_c}{f_{yh}} \right) \left(0.5 + \frac{1.4P}{f'_c A_g} \right) \quad (7.5-2)$$

where:

ρ_s = volumetric ratio of transverse reinforcement (volume of transverse reinforcement divided by volume of enclosed core),

f'_c = specified compressive strength of concrete,

f_{yh} = yield strength of transverse reinforcement, which shall not be taken greater than 85,000 psi (586 MPa),

A_g = pile cross-sectional area,

A_{ch} = core area defined by outside diameter of the transverse reinforcement, and

P = axial load on pile calculated in accordance with Sec. 4.2.2.

Where the transverse confinement reinforcement consists of rectangular hoops and cross ties, the total cross-sectional area of transverse reinforcement shall not be less than that required by Eq. 7.5-3 and 7.5-4.

$$A_{sh} = 0.3sh_c \left(\frac{f'_c}{f_{yh}} \right) \left(\frac{A_g}{A_{ch}} - 1 \right) \left(0.5 + \frac{1.4P}{f'_c A_g} \right) \quad (7.5-3)$$

$$A_{sh} = 0.12sh_c \left(\frac{f'_c}{f_{yh}} \right) \left(0.5 + \frac{1.4P}{f'_c A_g} \right) \quad (7.5-4)$$

where:

s = spacing of transverse reinforcement measured along length of pile,

h_c = cross-sectional dimension of pile core measured center-to-center of hoop reinforcement,

f'_c = specified compressive strength of concrete, and

f_{yh} = yield strength of transverse confinement reinforcement, which shall not be taken greater than 70,000 psi (483 Mpa).

Outside of the length of the pile requiring transverse confinement reinforcement, spiral or hoop reinforcement with a volumetric ratio not less than one-half of that required for transverse confinement reinforcement shall be provided.

Circular spiral reinforcement shall be spliced by lapping one full turn and bending the end of the spiral to a 90-degree hook or by use of a mechanical or welded splice complying with Sec. 12.14.3 of ACI 318. The required amount of spiral reinforcement shall be permitted to be obtained by providing an inner and outer spiral.

Hoops and cross ties shall have a diameter of not less than 3/8 in. (9.5 mm). Rectangular hoop ends shall terminate at a corner with seismic hooks.

7.5.4.5 Steel Piles. Design and detailing of H-piles shall conform to the provisions of AISC Seismic and the following. The connection between steel piles (including unfilled steel pipe piles) and pile caps shall be designed for a tensile force no smaller than 10 percent of the nominal compression strength of the pile.

Exception: The pile connection need not meet this requirement where it can be demonstrated that the pile connection has the strength to resist the axial forces and moments calculated in accordance with Sec. 4.2.2.2.

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