Recommended practice for design, manufacture, and installation of prestressed concrete piling

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Section 1—Introduction

Prestressed concrete piles are vital elements in the foundations of buildings, bridges, and marine structures throughout the world. They usually vary in size from 12 in. (305 mm) square piles used in building foundations to 66-in.-diameter (1680-mm) cylindrical piles used in marine structures and bridges. Many areas of North America have poor soil conditions requiring pile foundations for even relatively light structures. In such areas, prestressed concrete piling has come to be the usual method of construction, with prestressed concrete having been proved to be the logical choice of materials where permanence, durability, and economy must be considered. Heavy marine structures often rely on prestressed concrete piles driven through deep water or through deep layers of unsuitable material for their support. Prestressed concrete piles can be designed to safely support these heavy axial loads, as well as lateral loads caused by wind, waves, and earthquakes. In marine environments, these piles can resist corrosion caused by salt water and by thousands of cycles of wetting and drying.

1.1 Scope of report

The first version of this report was published in the March–April 1993 issue of the *PCI Journal*.[1] The document provided in-depth information on the design, detailing, manufacture, and installation of prestressed concrete piles. Equations for the required quantity of spiral reinforcement were presented as the industry response to building code requirements for pile ductility. Although much of the information related to the manufacture and installation of prestressed concrete piles has remained applicable over the years, significant changes in design and detailing practices have resulted from extensive research in these areas. This report is the third iteration, and it contains recommendations and guidelines for the design, detailing, manufacture, and installation of prestressed concrete piles based on current knowledge and standards. It updates the previous version of the report published in the July–August 2019 issue of the *PCI Journal*.[2]

The 2019 version of this report was used by the PCI Prestressed Concrete Piling Committee in the preparation of

ANSI/PCI *Specification for Precast, Prestressed Concrete Piles*[3] (ANSI/PCI 142-24) through the standard-development process. The intent of this update is to provide guidance for design and construction of precast, prestressed concrete piles using ANSI/PCI 142-24 and commentary; to provide supplemental information not covered in the standard; and to harmonize the language to more clearly illustrate the applicability to all types of structures. Although the pile cross sections discussed in this report are typical of those most commonly found throughout the United States and Canada, the intent of this report is not to limit the geometric configuration or material properties of prestressed concrete piling. Local prestressed concrete manufacturers should be consulted to determine readily available cross sections. Design tables and details presented are intended to aid the qualified designer. Actual design details, including the selection of materials, pile sizes, and pile shapes, should conform to local practices and code requirements.

1.1.1 Materials

Section 2 briefly discusses cements, aggregates, water, admixtures, and reinforcement.

1.1.2 Design

Section 3 begins with a discussion of various factors that should be considered in the design of prestressed concrete piles and pile foundations. Prescriptive and performance-based design provisions are discussed with reference to how they should be used in conjunction with governing codes and standards. Although some design aids are provided, reference is made to PCI's free software program (PCI PD-01) for developing axial-moment interaction diagrams for the ultimate capacity of commonly used pile sizes of varying concrete strengths and effective prestress levels.

Good design practice requires clear communication among the project engineer of record, the project geotechnical engineer, and, when applicable, the specialty engineer responsible for the design of the prestressed concrete piling.

1.1.3 Manufacture and transportation

Section 4 presents special requirements involved in the manufacture, handling, transportation, and tolerances for prestressed concrete piles.

1.1.4 Installation

The purpose of section 5 is to set forth general principles for proper prestressed concrete pile installation. Discussion of handling-induced and driving-induced compression, tension, bending, and torsion provides a basis for recommendations to prevent damage to prestressed concrete piles. Techniques related to the cutting or occasional extension of piles are suggested.

1.1.5 Current research and future applications for prestressed concrete piling

Section 6 concludes this report by highlighting some of the current issues and future research needs involving the design, manufacture, and installation of prestressed concrete piles. A state-of-the-practice overview of the mitigation and monitoring of the effects of pile-driving vibrations is included. Current pile-related research showing great promise is mentioned, and future research needs are also examined.

1.2 Standards and references

1.2.1 ASTM standards

ASTM A29/A29M, *Standard Specification for General Requirements for Steel Bars, Carbon and Alloy, Hot-Wrought*

ASTM A416/A416M, *Standard Specification for Low-Relaxation, Seven-Wire Steel Strand for Prestressed Concrete*

ASTM A572/A572M, *Standard Specification for High-Strength Low-Alloy Columbium-Vanadium Structural Steel*

ASTM A615/A615M, *Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement*

ASTM A706/A706M, *Standard Specification for Deformed and Plain Low-Alloy Steel Bars for Concrete Reinforcement*

ASTM A722/A722M, *Standard Specification for High-Strength Steel Bars for Prestressed Concrete*

ASTM A882/A882M, *Standard Specification for Filled Epoxy-Coated Seven-Wire Prestressing Steel Strand*

ASTM A884/A884M, *Standard Specification for Epoxy-Coated Steel Wire and Welded Wire Reinforcement*

ASTM A1060/A1060M, *Standard Specification for Zinc-Coated (Galvanized) Steel Welded Wire Reinforcement, Plain and Deformed, for Concrete*

ASTM A1064/A1064M, *Standard Specification for Carbon-Steel Wire and Welded Wire Reinforcement, Plain and Deformed, for Concrete*

ASTM C33/C33M, *Standard Specification for Concrete Aggregates*

ASTM C150/C150M, *Standard Specification for Portland Cement*

ASTM C260/C260M, *Standard Specification for Air-Entraining Admixtures for Concrete*

ASTM C330/C330M, *Standard Specification for Lightweight Aggregates for Structural Concrete*

ASTM C494/C494M, *Standard Specification for Chemical Admixtures for Concrete*

ASTM C595/C595M, *Standard Specification for Blended Hydraulic Cements*

ASTM C618, *Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete*

ASTM C989/C989M, *Standard Specification for Slag Cement for Use in Concrete and Mortars*

ASTM C1107/C1107M, *Standard Specification for Packaged Dry, Hydraulic-Cement Grout (Nonshrink)*

ASTM C1157/C1157M, *Standard Performance Specification for Hydraulic Cement*

ASTM C1240, *Standard Specification for Silica Fume Used in Cementitious Mixtures*

ASTM C1602/C1602M, *Standard Specification for Mixing Water Used in the Production of Hydraulic Cement Concrete*

ASTM C1778, *Standard Guide for Reducing the Risk of Deleterious Alkali-Aggregate Reaction in Concrete*

ASTM D1143/D1143M, *Standard Test Methods for Deep Foundations Under Static Axial Compressive Load*

ASTM D3689/D3689M, *Standard Test Methods for Deep Foundations Under Static Axial Tensile Load*

ASTM D3966/D3966M, *Standard Test Methods for Deep Foundations Under Static Lateral Load*

ASTM D4945, *Standard Test Method for High-Strain Dynamic Testing of Deep Foundations*

ASTM D7383, *Standard Test Methods for Axial Rapid Load (Compressive Force Pulse) Testing of Deep Foundations*

1.2.2 American Concrete Institute (ACI) standards and guides

ACI 201.2R, *Guide to Durable Concrete*

ACI 318, *Building Code Requirements for Structural Concrete and Commentary*

ACI 543R, *Guide to Design, Manufacture, and Installation of Concrete Piles*

1.2.3 PCI standards and references

ANSI/PCI 142, *Specification for Precast, Prestressed Concrete Piles*

PCI MNL 116, *Manual for Quality Control for Plants and Production of Structural Precast Concrete Products*

PCI MNL 133, *PCI Bridge Design Manual*

PCI MNL 135, *Tolerance Manual for Precast and Prestressed Concrete Construction*

PCI MNL 137, *Manual for the Evaluation and Repair of Precast, Prestressed Concrete Bridge Products*

PCI PD-01, *Calculation of Interaction Diagrams for Precast, Prestressed Concrete Piles*

1.2.4 American Welding Society (AWS) standards

AWS D1.1/D1.1M, *Structural Welding Code—Steel*

AWS D1.4/D1.4M, *Structural Welding Code—Steel Reinforcing Bars*

1.2.5 Post-Tensioning Institute (PTI) references

PTI M55.1, *Specification for Grouting of Post-Tensioned Structures*

Section 2—Materials

Material properties and requirements for prestressed concrete piles are almost identical to those for all other precast, prestressed concrete structural components. Piles, however, are subject to long-term contact with soil and moisture as well as submergence in water and other aggressive environments. Therefore, the in-service conditions require that materials used in piles be carefully selected to reduce long-term durability issues such as corrosion, alkali-silica reaction, and delayed ettringite formation. Special consideration should be given to using appropriate materials that ensure satisfactory short- and long-term performance of the piling. On any project, in addition to satisfying the recommendations provided in this report, designers must also consider local or state specifications governing the use and availability of certain products or materials used to construct prestressed concrete piles. Before casting prestressed concrete piles, the mixture proportions for the concrete should be submitted to the engineer or owner for review and approval. The *Specification for Precast, Prestressed Concrete Piles* (ANSI/PCI 142-24) provides provisions and extensive commentary related to cementitious materials, admixtures, aggregates, water, concrete strength, and steel reinforcement. This section presents additional information related to structural steel, grout, and anchorage as related to prestressed concrete pile construction.

2.1 Structural steel

For exceptionally hard pile-driving conditions, particularly for bearing on rock or penetration through hard strata, special treatment of the pile tip may be advantageous. This may take the form of added spiral or other reinforcement at the tip, steel shoes, or points. In some cases, a structural steel H-pile is used to provide a permanent, load-bearing structural tip, commonly called a *stinger*, on the end of a prestressed concrete pile. This material must withstand driving, so it should meet the requirements for steel H-pile sections (ASTM A572 Grade 50). The thickness of any steel in a pile tip should not be less than ⅜ in. (9.53 mm).

The suitability of the steel for welding should be predetermined because some producers prefer to cast the piles with just an embedded plate or only a short portion of the tip extending outside the pile. This practice preserves the casting capability of the bed and simplifies the fabrication of the precast concrete pile. The remainder of the specified length of the tip is then welded onto the plate or the protruding portion after the pile is removed from the bed.

Headed steel studs (conforming to ASTM A29) on each side of the web in the embedded portion of the steel stinger or deformed bar anchors, with or without a stinger plate, may be required in some cases for the anchorage of the embedded portion of the steel tip into the pile. The use and installation of headed steel studs should conform to the requirement of AWS D1.1.

2.2 Grout

The need for grout in prestressed concrete piles is not common, and is generally limited to either the grouting of dowels in pile heads or the bonding and protection of strands used to join sections of cylinder piles. The former application involves piles that are field-spliced with dowels in oversized holes, or it is used to provide pile-to-pile cap connections using grouted dowels. The latter case is common with large-diameter hollow cylinder piles available in several regions of the United States.

Cement grout, where used in prestressed concrete piles, should conform to ASTM C1107 and be composed of materials that conform to the requirements stipulated herein for cement, sand, admixtures, and water. Approved expanding admixtures or expansive cements may be used. However, some expanding admixtures contain calcium chloride and should not be used. Neat cement grout is frequently used to grout dowels in pile heads. Designers should consult PTI M55.1, *Specification for Grouting of Post-Tensioned Structures*, for information regarding grouting of prestressing tendons when designing segmented prestressed concrete piles. Epoxy grout may also be used in some applications.

2.3 Anchorages

Anchorage fittings for post-tensioning assemblies should conform to the requirements of ACI 318-19 Section 25.8.[4]

Section 3—Design

This section provides an overview of general design considerations and presents a few design aids for prestressed concrete piling. Load-capacity determination procedures, structural design and detailing procedures, and special considerations for compression, tension, flexure, shear, and combined actions are discussed. Detailed provisions for prescriptive and performance-based design are fully presented in the *Specification for Precast, Prestressed Concrete Piles* (ANSI/PCI 142-24). Therefore, this section aims to complement that standard by providing some additional guidance with a special emphasis on the application of the standard to different types of structures. Reference is made to PCI's free software program for developing axial-moment interaction diagrams for the ultimate capacity of commonly used pile sizes of varying concrete strengths and effective prestress levels.

3.1 Prestressed concrete pile design in accordance with ANSI/PCI 142-24

ANSI/PCI 142-24 contains prestressed concrete pile analysis, design, and detailing provisions for all types of structures. ANSI/PCI 142-24 has been written with an emphasis on appropriately developing provisions that complement and align with design philosophies implemented by building, bridge, and pier/wharf codes and standards, as well as other codes and standards that contain provisions for deep foundation elements. The code governing the design of the supported structure is referred to in ANSI/PCI 142-24 as the general code. Serviceability provisions, including allowable stress criteria, are presented for fabrication, handling, driving, wind load, wave load, and other general code-prescribed conditions. Seismic serviceability is not a design consideration. However, consistent with standard practice, performance-based design provisions allow for design that considers

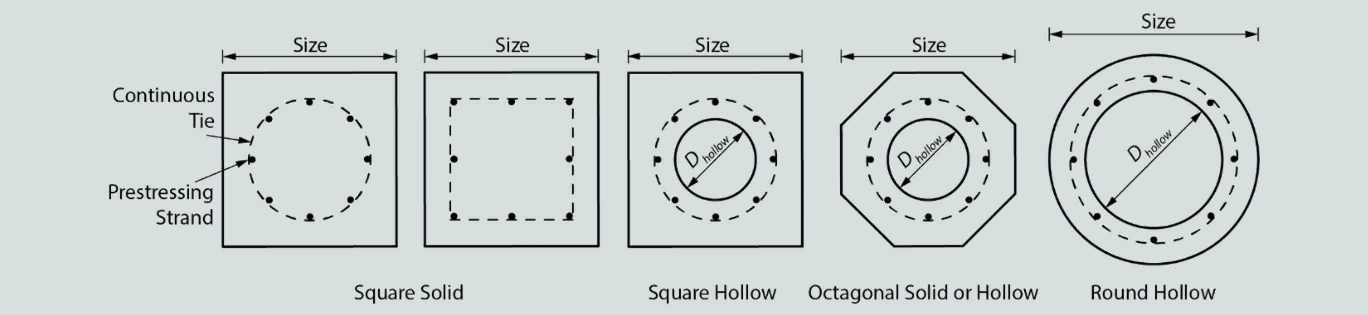

Figure 3.1. Cross sections of typical prestressed concrete piles (See Tables 3.1a and 3.1b for dimensions).

Table 3.1a. Allowable service loads of typical prestressed concrete piles—for preliminary design only. (I-P units)													
Size, in.	D_{hollow}, in.	Section properties*						Allowable concentric service load, ton†					
		Area, in.²	Weight, lb/ft	Moment of inertia, in.⁴	Section modulus, in.³	Radius of gyration, in.	Perimeter, ft	f'_c					
								5000 psi	6000 psi	7000 psi	8000 psi	9000 psi	10,000 psi
Square piles													
10	Solid	100	104	833	167	2.89	3.33	73	89	106	122	139	156
12	Solid	144	150	1728	288	3.46	4.00	105	129	152	176	200	224
14	Solid	196	204	3201	457	4.04	4.67	143	175	208	240	273	305
16	Solid	256	267	5461	683	4.62	5.33	187	229	271	314	356	398
18	Solid	324	338	8748	972	5.20	6.00	236	290	344	397	451	504
20	Solid	400	417	13,333	1333	5.77	6.67	292	358	424	490	556	622
20	11	305	318	12,615	1262	6.43	6.67	222	273	323	373	424	474
24	Solid	576	600	27,648	2304	6.93	8.00	420	515	610	705	801	896
24	12	463	482	26,630	2219	7.58	8.00	338	414	491	567	644	720
24	14	422	439	25,762	2147	7.81	8.00	308	378	448	517	587	656
24	15	399	415	25,163	2097	7.94	8.00	291	357	423	489	555	621
30	18	646	672	62,347	4157	9.82	10.00	471	578	685	792	898	1005
36	18	1042	1085	134,815	7490	11.38	12.00	761	933	1105	1277	1449	1621
Octagonal piles													
10	Solid	83	85	555	111	2.59	2.76	60	74	88	101	115	129
12	Solid	119	125	1134	189	3.09	3.31	86	106	126	145	165	185
14	Solid	162	169	2105	301	3.60	3.87	118	145	172	198	225	252
16	Solid	212	220	3592	449	4.12	4.42	154	189	224	259	295	330
18	Solid	268	280	5705	639	4.61	4.97	195	240	284	328	373	417
20	Solid	331	345	8770	877	5.15	5.52	241	296	351	405	460	515
20	11	236	245	8050	805	5.84	5.52	172	211	250	289	328	367
22	Solid	401	420	12,837	1167	5.66	6.08	292	359	425	491	558	624
22	13	268	280	11,440	1040	6.53	6.08	195	240	283	328	373	417
24	Solid	477	495	18,180	1515	6.17	6.63	348	427	506	584	663	742
24	15	300	315	15,696	1308	7.23	6.63	219	268	318	368	417	467
Round piles													
36	26	487	507	60,007	3334	11.10	9.43	355	436	516	596	677	758
42	32	581	605	101,273	4823	13.20	11.00	425	520	616	712	808	904
48	38	675	703	158,222	6592	15.31	12.57	493	604	715	827	939	1050
54	44	770	802	233,373	8643	17.41	14.14	562	689	816	943	1071	1198
66	54	1131	1178	514,027	15,577	21.32	17.28	826	1013	1199	1386	1573	1759

* Form dimensions may vary among producers, with corresponding slight variations in section properties.

† Allowable loads are based on 700 psi effective prestress after all losses. Check with local producers for available concrete strengths.

Table 3.1b. Allowable service loads of typical prestressed concrete piles—for preliminary design only. (metric units)

Size, mm	D_{hollow}, mm	Section properties*						Allowable concentric service load, kN†					
		Area, mm²	Weight, kg/m	Moment of inertia, mm⁴	Section modulus, mm³	Radius of gyration, mm	Perimeter, m	f'_c					
								34.5 MPa	41.4 MPa	48.3 MPa	55.2 MPa	62.1 MPa	68.9 MPa
Square piles													
254	Solid	64,520	155.02	3.47E+08	2.74E+06	73.4	1.02	649	792	943	1085	1237	1384
305	Solid	92,909	223.22	7.19E+08	4.72E+06	87.9	1.22	934	1148	1352	1566	1781	1993
356	Solid	126,459	303.83	1.33E+09	7.49E+06	102.6	1.42	1272	1557	1850	2135	2425	2712
406	Solid	165,171	396.84	2.27E+09	1.12E+07	117.3	1.63	1664	2037	2411	2793	3167	3543
457	Solid	209,045	502.26	3.64E+09	1.59E+07	132.1	1.83	2100	2580	3060	3532	4008	4484
508	Solid	258,080	620.07	5.55E+09	2.18E+07	146.6	2.03	2598	3185	3772	4359	4948	5535
508	279	196,786	472.73	5.25E+09	2.07E+07	163.3	2.03	1975	2429	2874	3318	3773	4221
610	Solid	371,635	892.90	1.15E+10	3.78E+07	176.0	2.44	3737	4582	5427	6272	7125	7971
610	305	298,728	717.56	1.11E+10	3.64E+07	192.5	2.44	3007	3683	4368	5044	5728	6407
610	356	272,274	654.24	1.07E+10	3.52E+07	198.4	2.44	2740	3354	3977	4599	5220	5840
610	381	257,435	618.93	1.05E+10	3.44E+07	201.7	2.44	2589	3176	3763	4341	4936	5522
762	457	416,799	1000.63	2.60E+10	6.81E+07	249.4	3.05	4190	5142	6094	7037	7991	8940
914	457	672,298	1614.50	5.61E+10	1.23E+08	289.1	3.66	6770	8300	9831	11,352	12,890	14,420
Octagonal piles													
254	Solid	53,552	126.49	2.31E+08	1.82E+06	65.8	0.84	534	658	783	899	1027	1149
305	Solid	76,779	186.02	4.72E+08	3.10E+06	78.5	1.01	765	943	1121	1290	1472	1647
356	Solid	104,522	251.50	8.76E+08	4.93E+06	91.4	1.18	1050	1290	1530	1761	2004	2242
406	Solid	136,782	327.40	1.50E+09	7.36E+06	104.6	1.35	1370	1681	1993	2304	2623	2934
457	Solid	172,914	416.69	2.37E+09	1.05E+07	117.1	1.52	1735	2135	2527	2918	3315	3709
508	Solid	213,561	513.42	3.65E+09	1.44E+07	130.8	1.68	2144	2633	3123	3603	4095	4581
508	279	152,267	364.60	3.35E+09	1.32E+07	148.3	1.68	1530	1877	2224	2571	2919	3266
559	Solid	258,725	625.03	5.34E+09	1.91E+07	143.8	1.85	2598	3194	3781	4368	4961	5549
559	330	172,914	416.69	4.76E+09	1.70E+07	165.9	1.85	1735	2135	2518	2918	3315	3709
610	Solid	307,760	736.64	7.57E+09	2.48E+07	156.7	2.02	3096	3799	4502	5196	5901	6601
610	381	193,560	468.77	6.53E+09	2.14E+07	183.6	2.02	1948	2384	2829	3274	3711	4152
Round piles													
914	660	314,212	754.50	2.50E+10	5.46E+07	281.9	2.88	3158	3879	4591	5302	6024	6739
1067	813	374,861	900.34	4.22E+10	7.90E+07	335.3	3.36	3772	4626	5480	6334	7187	8040
1219	965	435,510	1046.18	6.59E+10	1.08E+08	388.9	3.83	4386	5373	6361	7357	8350	9341
1372	1118	496,804	1193.51	9.71E+10	1.42E+08	442.2	4.31	5000	6130	7259	8389	9525	10,656
1676	1372	729,721	1753.06	2.14E+11	2.55E+08	541.5	5.27	7348	9012	10,667	12,330	13,991	15,651

* Form dimensions may vary among producers, with corresponding slight variations in section properties.

† Allowable loads are based on 4.8 MPa effective prestress after all losses. Check with local producers for available concrete strengths.

discrete earthquake return periods where different performance levels (that is, levels of damage) can be investigated.

In addition to serviceability design requirements applicable to all piles, ANSI/PCI 142-24 requires piles to be designed using allowable stress, strength, or performance-based (seismic only) design methods. For preliminary design purposes, **Fig. 3.1** and **Tables 3.1a** and **3.1b** provide section properties and allowable concentric service loads based on a 700 psi (4.8 MPa) effective prestress and concrete strengths of 5000 to 10,000 psi (35 to 69 MPa).

For strength design, ANSI/PCI 142-24 requires that prestressed concrete piles be designed to resist factored demands from load combinations prescribed in the general code. Similarly, the reduced nominal strength of the prestressed concrete pile must be calculated with procedures prescribed in the general code. PCI is currently updating (scheduled for release in 2025) their free software program (PCI PD-01) for consistency with ANSI/PCI 142-24. This updated program will perform both serviceability and strength designs of commonly used pile sizes of varying concrete strengths and effective prestress levels. In its current format, the program is still an excellent resource for developing axial-moment interaction diagrams that include slenderness effects. Specific pile characteristics—such as pile type and size, concrete strength, pretensioning strand size and pattern, and slenderness ratio—can be entered. The program can also be used to compute lifting points for precast concrete piles. The next version may also be used to help verify piling shear strength and seismic ductility requirements consistent with the general code.

A performance-based design can serve as an alternative to the prescriptive method, offering a more economical approach to pile confinement reinforcing. Given the varying approaches used by different general codes, ANSI/PCI 142-24 provides specific information on prestressed concrete piles that can be used for performance-based design conforming to general code provisions. Specifically, ANSI/PCI 142-24 provides strain limits, inelastic material stress-strain properties, cracked moment of inertia modeling assumptions, and plastic-hinge lengths.

3.2 Detailing provisions for prestressed concrete piles

3.2.1 Transverse reinforcement

Transverse reinforcement must be provided along the entire length of all prestressed concrete piles to confine the concrete core of the pile and to control any longitudinal cracks that may form during handling, driving, or under design load conditions.

When inelastic behavior of piles is a design consideration, increased levels of transverse reinforcing may be required at certain locations along the length of the pile to ensure stable inelastic hinging mechanisms can occur.

The concrete-confining effect of transverse reinforcement is well established in the literature (see Mander et al.[5] for discussion). Both circular and square patterns of mild transverse reinforcement work to restrain the lateral expansion of the concrete under combined axial compressive stresses that result from the effects of flexural and axial demands. As a result, the confined core area is stable under cyclic loading and is stronger (resists larger compressive stresses) and less brittle (resists much larger compressive strains before failure) than the unconfined concrete outside of the core area.

Typical seismic design detailing includes increased transverse reinforcement at certain locations along the length of the pile. The added transverse reinforcement increases the available ductility of the pile, which enables the pile to withstand significant displacements and inelastic curvatures. In the case of spalling of concrete cover due to high seismic demands and inelastic pile curvature, transverse reinforcement not only ensures that the confined concrete can resist compressive strains significantly greater than 0.003, but it also prevents buckling of compressed longitudinal reinforcing bars and tendons at large deformations and provides shear strength that supplements the shear strength of the concrete alone.

Ordinary piles are not used in moderate-to-high seismic areas, and it is common in low seismic areas to specify W3.5 wire spiral reinforcement (W4.0 for nominal pile sizes greater than 24 in. [610 mm]) to surround the strands. The spiral reinforcement is fabricated in a circular or square pattern, depending on the arrangement of the strands. Circular and square ties are also permitted, but are less commonly used. The spiral reinforcement pitch (longitudinal spacing between turns) is typically 6 in. (152 mm) for most of the pile length. The turns of the spiral reinforcement are more closely spaced at the ends of the pile to absorb energy and resist splitting forces during driving. Again, these typical details are used where ordinary piles are not anticipated to be subjected to significant seismic actions and therefore have no special detailing or design requirements.

There are two options for designing transverse reinforcement: prescriptive design and performance-based design. Both approaches are currently used in national codes and standards (for example, the *2021 International Building Code*,[6] the *AASHTO LRFD Bridge Design Specifications*,[7] and the 2019 Marine Oil Terminal Engineering and Maintenance Standards[8]). Building codes have traditionally focused on prescriptive design, which attempts to ensure a degree of available ductility in piles that is directly related to the seismicity of the site. This approach, focused on essentially elastic pile curvatures, usually results in overly conservative spiral reinforcement quantity and pile lateral-displacement limits mandated in these same codes. Bridge and pier/wharf codes and standards have traditionally used prescriptive design approaches for areas of low-to-moderate seismicity, whereas designs in areas of high seismicity have been based on performance-based design. Both options require that, as a minimum, the same transverse reinforcement discussed in the previous paragraph be provided for piles.

Current versions of building-related codes and standards identify structural elements as ordinary, intermediate, and special, depending on the provided level of seismic ductility capacity afforded via structural detailing and Seismic Design Category. ANSI/PCI 142-24 uses the same terminology. As such, in this document, piles are identified as ordinary, intermediate, or special concrete piles with detailing provided such that low-, moderate-, or high-ductility capacity is available in response to seismic loading.

3.2.1.1 Minimum transverse reinforcement requirements for ordinary, intermediate, and special concrete

For all structure types, and for both hollow and solid piles, the prestressing strands of the piles must be enclosed in a spiral transverse reinforcement (or equivalent transverse reinforcement ties) equal to or exceeding the following minimum requirements:

For nominal pile sizes less than or equal to 24 in. (610 mm):

- Spiral wire must be a minimum of W3.5 (A_{sp} = 0.035 in.^{2} [22.6 mm^2]).
- Spiral pitch of 1 in. (25.4 mm) for five turns (approximately 6 in. [152 mm]) at both ends of pile, then a pitch of 3 in. (76.2 mm) for 16 turns at both ends, followed by a pitch of 6 in. for the remainder of the pile.

For nominal pile sizes greater than 24 in. (610 mm):

- Spiral wire must be a minimum of W4.0 (A_{sp} = 0.040 in.^{2} [25.8 mm^2]).
- Spiral pitch of 1½ in. (38.1 mm) for four turns (approximately 6 in. [152 mm]) at both ends of pile, then a pitch of 2 in. (50.8 mm) for 16 turns at both ends, followed by a pitch of 4 in. (102 mm) for the remainder of the pile.

Figures 3.2 and **3.3** show the minimum spiral reinforcement details. It should be noted that the minimum transverse rein-

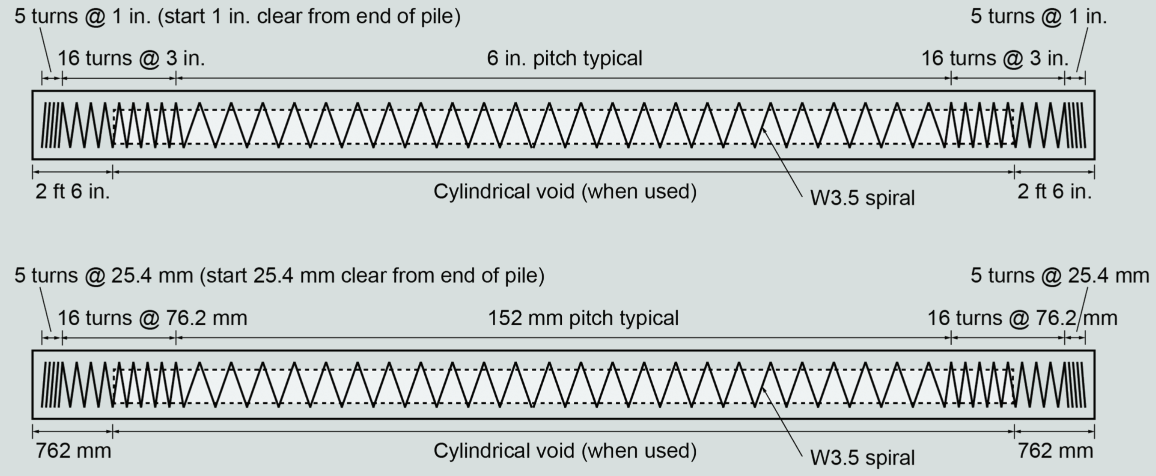

Figure 3.2. Spiral transverse reinforcement for piles 24 in. (610 mm) or less in width or diameter.

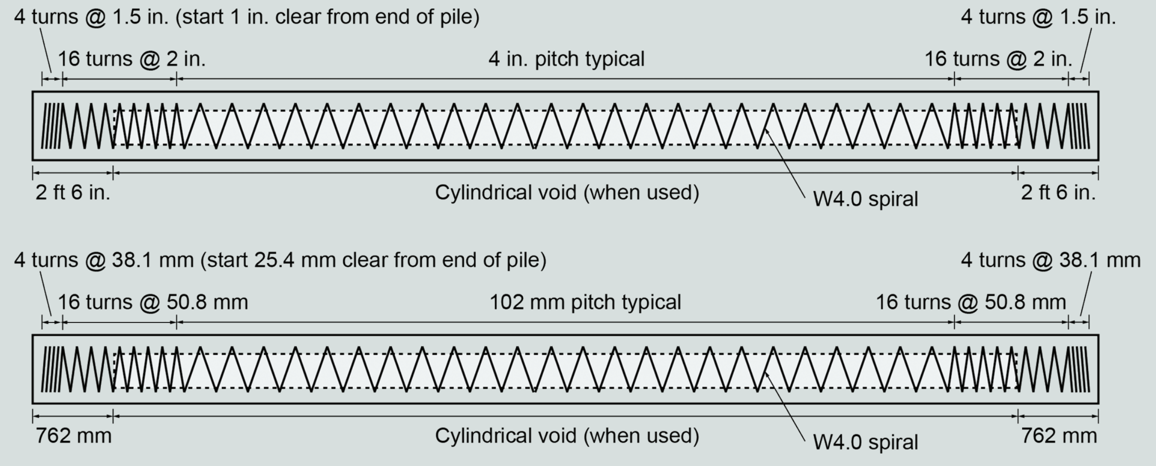

Figure 3.3. Spiral transverse reinforcement for piles greater than 24 in. (610 mm) in width or diameter.

forcement presented is required for all prestressed concrete piling and has been adopted into current building codes and standards via the *2021 International Building Code*.[6] The *AASHTO LRFD Bridge Design Specifications*[7] maintains ANSI/PCI 142-24 minimum transverse reinforcement requirements.

Although the minimum spiral reinforcement quantities presented herein apply to hollow piles, hollow piles are not recommended where seismic ductility capacity is needed or in any application where pile ductility is a design consideration. Research is needed to more fully assess the behavior of hollow piles subject to seismic loads and to develop applicable design equations or construction strategies. The equations presented in ANSI/PCI 142-24 were developed specifically for solid pile sections. Extrapolation of their use for hollow pile sections is not recommended. Alternatively, hollow piles can be filled with concrete and detailed to perform well during seismic events. However, required detailing (depth of fill, auger requirements before fill, cleaning requirements, connection details, and the like) is code specific and outside the scope of this report. Where hollow piles are filled with concrete for seismic performance, it is recommended that the performance-based design procedures be used. Empirically, it has been found that providing about 1% spiral reinforcement in the top 12 in. (305 mm) of the pile mitigates splitting of the pile head for diameters up to 54 in. (1370 mm).[1] However, because the selection of appropriate spiral reinforcement for cylinder piles is largely empirical and highly dependent on driving conditions, the ability to drive cylinder piles without cracking should be confirmed before pile production by conducting a pile-driving test using the planned driving equipment.

ANSI/PCI 142-24 provides design equations for confinement steel that depends on the ordinary, intermediate, and special designation and whether or not the pile is considered part of the seismic-force-resisting system. The wording "piles considered part of the seismic-force-resisting system" has a very specific definition. The case is meant primarily for the bridge and pier/wharf industries where piles that extend significantly above grade are used intentionally as the primary lateral force-resisting system for the structure. It is also for cases where an *R*-value is used for pile bent-type behavior in prescriptive design or, when performance-based design is used, pile hinging is a purposely selected energy-dissipation mechanism. For traditional building code applications using prescriptive design, the applicable case is usually "pile not considered part of the lateral force-resisting system."

Note that the definitions of ordinary, intermediate, and special are code specific and not defined here. However, the ductility capacity provided for piles is expected to be similar to that provided for ordinary, intermediate, and special reinforced concrete columns that are part of moment frames designed using ACI 318-19.[4]

3.2.1.2 Prescriptive design of transverse reinforcement

Ordinary piles are discussed in Section 3.2.1. For intermediate and special concrete piles, it is both practical and conservative, although sometimes possibly overly conservative, to detail transverse reinforcement using prescriptive equations that provide minimum volumetric ratios and pitch for the spiral reinforcement along specified lengths of the pile. Prestressed concrete piles can be considered part of or not part of the lateral force-resisting system. In most building applications, prestressed concrete piles are not considered part of the lateral force-resisting system (that is, pile demands are based on loads determined for the seismically damaged structure above the foundation and may or may not include system overstrength as discussed in this section). In building applications, such as those designed to meet the *2021 International Building Code*,[6] pile ductility demand is not permitted by code; however, pile ductility capacity is considered paramount. For bridge (for example, flat slab bridges with pile bents) and pier and wharf structures, prestressed concrete piles are often considered part of the lateral force-resisting system. In these cases, pile ductility demand and capacity are typically used as part of the overall design philosophy.

3.2.1.3 Performance-based design of transverse reinforcement

For many structures where moderate-to-high seismic ductility capacity is a design consideration, it is likely beneficial to detail the transverse reinforcement along the length of the pile using a performance-based design methodology. Performance-based design procedures typically involve nonlinear static analysis, which is also called pushover analysis, or nonlinear time history analysis. In this document, the nonlinear modeling requirement is the inclusion of axial load–dependent, nonlinear moment-rotation characteristics of the pile as defined by moment-curvature curves developed for each pile making up the foundation system. In addition to nonlinear pile-hinging considerations, performance-based design procedures require explicit modeling of the pile foundation system to include the effects of soil-structure interaction and appropriate modeling of pile-head fixity. Performance-based design can be used irrespective of whether or not the prestressed concrete pile is considered part of the lateral force-resisting system. Performance-based design requires the curvature of the pile to be fully defined along the length of the pile under all applicable load combinations. This approach aims to ensure that the transverse reinforcement is adequate to resist pile curvatures expected under design earthquake motions. The remaining portion of this section is not intended to provide or recommend complete performance-based design procedures, which are code specific; but to provide performance characteristics, experimentally and analytically proven modeling assumptions, and recommended detailing practices specific to prestressed concrete piles and their connections.

In performance-based design, axial-moment interaction failure of a pile occurs during the nonlinear analysis whenever a strain limit in a pile's ductile region is exceeded. Performance-based design does not permit the strain limit in the pile ductile region to be exceeded during the analysis for displacement demands resulting from code-prescribed design accelerations for the site. Practically speaking, failures occur when the lateral demand–induced curvature along the length of a pile causes a steel strand to reach a tensile strain limit established by the governing code, or when the concrete reaches its confined compressive strain limit within the core of the cross section.

It should be noted that the performance-based design process typically requires that the foundation system be modeled as part of a global model of the entire structure. This approach is in contrast to standard practice using prescriptive codes, which allow for the assumption of a fixed base with foundation loads sometimes provided to a separate pile designer working for the pile fabricator. Any decoupling of the foundation system model from the structural model above the foundation should require engineer of record approval.

3.2.1.3.1 Axial load limits for prestressed concrete piles

Research completed by Sritharan et al.[9] suggested that axial load limits should be applied to prestressed concrete piles for cases where significant moment drops occur upon pile spalling. However, subsequent research performed at The Citadel concluded that (a) moment drops occurred for other types of deep foundation elements and was not a code prohibition; (b) strength recovery unique to prestressed concrete piles would ensure safe and ductile seismic behavior; and (c) the proposed axial load limits were arbitrarily established.[10] Therefore, based on the results of the research, axial load limits are no longer recommended for prestressed concrete piles. See Ryan and Mays[10] for more information on The Citadel research on axial load limit considerations for prestressed concrete piles. It should be noted that axial load limits do not apply to performance-based design procedures since axial-moment interaction and structural stability are considered separately for every load case.

3.3 Pile splices and connections

3.3.1 Splices and buildups

Pile splices are defined as any method of joining prestressed concrete pile sections in the field during driving so that driving may continue. Pile splices may be used for a variety of reasons. The supplied length of a pile may not be sufficient to obtain the specified bearing capacity, and further driving may be required. On some projects, this issue may be caused by nonuniform substrata conditions that make it difficult to determine required pile lengths. More commonly, the estimated length of pile cannot be economically or feasibly transported to the site (or handled in the driver), and therefore a process whereby shorter piles spliced together to make one long pile is required. A pile may have one or more splices. Each splice must be capable of resisting all subsequent stresses and deformations that may be induced through driving or under service loads. Because there is no net prestress-induced compression at the ends of the two pile segments being spliced, any net load-induced tension transferred across the splice must be detailed to occur through properly developed reinforcing in the pile. The type of splice selected must depend primarily on service loads and conditions. Not all splices are capable of resisting moment or uplift.

Some codes and standards may require all pile splices to resist some portion of the moment or tensile capacity of the pile, and where prescriptive design methods are used, this approach is reasonable. However, when performance-based design is used, designers can ensure that the pile splice is located in a portion of the pile that will be subject, as a result of all applicable load combinations, only to compression. In such cases, the splice should be designed for the actual actions induced by all load combinations or as required by the nonlinear static analysis results.

Commonly used splices can be generally categorized as the following:

- Dowel with epoxy
- Welded
- Bolted or pinned
- Mechanical locking
- Connector ring
- Wedge
- Sleeve
- Post-tensioned

Illustrations of these pile splice types can be found in Chapter 20 of the *PCI Bridge Design Manual*[11] (PCI MNL 133). There is a variation in the behavior of various splices under field conditions. For some splice types, failure could occur directly in the joint, whereas in other cases, failure could occur at the dowels anchoring the splice to the piles. In some splice systems, failure would occur completely outside of the spliced region. The ability of a splice to develop the strength of the pile, or a reasonable percentage of that strength, depends on close tolerances and the use of proper procedures in making the splice. Careless workmanship or improper field procedures can result in significant deviations from the strength and behavior levels desired.

When piles are purposely overdriven a significant distance below the specified cutoff elevation to obtain required bearing capacity, a pile splice can be used. However, piles are sometimes accidentally or purposely overdriven only a short distance below the prescribed cutoff elevation, and lowering the pile cap is not considered a feasible option. Buildup is the term applied to any method of extending a driven pile to the required cutoff elevation. Buildup can be accomplished through the use of a precast concrete section, but is generally made of cast-in-place concrete. The buildup must be capable of developing the service- and strength-level stresses. Concrete quality must be compatible with the prestressed concrete pile. Typical buildup details are shown in Chapter 20 of PCI MNL 133.

When piles are driven to bearing capacity before reaching the predicted tip elevation, they should be cut to the specified elevation and orientation. Piles should be cut in a manner to minimize the likelihood of damage to the concrete at the pile head. Where projecting reinforcement is specified, reinforcement should not be damaged during pile-cutting operations.

3.3.2 Segmented cylinder piles

Large-diameter cylinder piles are often manufactured with centrifugal casting in segments measuring 8 to 16 ft (2.4 to 4.9 m) in length. Longitudinal holes are formed during casting to receive post-tensioning strands or wires. Post-tensioning follows the assembly of the segments and proper application of the joint sealant material. Such sealing material (generally polyester resin) should be of sufficient thickness to fill all voids between surfaces. The pile sections should be brought into contact and held together under compression while the sealing material sets. After completing the prestressing operation, all tendons should be fully grouted and stress in tendons maintained until the grout develops the required strength.

3.3.3 Connections between pile and pile cap

The design of the pile-to-pile cap connection depends on the load magnitude and how the load is directed. The load can be an axial load (tension or compression) or a bending moment, or a combination of axial load and moment. If the connection requires moment resistance, it must be recognized that the prestress in a pile, as in other pretensioned components, varies from zero at the end of the pile to fully effective prestress approximately 50 to 60 strand diameters from the end. A pinned-head condition allows rotation of the pile head with respect to the pile cap. A fixed-head condition minimizes the rotation of the pile head at the connection to the cap, and therefore extremely high moments may be transferred between the pile head and the cap.

A pinned pile-to-pile cap connection can be used where moment transfer between the pile and pile cap is not required or considered in the structural model. If the pile is expected to remain in compression, it can be embedded into the pile cap without a mechanical connection. (Note that some codes and agencies require mechanical connection details for all pile-to-pile cap connections.) The embedment distance should be sufficient to ensure a positive connection while still permitting some rotation to eliminate excessive moment development. Specific requirements for pinned connections—such as embedment lengths, roughening the pile surface over the embedded length, exposing strands, extending mild steel reinforcement, or providing spiral reinforcement around the embedded length—are code specific and are not discussed here.

A fixed pile-to-pile cap connection is required whenever moment must be transferred between the pile cap and the top of the pile. Common methods of fixed connections include the following:

- Pile head extension: The pile head is extended into the cap, generally one pile dimension minimum. Embedded surfaces of the pile must be clean and preferably roughened before casting the cap concrete.

- Strand extension: Prestressing strands are extended into the pile cap. Prestressing steel in this case cannot be assigned an allowable stress greater than that of the reinforcing steel (maximum allowable stress of about 30,000 psi [210 MPa]). Embedded lengths depend on design requirements but should be 18 in. (460 mm) minimum.

- Mild steel dowels: Dowels can be cast in the head of piles either projecting or fully embedded for exposure after driving. When piles are cast with projecting dowels, a special driving helmet must be provided. The same applies to piles cast with projecting strand.

    - The preferable method of connection is to cast piles with formed holes in the pile head. Dowels are grouted into these holes following pile driving. Holes can also be drilled into the pile head after driving to accommodate grouted dowels. The area of the holes in the pile head should not exceed 6% of the gross area of the pile. In addition, the terminus points of embedded reinforcement or dowel holes within the pile should be staggered.

    - It should be recognized that either embedded mild steel or holes cast to receive dowels can change the effective prestress level in the pile near the pile head.

- Other connections: For cylindrical piles, a cage of reinforcement can be concreted into the pile core following driving. A form must be provided; it can be made of disposable materials, such as wood, or a precast concrete plug, which is grouted into the core. Structural steel members can also be used as connectors in cylindrical piles.

- Various extensions: Combinations of pile head extension, strand extension, and/or dowels can be used.

Refer to Chapter 20 of PCI MNL 133 for typical pile-to-pile cap details and discussion of design philosophies.

Section 4—Manufacture and transportation of prestressed concrete piles

This section covers important considerations specifically related to the manufacture and transportation of prestressed concrete piles. More detailed information on these topics can be found in Chapter 20 of PCI MNL 133.

4.1 Manufacturing plants

Because casting of prestressed concrete piles is repetitive, and the work is performed by experienced, trained personnel in a controlled environment, the quality of plant-manufactured prestressed concrete piles is ensured and consistently maintained. Specifications should require that manufacturers be regularly engaged in the production of prestressed concrete piles and be able to demonstrate, through past performance, their ability to achieve the required quality. Proven capability should be shown through participation in the PCI Plant Certification Program.

Plant operations often include a central concrete batch plant and delivery vehicles to transfer concrete from the batch plant to the casting beds. Casting beds for piles are usually constructed in long lines, and casting is done on a continuous, daily cycle.

4.2 Handling and storage

Damage to piles can occur during the handling, storage, and transporting stages. Handling should be done using designed lifting points. On many long or slender piles, three, four, or five pickup points may be required and can be accomplished using equalizing slings and strongbacks. If proper care and caution are not used, severe damage to the pile can occur. Piles in storage should be properly supported to avoid permanent sweep introduced during curing. Points at which piles are to be lifted or supported should be clearly apparent. When other picking methods are used (for example, inserts, slings, or vacuum pads), suitable markings to indicate correct support points should be provided. Piles stacked in storage should have intermediate dunnage supports in vertical alignment.

4.3 Transporting

Prestressed concrete piles are normally delivered from the manufacturing plant to the construction site via barge, truck, or rail. Piles up to approximately 50 ft (15 m) long can be carried on flatbed trailers. Piles over this length are generally carried on expandable flatbed trailers or telescoping pole trailers.

For piles requiring more than two support points, special supports should be articulated to avoid excessive bending stress in the pile. One method is to build A-frames, one at the tractor end and one at the dolly end. On top of the A-frames, a long steel support will provide the pile two or more supports at each end and will bring the load down to single points at the front and back of the hauling unit. Before delivery, jobsite access should be reviewed and all obstructions, ruts, holes, or dangerous conditions corrected.

4.4 Tolerances

Piles are typically manufactured in steel forms on a long-line casting bed using steel headers or plates that form the ends of each pile, and cross-sectional dimensions are defined by the form. Strands are held in the proper position at pile ends as they pass through holes in the headers. In long piles, where the tensioned strands may sag between headers, chairs or other means are used to properly support the strands.

Piles should be fabricated in accordance with the generally accepted dimensional tolerances found in PCI MNL 135. Tighter tolerances, as recommended by the splice manufacturer, are required when using mechanical splices.

Section 5—Installation of prestressed concrete piles

5.1 Structural integrity

A properly designed pile is only capable of serving its intended purpose if it is properly installed and is not damaged during the installation process. When piles are damaged during the installation process, they must be extracted or repaired to the satisfaction of the engineer of record, or in accordance with the governing code or standard applicable to the structure.

A wide variety of methods have been used to install prestressed concrete piles. These methods differ according to the factors listed below, but all have one common objective: every prestressed concrete pile should be installed in a manner that ensures the structural integrity of the pile itself, so that it is able to resist known site conditions and imposed design loads. The selection and appropriate use of equipment that considers a matching of the driving system to the pile-soil system are key aspects of any successful installation process.

5.2 Factors affecting installation

Installation methods may vary with the following factors (see Chapter 20 of PCI MNL 133 for detailed information):

- Size, type, and length of the pile
- Required driving capacity of the pile
- Inclination of the pile (vertical or battered)
- Type of soil/rock into which the pile is to be installed
- Surrounding element (soil or water)
- Uniformity of the soil strata from bent to bent

- Effective prestress in the pile
- Pile group arrangement
- Site location and accessibility (for example, the presence of surrounding structures or the potential to use larger equipment supported by floating barges as opposed to land-based equipment)
- The number of piles used on the project and the construction schedule (economy of scale)

5.3 Installation methods

The most common method of installing prestressed concrete piles is to drive them with an impact hammer. Commonly used hammer types are air powered, diesel powered, and hydraulic powered. Each of these types may be either single-acting or double-acting. In single-acting hammers, the ram is powered upward only and allowed to gravity fall. In double-acting hammers, the ram is powered both upward and downward.

For on-land installation applications, rigs are usually mounted on tracked treads or rubber tires with outriggers. Templates are not as commonly used for land applications because alignment is facilitated by ground stability. Water installation is more difficult and is performed from a barge or temporary work platform. Templates that hold the piles in position are often required for water installations.

5.3.1 Hammer selection

Matching of an appropriate hammer to the pile-soil system is of critical importance. The hammer selected must be able to drive the pile to the required capacity or depth without damaging the pile. In comparing hammers of equal energy, those with a heavier ram and lower impact velocity, such as air hammers, are less likely to cause damaging stresses in the pile. Knowledge of the particular soils, experience of local geotechnical consultants, and experience of pile-driving contractors are often the primary sources of information in the selection of hammers.

Wave equation analysis may be used to aid in hammer selection. The wave equation is used to predict pile capacity, driving resistance, and stresses in the pile.

In the field, dynamic testing of selected piles during driving may be helpful, or even necessary in some cases, to evaluate the effectiveness of the selected pile installation system.

Driving stresses caused by hammer impact must be maintained below levels that could result in pile damage. Pile cushion material and thickness can be varied to alter driving stresses, particularly tensile stresses, which are critical in longer piles. Similarly, the hammer may be operated with a lower drop height or fuel setting to reduce driving stresses.

5.3.2 Dynamic pile testing

Dynamic pile testing uses electronic equipment to monitor production or designated test piles during driving. The objective is to provide the engineer with information for evaluating pile hammer performance, cushion adequacy, driving stresses, and pile load capacity. These data are particularly useful for estimating the capacity on restruck piles. Restruck piles are piles that are restruck by the pile hammer sometime after installation (typically one to seven days). The idle period allows capacity gain to occur with time (for example, setup or freeze).

5.3.3 Driving heads (helmets, cap blocks) and pile cushions

Piles driven by impact require an adequate driving head to distribute the hammer blow to the head of the pile. This driving head should be axially aligned with the hammer and pile. It should not fit tightly on the pile head because a tight fit might cause transfer of moment or torsion and result in damage to the pile head. The driving head itself is intended to transmit the hammer energy to the pile without dissipating a significant amount of the energy. The driving head also holds or retains the cushion block to reduce the shock of the blow and distribute the driving force evenly over the pile head. Pile cushions are typically constructed of wood, although other materials have been used. A new cushion is typically used for each pile installation.

5.3.4 Jetting (jet spudding, prejetting)

Prejetting is the technique of inserting into the soil, before pile installation, a weighted jet for the purpose of breaking up hard soil layers. The jet is then withdrawn, and the pile is installed in the same location. This prejetting may also leave the soils in a temporarily suspended or liquefied condition, which will permit easier penetration of the pile. Jetting will temporarily reduce the skin friction in sands and sandy material.

When jet pipes are installed in the piles and used in conjunction with driving, precautions should be taken in choosing the material used for the embedded jet pipe to ensure the compatibility of the pipe with the surrounding concrete. For example, differences in the modulus of elasticity between polyvinylchloride (PVC) and concrete may cause damage to joints in the pipe, with corresponding damage to piles. Jetting while driving may not be recommended by the geotechnical engineer, as pile capacity may be compromised.

5.3.5 Predrilling

Predrilling a starter hole may be appropriate to locate or penetrate subsurface obstructions that may interfere with pile installation. Predrilling may also be used to break up hard strata or simply to loosen upper soils to facilitate pile installation.

An experienced pile-driving contractor often recommends the drill size and depth of predrilling, subject to the approval of the engineer of record.

5.3.6 Spudding

Spudding is the technique of inserting into the soil, before pile installation, a shaft or mandrel for the purpose of forcing a hole through hard soil layers, trash, overlying fill, and other conditions. Spudding a starter hole may be helpful in penetrating especially difficult material located near the surface that may tend to deflect the pile when driven.

5.3.7 Followers

Sometimes, a rigid structural member, also called a follower, is installed between the drive head and the pile head to drive the pile to a given depth below grade. Followers are not recommended because their use modifies the dynamic energy transferred to the pile during driving. In cases where a follower is required and its use is approved by the engineer of record, a wave equation analysis may be necessary to better assess the pile's behavior.

5.3.8 Excavating

Driving, jetting, predrilling, or spudding are not always feasible to penetrate obstructions or difficult material. It may be necessary to excavate and remove material before pile installation.

5.3.9 Batter piles

The installation of batter piles is more difficult than the installation of plumb piles and must be carried out by a skilled pile-driving contractor who has knowledge of local subsurface conditions and experience with the equipment being used and the type of piles being driven. Maintaining the proper alignment during installation is challenging. Long, slender batter piles tend to bend downward due to gravity during driving. When a hammer hits the pile, these deflections create additional bending stresses in the pile, which must be taken into consideration.

5.4 Damage prevention

Piles may be damaged during handling, transportation, or storage, but this type of damage is similar to that for other precast concrete components and can usually be corrected or repaired using conventional repair methods (refer to PCI's *Manual for the Evaluation and Repair of Precast, Prestressed Concrete Bridge Products* [PCI MNL 137] for information on these methods). In some cases, prestressed concrete piles may crack or spall during driving. The damage or failure of such concrete piles occurring during driving can be classified into four types:

- Spalling of concrete at the head of the pile due to high compressive stress
- Spalling of concrete at the tip of the pile due to hard driving resistance at the tip
- Transverse cracking, sometimes accompanied by spalling at the crack, or breaking of the pile, due to torsion or reflected tensile stress
- Bursting of hollow prestressed concrete piles

5.4.1 Compression damage at head

Spalling of concrete at the head of a pile is due to very high or nonuniform compressive stresses or compression stress concentrations. The following are possible causes of this type of damage:

- Insufficient cushioning material between the driving head and the concrete pile will result in very high compressive stresses on impact of the pile driver ram.
- When the top of the pile is not square or perpendicular to the longitudinal axis of the pile, the ram impact force will be concentrated on one edge. A warped or worn helmet can create the same situation.
- Improper fit (generally too tight) of the driving head on top of the pile may damage the head of the pile.
- If the prestressing steel is not cut flush with the end of the pile, the ram impact force may be transmitted to the concrete through the projecting prestressing steel, resulting in high stress concentrations in the concrete adjacent to the steel.
- Lack of adequate spiral reinforcing steel at the pile head or pile tip may lead to spalling or longitudinal splitting. In prestressed concrete piles, anchorage of the strands is developed in these areas and transverse tensile stresses are present.
- If the top edges and corners of the concrete pile are not adequately chamfered, they are likely to spall on impact of the ram.

5.4.2 Compression damage at pile tip

Spalling of concrete at the tip of a pile can be caused by extremely hard driving resistance at the tip. Such resistance may be encountered when founding the pile tip on bedrock. When driving on bare rock, compressive stresses can theoretically be twice the magnitude of those produced at the head of the pile by the hammer impact.

Under such conditions, overdriving of the pile and, particularly, high ram velocity should be avoided. In the more normal cases, with overburden of soil overlying the rock, tip stresses will generally be of the same order of magnitude as, but slightly lower than, the head stresses.

5.4.3 Transverse cracking

Transverse cracking of a pile due to reflected tensile stress can lead to failure of the pile during driving. This type of cracking is indicated by the presence of parallel cracks, often initiated at points of discontinuity (such as lifting loops, inserts, honeycombs, and the like), perpendicular to the longitudinal axis of the pile. Repeated driving after cracking has initiated produces puffs of concrete dust and can result in spalling and widening of the cracks, possibly followed by localized fatigue of the concrete and brittle fracture of the prestressing tendons.

This type of transverse cracking, although rare, occurs most often when driving in very soft soil. It can, however, also occur when driving resistance is extremely hard, as when the tip of the pile bears on solid rock.

When the pile driver ram strikes the head of a pile, compressive stress is produced at the head of the pile. This compressive stress travels as a wave down the pile at a velocity of approximately 12,000 to 15,000 ft/sec (3660 to 4570 m/sec). The intensity of the stress wave depends on the ram, the impact velocity, the cushion at the head of the pile, the structural characteristics of the pile, and the soil resistance.

Because the stress wave in a given pile travels at a constant velocity, the length of the stress wave period will depend, among other things, on the amount of time the ram is in contact with the cushion or pile head. A heavy ram will stay in contact with the cushion or pile head for a longer time than a light ram with equal energy, thus providing a longer stress wave period. If a ram strikes a thick or soft cushion, it will also stay in contact for a longer time than if it strikes a thin, hard cushion. The longer contact time generally results in a decrease in driving stress.

The compressive stress wave traveling down the pile may be reflected from the point of the pile as either a tensile or compressive stress, depending on the soil resistance at the tip. For the pile to penetrate the soil, the compressive stress wave must pass into the soil. If little or no soil resistance is present at the pile tip, the compressive stress wave will be reflected as a tensile stress wave.

The net tensile stress in the pile at any point is the algebraic sum of the compressive stress traveling down the pile and the tensile stress traveling up the pile. Whether a critical tensile stress will result depends on the magnitude of the initial compressive stress and the length of the stress wave relative to the pile length. A long stress wave is desirable to prevent damaging the pile.

If the soil resistance at the tip of the pile is very hard or firm, the initial compressive stress wave traveling down the pile will be reflected back up the pile as a compressive stress wave. Tensile stresses in the pile will not occur under these conditions until this compressive stress wave reaches the top (free) end of the pile and is reflected back down the pile as a tensile stress wave. It is possible for critical tensile stress to occur near the pile head in this case. Internal damping characteristics of the pile and the surrounding soil may reduce the magnitude of the reflected tensile stress wave. However, cracking has occurred when driving onto rock with very light hammers.

In summary, tensile cracking of prestressed concrete piles can be caused by the following:

- When insufficient cushioning material is used between the pile driver's steel helmet, or cap, and the concrete pile, a stress wave of high amplitude and of short length is produced, both characteristics being undesirable because of potential pile damage.

- Use of adequate softwood cushions is frequently the most effective way of reducing driving stresses, with reductions in the order of 50% being obtained with new uncrushed cushions. As the cushion is compressed by hard driving, the intensity of the stress wave increases; therefore, a new cushion for each pile is recommended.

- When a pile is struck by a ram at a very high velocity, a stress wave of high amplitude is produced. The stress developed in the pile is proportional to the ram velocity.

- When little or no soil resistance at the tip of long piles (50 ft [15 m] or more in length) is present during driving, critical tensile stresses may occur in the pile. Tensile driving stresses greater than the ultimate concrete tensile stress plus the effective prestress can result in development of transverse cracks. This may occur when driving through a hard layer into a softer layer below, or when the soil at the tip has been weakened by jetting or drilling. Most commonly, these critical tensile stresses occur near the upper third of the pile length, but they may also occur at midlength or the lower half.

- When very hard driving resistance is encountered at the tip of piles (50 ft [15 m] or more in length), critical tensile stresses may occur in the upper half of the pile when a tensile stress is reflected from the pile head.

5.4.4 Bursting of hollow prestressed concrete piles

Longitudinal splits due to internal bursting pressure may occur with open-ended, hollow prestressed concrete piles. When driving in extremely soft, semifluid soils, the fluid pressure builds up and a hydraulic ram effect known as "water hammer" occurs.

When driving open-ended precast concrete piles in sands, a plug can form and exert an internal bursting/splitting force in the pile shell wall. This plug can be broken up with a jet during driving, but the most practicable remedy may be to provide adequate lateral steel in the form of spiral or tie reinforcement. Use of a solid or steel armored tip will eliminate the splitting problems mentioned, but may not be compatible with other installation requirements.

5.5 Repair of damaged piles

Damaged piles can often be repaired when damage has been sustained during handling or driving.

5.5.1 Concrete spalling at the head of the pile

When the head of a pile is damaged during handling, the broken concrete should be removed, the surface cleaned, and a patch applied and allowed to thoroughly cure before the pile is driven. Patching material may consist of prepackaged grout with rapid-setting characteristics or epoxy patching compounds.

When spalling occurs at the head of a pile during driving and the pile is damaged to the extent that driving must be discontinued, it is often possible to cut off the pile and resume driving. The pile must be cut at a point below any damage, and cutting must be done in such a manner to provide a square, flat end at the top of the pile. When driving is resumed on a pile that has been cut, precautions should be taken to provide cushioning that is thicker than the normal cushion block. Piles can often be driven to their final elevation after cutting, even though closely spaced spiral reinforcement at the head of the pile has been cut off.

5.5.2 Cracks in piles

Cracks can be repaired, if necessary, by injecting epoxy under pressure into the cracks. Generally recognized guidelines suggest that cracks wider than 0.007 in. (0.18 mm) can be successfully injected. Smaller cracks often need no repair.

5.6 Good driving practices

Some guidelines for good driving practices for prestressed concrete piles can be summarized as follows:

- Use the proper hammer.
- Use adequate cushioning material between the driving head and the concrete pile.
- To reduce driving stresses, use a heavy ram with a low impact velocity (short stroke) to obtain the desired driving energy rather than a light ram with a high impact velocity (large stroke). Driving stresses are proportional to the ram impact velocity
- Reduce the ram velocity or stroke during early driving when light soil resistance is encountered. Anticipate soft driving, reducing the ram velocity or stroke to avoid critical tensile stresses. This practice is very effective when driving long piles through very soft soil.
- If predrilling or jetting is permitted when placing the piles, ensure that the pile tip is well seated with moderate soil resistance at the tip before full driving energy is used.
- When jetting, avoid jetting near or below the tip of the pile to produce low resistance at the tip. In many sands, it is preferable and desirable to drive with larger hammers or greater resistances, rather than to jet and drive simultaneously.
- Ensure that the driving head fits loosely around the pile top so that the pile may rotate easily within the driving head.
- Ensure that bearing piles are straight and not cambered. High flexural stresses may result during driving of an initially bent pile.
- Ensure that the top of the pile is square, or perpendicular, to the longitudinal axis of the pile, and that no strands or reinforcing bars protrude from the head. Chamfer top edges and comers of the pile head.
- Use adequate spiral reinforcement throughout the pile, particularly near the head and tip.
- The level of prestress should be adequate to prevent cracking during transport and handling; in addition, the values should be adequate to resist reflected tensile stresses.
- The prestress level found to be effective in resisting these effects has been established empirically to be about 700 to 1200 psi (4.8 to 8.3 MPa) after losses. Very short piles have been installed with lower prestress levels (350 to 400 psi [2.4 to 2.8 MPa]). Where moment resistance in service is a requirement, effective prestress levels up to $0.2 f_c'$ and even higher, have been used without difficulty.

5.6.1 Pile cushioning

A wood cushioning material that is 3 or 4 in. (76 or 102 mm) thick may be adequate for short piles (50 ft [15.2 m] or less) with moderate tip resistances. A wood cushioning material that is between 6 and 20 in. (152 and 508 mm) thick may be required when driving longer piles in very soft soil.

When the wood cushioning becomes highly compressed, or chars or burns, it should be replaced. A new cushion should be provided for each pile. If driving is extremely hard, the cushion may have to be replaced during driving of a single pile. Use of an adequate cushion is usually an economical means of controlling driving stresses.

In the past, concern has been expressed that cushioning might reduce the effectiveness of the driving energy transmitted to the pile. Actual experience with concrete piles and recent dynamic wave theory both indicate that normal cushioning, by lengthening the time that the ram is in contact with the head of the pile, may in some cases increase the penetrating power of the pile.

Further, as the pile nears final tip elevation, the cushion is usually substantially compressed. Within practical limits, adequate cushioning does not reduce driving penetration. Thus, the computed pile capacities from dynamic formulas are usually not significantly altered.

5.6.2 Handling and transportation

Prestressed concrete piles should be picked up, handled, and transported using methods that avoid tensile cracking and any impact damage. If piles are cracked due to mishandling, they may not reliably resist driving tensile stresses that may develop.

Superficial surface cracks, minor chips, and spalls may occur during handling and installation and are often unavoidable. As long as these minor imperfections do not affect the structural integrity or the drivability of the pile, they should not be cause for rejection. Damage that may impair performance must be repaired. For further information, see PCI's MNL 137, *Manual for the Evaluation and Repair of Precast, Prestressed Concrete Bridge Products*.

5.6.3 Positioning and alignment

Correct position can best be ensured by accurate setting of the pile. Removal of surface obstructions will aid in attaining accurate positioning. When the accuracy of a position is critical, a template or a predrilled starter hole, or both, may be employed to advantage. The position is largely established when the pile is set. Attempts to correct position after driving has commenced usually result in excessive bending and damage to the pile, and should not be permitted.

As a general statement, proper control of alignment should be ensured before driving starts. It is almost impossible to correct vertical or lateral alignment after driving has commenced without inducing bending stresses.

Caution must be taken to see that the pile is started truly vertically or on the proper batter, as the case may be. Once the driving starts, the hammer blow should be delivered essentially axially, and excessive sway should be prevented at the pile head. The use of fixed leads, which are often specified, is primarily a means to ensure these two conditions.

Attempting to correct misalignment by chocking at the base of the leads may, except at the start of driving, introduce excessive bending and damage the piles.

Long piles should be given necessary support in the leads. Batter piles should be supported to reduce gravity bending to acceptable limits; use of rollers in the leads is one method.

Long slender vertical piles may require guides at intervals to prevent buckling under the hammer blow.

When driving piles a long way below the leads, especially with batter piles, telescopic support leads or other appropriate means should be provided to prevent excessive bending and buckling.

If the pile is installed in water, the pile should be protected against excessive bending from waves, currents, dead weight (in case of batter piles), and accidental impact. Staying and girting should be employed until the pile is finally tied into the structure it is supporting. Pile heads should be stayed to eliminate bending. This is particularly relevant to batter piles, where the head should be lifted to overcome the dead weight of the pile. Frequently, when driving in deep water, a batter pile should be stayed before it is released from the hammer.

The heads of piles, even in water, cannot be pulled into position without inducing bending. Because of the long lever arms available in many water installations, piles can be severely damaged even when the pulling force is relatively small. Strict pulling limits should be set by the designer.

Section 6—Current research and future applications for prestressed concrete piles

Significant research on precast concrete pile ductility has been performed, a better understanding of soil structure interaction principles has been promulgated by various experts, pile-driving monitoring equipment technology has improved, and the ability of modern software to incorporate complex modeling conditions has drastically improved. This section provides a few brief summaries of the current state of such research and suggests what impact this research could have on the prestressed concrete pile industry.

6.1 Ultra-high-performance concrete (UHPC) piles

In 2008, with an objective of producing a minimum service life of 75 years and reduced maintenance costs over time, Vande Voort et al.[12] studied the feasibility of using UHPC piles in design practice. After exploring typical precast concrete pile shapes, they introduced tapered, H-shaped prestressed UHPC piles as an effective substitute for traditional steel H-piles commonly used in bridge foundations (**Fig. 6.1**). UHPC has high compressive strength, on the order of several times that of conventional concrete used in traditional concrete pile applications (for example, a 26 ksi [180 MPa] UHPC mixture was used in the subject research). Although the tensile strength of UHPC is somewhat increased, it is the increased compressive strength that makes UHPC an ideal material for prestressed concrete piles because piles constructed with this material can be subjected to a high degree of precompression, effectively increasing the resistance to tensile stress in excess of 6 ksi (41 MPa) due to externally applied

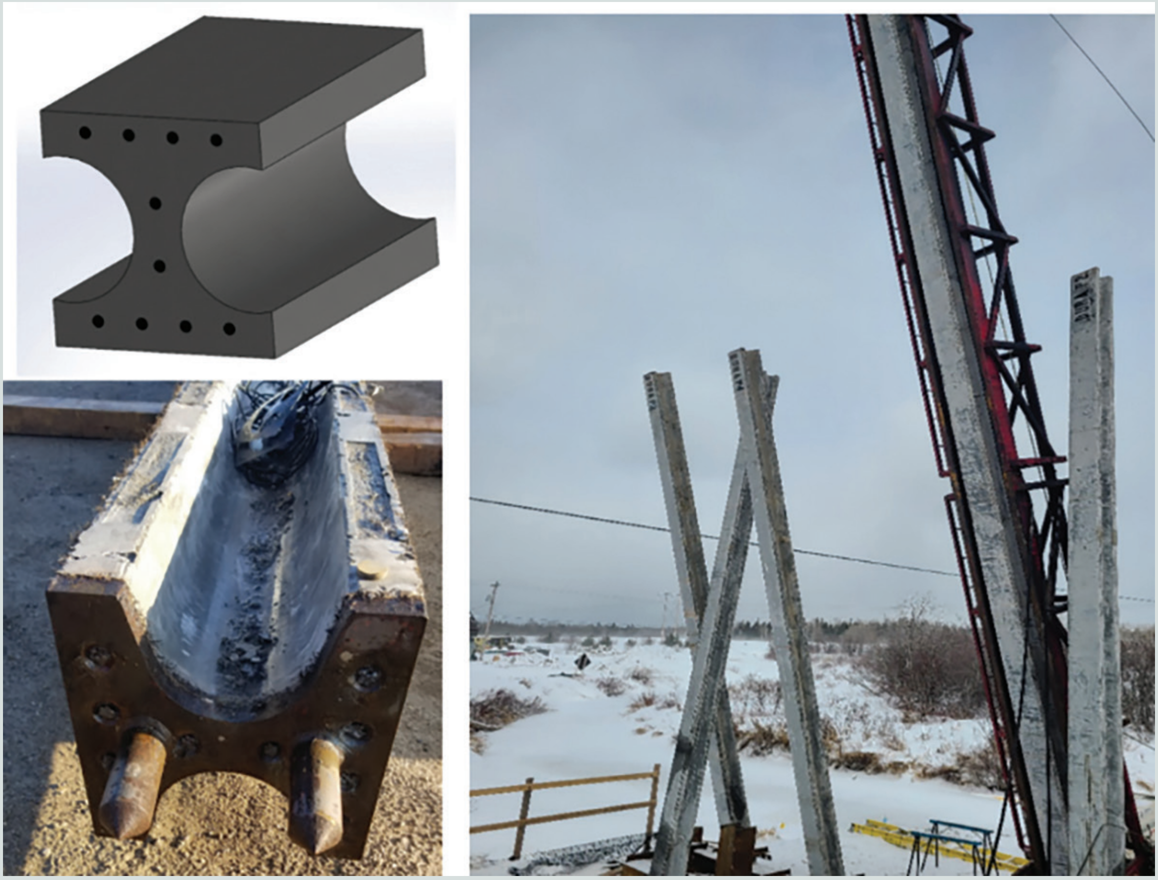

Figure 6.1. Ultra-high-performance concrete battered pile with steel shoe driven by Facca Inc. in Ontario, Canada.

loads. UHPC has a higher modulus of elasticity than conventional concrete, approximately 7000 ksi (48 GPa).

A benefit of highly prestressed UHPC H-piles is that the impact of driving stresses will be minimal even when the piles are driven through hard soils, as was demonstrated by Vande Voort et al. Relative to steel piles, UHPC piles have larger cross-sectional areas that can offer dependable end-bearing capabilities. Therefore, UHPC piles provide higher total resistance when compared with equivalent steel sections while remaining a low displacement pile.[12]

According to research and physical testing, UHPC piles are very effective and durable.[12–14] Most importantly, the capillary porosity of UHPC is very low, the material is extremely resistant to chloride permeability, and it exhibits almost no deterioration due to freezing and thawing. It is anticipated that UHPC piles may reduce maintenance costs when compared with traditional steel and prestressed concrete pile applications.

By taking advantage of the self-leveling nature of UHPC, along with the presence of a high volume of discrete steel fibers (typically 2%), UHPC piles can be constructed using a reduced cross section and no transverse reinforcement. The high material strengths and stiffness (compressive, tensile, and modulus of elasticity) and improved durability can be used to optimize the cross-sectional properties such that UHPC piles have outer dimensions, weights, and flexural

Figure 6.2. Ultra-high-performance prestressed concrete pile end after driving.

stiffnesses similar to those of standard steel H-piles, allowing the UHPC piles to be hoisted and driven like steel piles.

Subsequent research on UHPC piles has included the development of UHPC pile sections comparable to 12-, 14-, and 16-in. steel HP sections; a modified cross section for an alternative casting (**Fig. 6.2**); connection details for field splicing; and details for anchoring piles into pile caps and bridge abutments.[14] Splices for UHPC piles have been tested in the laboratory and in the field, and the authors have noted that the results are excellent for both vertical and lateral resistances of the splice.[14]

The current pile-to-pile cap connection detail of a simple pile embedment connection has been shown to develop the pile flexural capacity without causing any distress to the connection region.[13] Following a successful detailed geotechnical investigation, including driving of test piles, the Iowa Department of Transportation installed a 60-ft-long (18-m) UHPC H-pile to replace a steel H-pile in an integral abutment bridge.[16] Because UHPC piles require no special installation methods or additional labor costs, the only limiting factor is the cost of the UHPC itself, which is significantly more expensive than the traditional concrete used for prestressed concrete piles. However, on a pound-for-pound basis, the material cost of a UHPC pile is similar to that of a traditional steel pile. A demonstration of single-span bridge project for the Ontario, Canada, Ministry of Transportation, with the one abutment supported steel H-piles and the other on UHPC H-piles, showed that the latter achieved the required geotechnical axial resistance at a shallower depth than the former, making UHPC H-piles a cost-competitive option. It is expected that as UHPC becomes more readily available, and as researchers help develop recommendations on the use of these piles in accordance with governing codes and standards, UHPC piles can be used in applications where steel H-piles and pipe piles would have once been selected.

6.2 High-performance fiber-reinforced concrete (HPFRC) piles

HPFRC is constructed by adding hooked and twisted steel fibers to a traditional concrete mixture. The concrete compressive strength remains as expected, but the special fiber reinforcement helps create a concrete that exhibits a tensile strain-hardening when the concrete goes into tension, and when in compression, the concrete acts more like well-confined concrete. Noting that the prestressed concrete pile industry relies on transverse reinforcement to create confined concrete cores needed for seismic resistance and for resisting driving stresses, the use of HPFRC for piles appears to be extremely promising.

Although no known research currently exists on this topic, it is anticipated that the use of HPFRC for prestressed concrete piles may reduce the amount of transverse reinforcement required for shear resistance, seismic ductility, and possibly even the resistance of driving stresses. In 2014, the results of a very similar application were presented by Aviram et al.[17] In that study, the authors clearly demonstrated that the use of HPFRC in reinforced concrete columns (1.5% to 2% steel fibers by volume) may result a reduction of the transverse reinforcement required by more than 50%. In fact, the experimental testing showed that when compared with the results of a seismically detailed column meeting the *Caltrans Seismic Design Criteria*, a similar HPFRC column with the same longitudinal steel reinforcement but only half the spiral reinforcement quantity had significantly more ductility, significantly more energy dissipation capacity, and significantly less damage at the same drift ratios, while resisting a larger shear demand during the testing.

Although it is not yet proven, it is expected that the use of HPFRC piles may allow for a reduction in required transverse reinforcement for seismic resistance while still meeting the performance-based design provisions previously presented in this report. It is unclear whether the presence of the steel fibers will allow a reduction in transverse reinforcement to a level less than the minimum prescriptive requirement for pile driving. Another limiting factor is the additional cost of the steel fibers, which may or may not offset the cost savings that result from reduced transverse reinforcement. Even if the costs are simply competitive, the use of HPFRC may result in significantly less steel congestion in areas where more seismic ductility capacity is required.

6.3 Fiber-reinforced-polymer reinforcement

While widespread use of composite materials to replace strands and deformed bars in prestressed concrete piles is not likely in the near future, use of such materials as external transverse reinforcement for prestressed concrete piles may gain more rapid acceptance. Fiberglass and carbon fibers embedded in polymeric resins are already being used to wrap columns and other concrete components in repair, strengthening, and seismic applications. This same method is being employed by at least one piling manufacturer to encase prestressed concrete piles in a composite shell. Although composite shells may eventually be used in place of steel spiral reinforcement, presently their primary purpose is for corrosion protection in marine applications and other aggressive environments.

Because the use of composite materials is a developing technology, it is essential that designers verify the acceptability and availability of these materials for use in piles before incorporating them into a project. Pile manufacturers should be consulted concerning recent advances and the availability of products in a certain region. They are generally aware of projects and locations where a particular piling product has been used. The designer should also verify that the intended product meets the specifications governing the project or, if necessary, that special provisions are written to ensure the owner's requirements are met.

6.4 Pile-driving vibrations

The installation of driven piles produces ground vibrations that, if not monitored and controlled, can be considered anywhere from a general annoyance to the actual source of minor or even major structural damage to an adjacent structure. The magnitude or level of vibrations caused by pile driving is usually measured in the field as peak particle velocity (PPV). In the context of this report, the PPV is the maximum speed of a particle on the ground surface at a given location as it oscillates about a point of equilibrium that is moved by a passing wave generated by the pile-driving process. It is well known that the PPV is directly related to the physical properties of the pile, input energy associated with the pile installation method, and the geotechnical properties of the soil into which the pile is driven. For more information and theory related to the mechanics of ground motion caused by pile driving, the reader is referred to Woods[18] (see **Table 6.1**). There is no consensus on the exact limits of PPV values that would prevent vibration-induced damage and human complaints; however, much research over the past 40 years has attempted to quantify these values for certain adjacent structural system types and governing geotechnical conditions.

Table 6.1. Frequency-independent peak particle velocity limits recommended by Woods[18]

Structure and condition	Limiting particle velocity, in./sec
Historic and some old structures	0.1 to 0.5*
Residential structures	0.5
New residential structures	1.0
Industrial building	2.0
Bridges	2.0

Note: 1 in./sec = 25 mm/sec.

*The 0.5 value may be unconservative; see, for example, Mingjiang and Zhang[23]

According to Woods,[18] there are three primary concerns regarding pile-driving-induced vibrations: human response, direct damage to structures, and vibration-induced settlement. Human response is the most difficult to quantify because sensitivity levels for humans vary from person to person and are affected by external factors such as ambient or background vibrations and noise. Small vibrations that are perceptible to humans but are not damaging to structures can generate complaints from adjacent residents and building occupants. As shown in **Fig. 6.3**, Bay presents a summary of human perceptibility levels that indicates that very disturbing levels of pile-driving vibrations typically occur at PPV values greater than 1 in./sec (25 mm/sec).[19] Note that even PPV values as low as 0.01 in./sec (0.25 mm/sec) may still be perceptible.

The most commonly referenced PPV limits for preventing damage to adjacent structures appear to be the United States Bureau of Mines (USBM) recommendations presented by Siskind et al.[20] **Figure 6.4** shows these limits graphically, and although developed for blast-generated vibrations, they have been applied to pile-driving vibrations throughout the literature. Note that these limits are intended to prevent cosmetic damage (such as cracking of plaster or wallboard joints), and the structural damage threshold would be much higher. The PPV limits shown as 0.5 in./sec (13 mm/sec) for plaster and 0.75 in./sec (19 mm/sec) for drywall are for a frequency range associated with resonant frequencies for residential structures. Vibration criteria developed for historic structures include those provided by Konon and Schuring.[21] The German Institute for Standardization (DIN) has published criteria developed for various types of structures such as residential structures and office buildings.[22] Along with the USBM criteria, Fig. 6.4 presents the Konon and Schuring and DIN criteria. In line with theory, all the aforementioned criteria provide PPV limits that are a function of vibration frequency, but conservative absolute limits are suggested as well.[18] It should

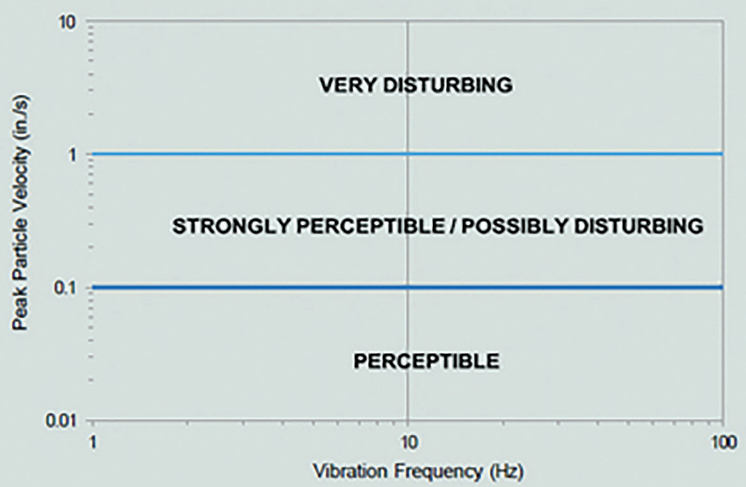

Figure 6.3. Perceptibility of vibration levels for humans.
Source: Adapted from Bay.[19]
Note: 1 in./sec = 25 mm/sec.

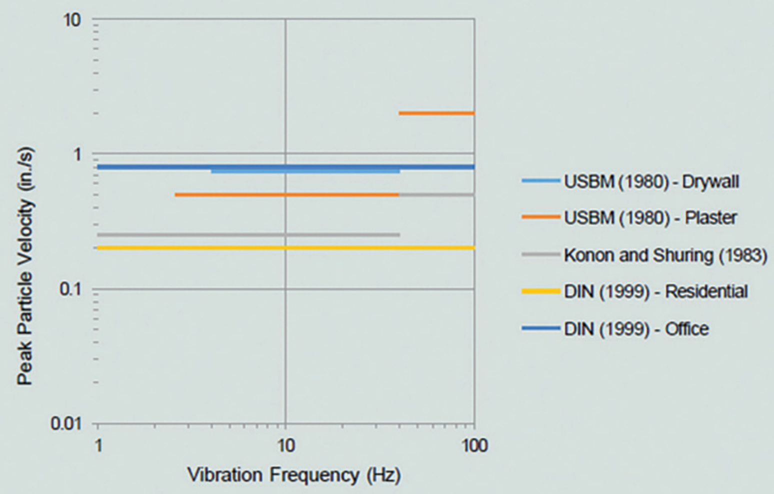

Figure 6.4. Commonly cited vibration criteria currently in use.
Source: Adapted from Woods,[18] with criteria from the U.S. Bureau of Mines (USBM),[20] Konon and Schuring,[21] and the German Institute for Standardization (DIN).[22]
Note: 1 in./sec = 25 mm/sec.

also be noted that state-specific (such as Mingjiang and Zhang[23]) and city-specific (Hajduk et al.[24]) pile-driving vibration criteria have been proposed with evidence of successful use.

Vibration-induced settlement is also a major concern because it can lead to structural damage on adjacent property. Although pile-driving-induced settlement of cohesive soils is not common, the presence of loose sandy soils is a major concern during pile driving. When such soils are present, reductions in the PPV limits presented previously should be considered.

Because there is no national standard controlling pile-driving-induced vibrations, it is recommended that each project have a project-specific pile-driving vibration monitoring specification and plan that considers application of the following best practices, as established in the literature (for example, Woods[18] and Mingjiang and Zhang[23]) and well known in the pile-driving industry.

To immediately begin to address the human perception factor, the pile-driving contractor should contact residents and adjacent business establishments that are within a project-specific area to inform them that piles will be driven nearby and that precautions are being taken to ensure that adjacent properties will not be damaged. Next, a preconstruction survey should be performed to determine the susceptibility of adjacent structures to permanent ground movements, cosmetic cracking, structural damage, and temporary impacts on sensitive equipment. The preconstruction survey results are used to select limiting PPV values and to confirm the adequacy of site-specific construction survey area and vibration monitoring area.

After the project criteria have been selected, a preconstruction building survey should be performed to document the existing conditions of neighboring buildings. This documentation may be necessary later to show that pile-driving operations did not cause new damage. Ideally, both interior and exterior surveys should be performed, but access is not always possible. Engineering notes, photographs, and video records are all recommended.

During pile installation, all three components (longitudinal, transverse, and vertical) of particle velocity should be measured on the ground and the largest value used as the controlling value for comparison with the aforementioned PPV limits. Because the PPV will decrease with distance, the measurements should be performed at the locations of structures of interest or at comparable distances from current pile-driving activities.

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