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Pile Types and Guidelines for Selection

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2. Pile Types and Guidelines for Selection

Piles can be categorized in two main types: load bearing piles and sheet piles.

There are numerous types of load bearing piles. Figure 2-1 shows a pile classification system based on type of material, configuration, installation technique and equipment used for installation. Load bearing piles can also be classified based on their method of load transfer from the pile to the soil mass. Load transfer can be by friction, toe bearing or a combination.

2.1. Bearing Piles

2.1.1. Steel Piles

The general category of steel piles includes H-piles and pipe piles. Since steel piles are a manufactured product, their properties are controlled and well known prior to installation. Among all piling materials steel piles are allotted the highest allowable unit working stresses, but not necessarily the highest in proportion to the ultimate strength of the material. Steel piles are generally considered to be high capacity piles but have been historically used for a wide range of loadings.

2.1.1.1. Steel H-Piles

Steel H-piles are a specially designed sub-group of wide flange shapes with equal thickness in the web and flanges. The depth of the section is approximately equal to the width. H-piles are hot rolled from ingots on the same type mill used to manufacture wide flange structural shapes. A table of the various sizes commonly available is shown in Table 2-1. Other wide flange shapes have been used for foundation piles in special situations.

Figure 2-1 Pile Classification

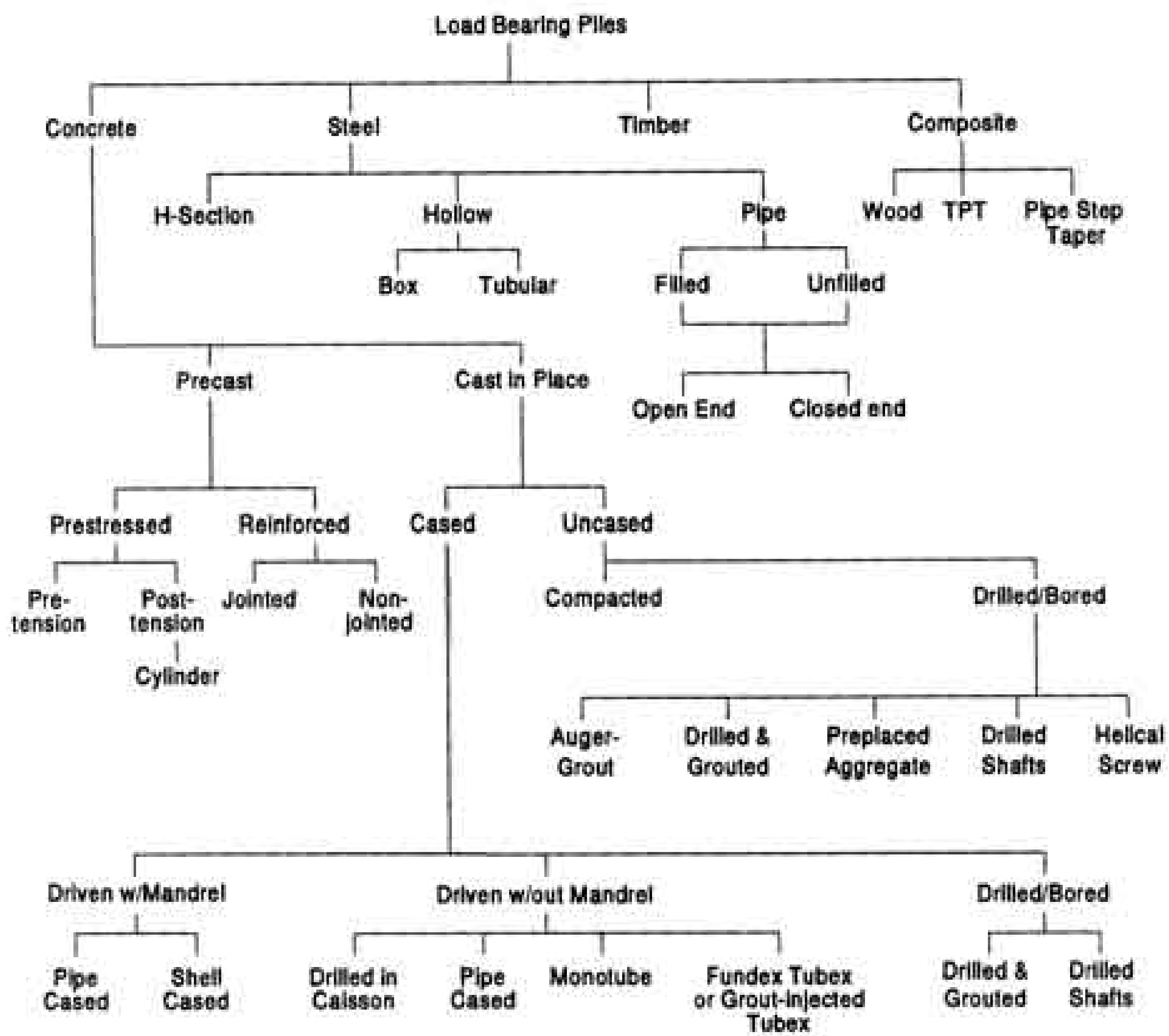


Table 2-1 Standard H-Pile Sections

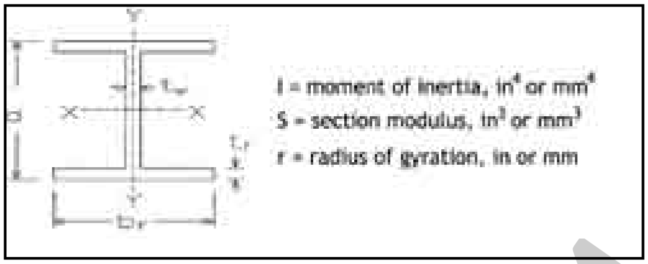


Table 2-1 Standard H-Pile Sections

Designation	Cross-Sectional Area A	Depth d	Flange Width b_f	Flange Thickness t_f	Web Thickness t_w	Axis X-X I	Axis X-X S	Axis X-X r	Axis Y-Y I	Axis Y-Y S	Axis Y-Y r
English Units	in^2	in	in	in	in	in^4	in^3	in	in^4	in^3	in
HP14 x 117	34.4	14.21	14.885	0.805	0.805	1220	172.0	5.96	463.0	59.5	3.59
HP14 x 102	30.0	14.01	14.785	0.705	0.705	1050	150.0	5.92	380.0	51.4	3.56
HP14 x 89	26.1	13.83	14.695	0.615	0.615	904	131.0	5.88	326.0	44.3	3.53
HP14 x 73	21.4	13.61	14.585	0.505	0.505	729	107.0	5.84	261.0	35.8	3.49
HP13 x 100	29.4	13.15	13.205	0.765	0.765	886	135.0	5.49	294.0	44.5	3.16
HP13 x 87	25.5	12.95	13.105	0.665	0.665	775	117.0	5.45	250.0	38.1	3.13
HP13 x 73	21.6	12.75	13.005	0.565	0.565	630	98.8	5.40	207.0	31.9	3.10
HP13 x 60	17.5	12.54	12.900	0.460	0.460	503	80.3	5.36	165.0	25.5	3.07
HP12 x 84	24.6	12.28	12.295	0.685	0.685	650	106.0	5.14	213.0	34.6	2.94
HP12 x 74	21.8	12.13	12.215	0.610	0.610	569	93.8	5.11	186.0	30.4	2.92
HP12 x 63	18.4	11.94	12.125	0.515	0.515	472	79.1	5.06	153.0	25.3	2.88
HP12 x 53	15.5	11.78	12.045	0.435	0.435	393	66.8	5.03	127.0	21.1	2.86
HP10 x57	16.8	9.99	10.225	0.565	0.565	294	58.8	4.18	101.0	19.7	2.45
HP10 x42	12.4	9.70	10.075	0.420	0.420	210	43.4	4.13	71.7	14.2	2.41
HP8 x 36	10.6	8.02	8.155	0.445	0.445	119	29.8	3.36	40.3	9.88	1.95
SI Units	mm^2	mm	mm	mm	mm	mm^4	mm^3	mm	mm^4	mm^3	mm
HP360 x 174	22200	361	378	20.4	20.4	504	2810	151	184	974	91.0
HP360 x 152	19400	356	376	17.9	17.9	639	2470	150	159	846	90.5
HP360 x132	16900	351	373	15.6	15.6	375	2140	149	135	724	89.4
HP360 x 108	13800	346	370	12.8	12.8	303	1750	148	108	584	88.5
HP330 x 149	19000	334	335	19.4	19.4	368	2200	139	122	728	80.1
HP330 x 129	16400	329	333	16.9	16.9	315	1910	139	104	625	79.6
HP330 x 109	13900	324	330	14.4	14.4	263	1620	138	86.3	523	78.8
HP330 x 89	11300	319	328	11.7	11.7	211	1320	137	68.9	420	78.1
HP310 x 125	15900	312	312	17.4	17.4	270	1730	130	88.2	565	74.5
HP310 x 110	14100	308	310	15.5	15.4	237	1540	130	77.1	497	73.9
HP310 x 93	11900	303	308	13.1	13.1	196	1290	128	63.9	415	73.3
HP310 x 79	10000	299	306	11.0	11.0	163	1090	128	52.6	344	72.5
HP250 x 85	10800	254	260	14 4	14.4	123	969	107	42 3	325	62.6
HP250 x 62	7970	246	256	10.7	10.5	87.5	711	105	30.0	234	61.4
HP200 x 53	6820	204	207	11.3	11.3	49.8	488	85.5	16.7	161	49.5

H-piles are very versatile pile type. They can be used for both friction and end bearing applications. They are manufactured as a finished product, which can be driven with standard equipment. Advantages and disadvantages of H-Piles are shown in Table 2-2.

H-piles can be considered for a design load between 80 kips (356 kN) and 500 kips (2224 kN). They function most efficiently for end-bearing or partial end-bearing applications. They are a standard in many states for highway bridge piers and abutments where the job sites are remote, compacted fill approach embankments must be penetrated, battered piles are often required and pile loadings are in the medium to high medium range (80 kips (356 kN) to 180 kips (800 kN)).

H-piles are also commonly applied for high unit dead and live loads associated with multi-storey buildings. The magnitude of these loads generally requires high capacity piles driven to end-bearing conditions to limit settlements and for space and economic reasons. H-piles have carried design loads of over 400 kips (1779 kN) in a number of such applications.

H-piles are good piles in tension – the constant cross-section together with the entrapment of soil between the flanges provides excellent resistance to pullout when that is a factor. H-piles are used as battered tension piles to anchor sheet pile bulkheads. Uplift due to hydrostatic or wind conditions is an important consideration in many foundation designs, and steel H-piles have the ability to work both as compression and tension piles. Their low-displacement characteristic would favor H-piles over displacement piles where ground heave might be a problem.

The ability to resist hard driving enable H-piles to penetrate soils where other piles may not.

2.1.1.1.1. Grades of Steel H-Piles

Steel H-piles are produced to either ASTM Specification A-36 or A-572. The properties for these specifications (and their grades) are shown in Table 2-3. In addition, they can be produced to ASTM A-690 when specified.

Table 2-2 Advantages and Disadvantages of Steel H-Piles

Advantages	Disadvantages
High individual load capacity when driven to bear on or in hard or dense materials.	Relatively higher cost unless efficiently loaded.
Ready availability; can be installed with standard driving equipment; lengths can be easily extended or reduced to fit job requirements.	Inability to inspect the physical condition after driving (an advantage for closed ended tubular piles)
Compact shape with low displacement – minimum disturbance to adjacent piles or structures; able to penetrate where many other types could not.	Non-constant radius of gyration (an advantage of pipe piles for certain situations).
High bending strength for applications involving lateral loads. Readily driven on a batter if required.	Corrosion problems in certain environmental situations if unprotected.
Good tension piles for uplift – constant cross-section, plus steel is best material for tensile strength.	

This formulation is a 50 ksi (345 MPa) steel with improved corrosion performance in the salt-water splash zone. This grade is occasionally specified as "weathering" type steel for appearance-sake above ground.

Experience indicates that corrosion is not a practical problem for steel piles driven in natural soil, due primarily to the absence of oxygen in the soil. However, in fill ground at or above the water table, moderate corrosion may occur and protection may be needed. Commonly used protection methods include coatings applied before driving. Coal-tar epoxies, fusion bonded epoxies, metallized aluminum and Phenolic mastics are used to provide protection. Encasement by cast-in-place concrete or precast concrete jackets or cathodic protection can also provide needed protection for piles extending above ground. Sometimes heavier sections are used to meet long-term service requirements.

Splices are commonly made by full penetration butt welds. The splice should be as strong as the pile. Proprietary splicers are also used for quick splicing H-piles.

A steel load transfer cap is not required if the head of the pile is adequately embedded in a concrete cap.

H-piles may require toe reinforcement for driving through dense soil or soil containing boulders or rock. Toe reinforcement is also used for penetration into a sloping rock surface. Proprietary pile points welded to pile toes are used commonly. H-piles are suitable for use as end bearing piles, and combinations of friction and end bearing. Since H-piles generally displace a minimum of material, they can be driven more easily through dense granular layers and very stiff clays. Using H-piles often reduces the problems associated with soil heave and ground vibrations during foundation installation. H-piles can be used for driving into soils containing obstructions such as boulders when properly protected at the toe. They are commonly used for any depth since splicing is relatively easy.

2.1.1.1.2. H-Piles as End-Bearing Piles

H-piles are most efficient when they can be driven to refusal or practical refusal on rock, or into dense materials overlying rock. The pile functions as a short column, hence the rock may be stronger than the steel for the maximum design load that can be applied. It is generally accepted that competent rock in its natural bed can resist very high stress concentrations without crushing, except when the pile is installed through extremely soft soils. This combination therefore provides at least the potential for some high and therefore very efficient pile loadings. Other end-bearing materials include hardpan, marl, dense sand, and softer rock. Here the strength of the supporting material is often considerably less than that of the steel. H-piles driven into these materials obtain support by the development of an increased bulb of pressure around the toe and friction along the embedded development length.

Table 2-3 Mechanical Properties of Steel Grades for H-Piles

Specification and Grade	Yield Point (minimum)	Tensile Strength (minimum)	Minimum Elongation, 8" (203.2 mm), %	Minimum Elongation, 2" (50.8 mm), %
ASTM A36	36 ksi/248 MPa	58-80 ksi (406-552 MPa)	20	21
ASTM A572 Grade 42	42 ksi/290 MPa	60 ksi (414 MPa)	20	24
ASTM A572 Grade 50	50 ksi/345 MPa	65 ksi (448 MPa)	18	21
ASTM A572 Grade 60	60 ksi/414 MPa	75 ksi (517 MPa)	16	18

Building codes set limits on loads and unit stresses as well as allowable settlements, which reflect the experience and recommendations of the related engineering community. Piles installed to end bearing are often permitted much higher loads than friction piles and those that are tested are allowed higher loads than those that are not.

Based on recorded experience, H-piles are probably most efficient when driven through relatively deep, soft to medium stiff clays to end bearing.

Fine grained soils (clays) are the most likely to exhibit large increases in capacity after installation. The extent to which soil freeze contributes to capacity of end-bearing piles is subject to much discussion. Soil freeze may be estimated using experience and static methods. With wave equation analysis, incorrect modeling of the setup (freeze) effects may lead to the discrepancies that are observed between estimated and actual driving performance.

2.1.1.1.3. H-Piles as Friction Piles

While many meters of H-piles have been driven for friction applications, they are non-displacement piles and tend to drive further in loose sands and silty sand. There may be good reasons however to select H-piles for this use if, for example, a significant scour depth is computed for a bridge pier abutment.

When H-piles are driven into stiff clays with cohesion between 1 and 2 ksf, soil is usually trapped between the flange and the web and is compacted. In this case, the soil becomes a part of the pile and is carried down with it. An example of this (known as "H-pile plugging") is shown in Figure 2-2. This core aids in compressing the surrounding soil and building up resistance to further displacement. The principal load transfer is through frictional forces and not from end bearing. It is somewhat difficult to predict the capacity of any given length of pile driven in stiff clays and load testing is generally advisable. When soft or medium clays and silts are encountered, piles will develop shaft friction resistance almost equal to the surface area of the pile multiplied by the shear strength. These soils have high moisture content, which will make the pile resistance to driving seem lower than predicted. A time interval of a few hours to several weeks may be necessary to attain the true measure of the pile's long term geotechnical capacity.

Figure 2-2 H-pile Plug

2.1.1.1.4. H-Piles as Soldier Beams

One common application of H-piles is their use as soldier beams for retaining walls. These retaining walls can be either permanent or temporary for excavations and braced cuts. Typically, the H-piles are driven on 6' – 8' (1.8 – 2.4 m) centers in a row with the flanges facing each other. The lagging – either concrete or timber – is then stacked with the ends of the flanges facing the webs. The flanges of the H-piles thus retain the lagging. Cross bracing (in the case of braced cuts) or tieback systems can be used to provide additional lateral support for higher walls or loads.[1] H-piles also are used in conjunction with sheeting to form high-modulus walls; these are discussed in detain in the Pile Buck Sheet Piling Design Manual.

2.1.1.2. Steel Pipe Piles

Pipe piles usually consist of seamless, welded or spiral welded steel pipes of wall thickness in the range of 0.109” to 2.500” (2.8 – 63.5 mm). The piles are available in 8” (203.2 mm) to 48” (1219 mm) diameters. Typical pipe pile sizes are shown in Table 2-4. Much larger sizes and also used in special situations.

Common sizes of pipe piles can be considered for loads between 60 kips (267 kN) to over 400 kips (1779

Table 2-4 Typical Steel Pipe Pile Sizes

Designation and Outside Diameter, in.	Wall Thickness, in.	Area A, in.^{2}	Weight per foot, lb/ft	I, in.^{4}	S, in.^{3}	R, in.	Area of Exterior Surface, ft^2/ft	Inside Cross-Sectional Area, in.^{2}	Inside Volume, yd^3/ft	External Collapse Index
PP10	.109	3.39	11.51	41.4	8.28	3.50	2.62	75.2	.0193	62
	.120	3.72	12.66	45.5	9.09	3.49	2.62	74.8	.0192	83
	.134	4.15	14.12	50.5	10.1	3.49	2.62	74.4	.0191	116
	.141	4.37	14.85	53.1	10.6	3.49	2.62	74.2	.0191	135
	.150	4.64	15.78	56.3	11.3	3.48	2.62	73.9	.0190	163
	.164	5.07	17.23	61.3	12.3	3.48	2.62	73.5	.0189	214
	.172	5.31	18.05	64.1	12.8	3.48	2.62	73.2	.0188	247
	.179	5.52	18.78	66.6	13.3	3.47	2.62	73.0	.0188	279
	.188	5.80	19.70	69.8	14.0	3.47	2.62	72.7	.0187	324
	.203	6.25	21.24	75.0	15.0	3.46	2.62	72.3	.0186	409
	.219	6.73	22.88	80.5	16.1	3.46	2.62	71.8	.0185	515
	.230	7.06	24.00	84.3	16.9	3.46	2.62	71.5	.0184	588
	.250	7.66	26.03	91.1	18.2	3.45	2.62	70.9	.0182	719
PP10-3/4	.109	3.64	12.39	51.6	9.60	3.76	2.81	87.1	.0224	50
	.120	4.01	13.62	56.6	10.5	3.76	2.81	86.8	.0223	67
	.125	4.17	14.18	58.9	11.0	3.76	2.81	86.6	.0223	76
	.141	4.70	15.98	66.1	12.3	3.75	2.81	86.1	.0221	109
	.150	5.00	16.98	70.2	13.1	3.75	2.81	85.8	.0221	131
	.156	5.19	17.65	72.9	13.6	3.75	2.81	85.6	.0220	148
	.164	5.45	18.54	76.4	14.2	3.74	2.81	85.3	.0219	172
	.172	5.72	19.43	80.0	14.9	3.74	2.81	85.0	.0219	199
	.179	5.94	20.21	83.1	15.5	3.74	2.81	84.8	.0218	224
	.188	6.24	21.21	87.0	16.2	3.73	2.81	84.5	.0217	260
	.219	7.25	24.63	100	18.7	3.72	2.81	83.5	.0215	414
	.230	7.60	25.84	105	19.6	3.72	2.81	83.2	.0214	480
	.250	8.25	28.04	114	21.2	3.71	2.81	82.5	.0212	605
	.279	9.18	31.20	126	23.4	3.70	2.81	81.6	.0210	781
	.307	10.1	34.24	137	25.6	3.69	2.81	80.7	.0208	951
	.344	11.2	38.23	152	28.4	3.68	2.81	79.5	.0205	1,180
	.365	11.9	40.48	161	29.9	3.67	2.81	78.9	.0203	1,320
	.438	14.2	48.24	189	35.2	3.65	2.81	76.6	.0197	1,890
	.500	16.1	54.74	212	39.4	3.63	2.81	74.7	.0192	2,380
PP12	.134	5.00	16.98	87.9	14.7	4.20	3.14	108	.0278	67
	.141	5.25	17.86	92.4	15.4	4.19	3.14	108	.0277	78
	.150	5.58	18.98	98.0	16.3	4.19	3.14	108	.0277	94
	.172	6.39	21.73	112	18.6	4.18	3.14	107	.0274	142
	.179	6.65	22.60	116	19.4	4.18	3.14	106	.0274	161
	.188	6.98	23.72	122	20.3	4.18	3.14	106	.0273	186
	.203	7.52	25.58	131	21.8	4.17	3.14	106	.0272	235
	.219	8.11	27.55	141	23.4	4.17	3.14	105	.0270	296
	.230	8.50	28.91	147	24.6	4.16	3.14	105	.0269	344
	.250	9.23	31.37	159	26.6	4.16	3.14	104	.0267	443
	.281	10.3	35.17	178	29.6	4.14	3.14	103	.0264	616
	.312	11.5	38.95	196	32.6	4.13	3.14	102	.0261	784
PP12-3/4	.109	4.33	14.72	86.5	13.6	4.47	3.34	123	.0317	30
	.125	4.96	16.85	98.8	15.5	4.46	3.34	123	.0316	45
	.134	5.31	18.06	106	16.6	4.46	3.34	122	.0315	56
	.150	5.94	20.19	118	18.5	4.46	3.34	122	.0313	78
	.156	6.17	20.98	122	19.2	4.45	3.34	122	.0313	88
	.164	6.48	22.04	128	20.1	4.45	3.34	121	.0312	103
	.172	6.80	23.11	134	21.1	4.45	3.34	121	.0311	118
	.179	7.07	24.03	140	21.9	4.45	3.34	121	.0310	134
	.188	7.42	25.22	146	23.0	4.44	3.34	120	.0309	155
	.203	8.00	27.20	158	24.7	4.44	3.34	120	.0308	196
	.230	9.05	30.75	177	27.8	4.43	3.34	119	.0305	286
	.250	9.82	33.38	192	30.1	4.42	3.34	118	.0303	368
	.281	11.0	37.42	214	33.6	4.41	3.34	117	.0300	526
	.312	12.2	41.45	236	37.0	4.40	3.34	115	.0297	684
	.330	12.9	43.77	248	39.0	4.39	3.34	115	.0295	776
	.344	13.4	45.58	258	40.5	4.39	3.34	114	.0294	848

Table 2-4 Typical Steel Pipe Pile Sizes (continued)

Designation and Outside Diameter, in.	Wall Thickness, in.	Area A, in.^{2}	Weight per foot, lb/ft	I, in.^{4}	S, in.^{3}	R, in.	Area of Exterior Surface, ft^2/ft	Inside Cross-Sectional Area, in.^{2}	Inside Volume, yd^3/ft	External Collapse Index
	.375	14.6	49.56	279	43.8	4.38	3.34	113	.0291	1,010
	.406	15.7	53.52	300	47.1	4.37	3.34	112	.0288	1,170
	.438	16.9	57.59	321	50.4	4.36	3.34	111	.0285	1,350
	.500	19.2	65.42	362	56.7	4.33	3.34	108	.0279	1,760
PP14	.134	5.84	19.84	140	20.0	4.90	3.67	148	.0381	42
	.141	6.14	20.87	147	21.1	4.90	3.67	148	.0380	49
	.150	6.53	22.19	157	22.4	4.90	3.67	147	.0379	59
	.156	6.78	23.07	163	23.2	4.89	3.67	147	.0378	66
	.172	7.47	25.40	179	25.5	4.89	3.67	146	.0377	89
	.179	7.77	26.42	186	26.5	4.89	3.67	146	.0376	101
	.188	8.16	27.73	195	27.8	4.88	3.67	146	.0375	117
	.203	8.80	29.91	209	29.9	4.88	3.67	145	.0373	147
	.210	9.10	30.93	216	30.9	4.88	3.67	145	.0373	163
	.219	9.48	32.23	225	32.2	4.87	3.67	144	.0372	185
	.230	9.95	33.82	236	33.7	4.87	3.67	144	.0370	215
	.250	10.8	36.71	255	36.5	4.86	3.67	143	.0368	277
	.281	12.1	41.17	285	40.7	4.85	3.67	142	.0365	395
	.344	14.8	50.17	344	49.2	4.83	3.67	139	.0358	691
	.375	16.1	54.57	373	53.3	4.82	3.67	138	.0355	835
	.438	18.7	63.44	429	61.4	4.80	3.67	135	.0348	1,130
	.469	19.9	67.78	457	65.3	4.79	3.67	134	.0345	1,280
	.500	21.2	72.09	484	69.1	4.78	3.67	133	.0341	1,460
PP16	.134	6.68	22.71	210	26.3	5.61	4.19	194	.0500	28
	.141	7.02	23.88	221	27.6	5.61	4.19	194	.0499	33
	.150	7.47	25.39	235	29.3	5.60	4.19	194	.0498	39
	.164	8.16	27.74	256	32.0	5.60	4.19	193	.0496	52
	.172	8.55	29.08	268	33.5	5.60	4.19	193	.0495	60
	.179	8.90	30.25	278	34.8	5.59	4.19	192	.0494	67
	.188	9.34	31.75	292	36.5	5.59	4.19	192	.0493	78
	.203	10.1	34.25	314	39.3	5.59	4.19	191	.0491	98
	.219	10.9	36.91	338	42.3	5.58	4.19	190	.0489	124
	.230	11.4	38.74	354	44.3	5.58	4.19	190	.0488	144
	.250	12.4	42.05	384	48.0	5.57	4.19	189	.0485	185
	.281	13.9	47.17	429	53.6	5.56	4.19	187	.0481	264
	.312	15.4	52.27	473	59.2	5.55	4.19	186	.0478	362
	.344	16.9	57.52	519	64.8	5.54	4.19	184	.0474	487
	.375	18.4	62.58	562	70.3	5.53	4.19	183	.0470	617
	.438	21.4	72.80	649	81.1	5.50	4.19	180	.0462	874
	.469	22.9	77.79	691	86.3	5.49	4.19	178	.0458	1,000
	.500	24.3	82.77	732	91.5	5.48	4.19	177	.0455.	1,130

kN). They are very competitive as combination end-bearing/friction piles for loads from 120 kips (534 kN) to 240 kips (1068 kN), driven closed-end and filled with concrete (particularly where pile lengths do not favor mandrel-driven piles.) Pipe also provides a strong casing for concrete fill where underground pressures are high. Pipe piles may be driven with an open end or a closed end.

Advantages and disadvantages of steel pipe pile are shown in Table 2-5.

2.1.1.2.1. Specifications

The basic specification for pipe piles is ASTM A-252, which covers welded and seamless product. There are three grades listed:

- Grade 1 has a minimum yield strength of 30 ksi (207 MPa);
- Grade 2 has a minimum yield of 35 ksi (241 MPa); and
- Grade 3 has a minimum yield of 45 ksi (310 MPa).

There are elongation requirements for ductility, but only minimum chemistry requirements.

2.1.1.2.1. Manufacture

Seamless pipe is rarely specified for pipe piles due to its relative cost. It generally comes on the market as surplus pipe. As the name implies, seamless pipe has no seams but is made in one piece from a hot steel billet by piercing the centre and expanding the steel to the shape and size desired.

Electric weld pipe is the most common type of pipe used for piles. Several manufacturing processes can be used:

Table 2-5 Advantages and Disadvantages of Steel Pipe Pile

Advantages	Disadvantages
Wide selection of sizes and thicknesses available to choose from.	Open-end pipe piles are not as favorable as H-piles for non-displacement applications since the plug of soil inside the pipe also offers resistance to penetration.
Delivery is excellent since there are many manufacturers and distributors; popular sizes are stocked.	Closed-end they are full displacement piles with certain potential problems associated with displacement.
Standard sizes of pipe pile can be driven with conventional driving equipment. Light wall pipe makes an efficient shell for concrete fill when mandrel-driven.	They may not be price-competitive with other displacement piles.
Pipe piles driven open-end to rock, cleaned, inspected and filled with concrete can resist very high individual loads.	
Pipe piles with wall thickness over about 1/8" (3.2 mm) and filled with concrete are treated as a composite pile with both the steel and the concrete sharing the applied load. The advantages of both steel and concrete are enjoyed.	
Pipe piles can be inspected for material damage and curvature prior to acceptance.	
They can be readily spliced to extend lengths, resist hard driving, and drive straighter because of their constant radius of gyration. They make a more efficient column where unsupported length and large loads are design requirements.	

- Electric resistance welding
- Fusion welding
- Flash welding.

The seams of these pipes may be straight, spiral-butt or spiral-lap construction. In each case, the manufacturer begins with hot rolled sheets or plates in either coils or flats. The production equipment determines how the pipe is assembled and the seams are welded. So-called "spiral mills" produce spiral pipe by butting or lapping the seams. This process accounts for a large share of the pipe pile produced. Larger and thicker pipe piles are generally made on the same mills which produce large diameter line pipe by the straight seam, electric butt-weld process. In some cases very heavy wall pipe piles are fabricated in specialty shops where penstocks or caissons might be fabricated. There seems to be no particular advantage of one process over the other as far as the pile foundation designer is concerned.

2.1.1.2.1. Closed Ended Pipe Piles

A closed ended pipe pile is shown in Figure 2-3. They may be filled with concrete or left unfilled. They may be filled with a structural shape such as an H-section in addition to the concrete and socketed into bedrock (rock socketed piles). If bearing capacity from the entire pile toe area is required, the pile toe should be closed with a plate or a conical tip. Mandrels are usually not used for driving pipe piles, which are generally driven from the pile head. When the end of a pipe pile is equipped with a closure device, the pile becomes a displacement pile and functions well as a friction pile particularly in loose sands. When driven open or closed end it can also function as a high capacity end-bearing pile.

Figure 2-3 Closed End Pipe Piles

A flat plate of 1/2" to 2" (13-51 mm) thickness, or a conical point generally forms a closed ended pile. When pipe piles are driven to weathered rock or through boulders, a cruciform end plate or a conical point with rounded nose is often used to prevent distortion of the pile toe.

2.1.1.2.2. Open Ended Pipe Piles

Open-ended pipe piles are driven when hard driving, caused by the presence of debris, small boulders and the like is anticipated. The pipe can be fitted with a special driving shoe, which adds steel thickness at the toe to reduce stresses and damage. Periodically, the plugger materials are removed to aid in driving. Open-ended pipe piles may also be partially socketed into rock at site of steeply sloping bedrock or where pile fixity at the toe is a design requirement. Pipe piles driven open-end may be filled with concrete after cleaning out the plug, backfilled with sand, or the plug ignored. In the last two cases, the steel wall takes all stress and the pile would be treated similar to an H-pile for design purposes.

In driving through dense materials, open-ended piles may form soil plugs. The plug may make the pile act like a closed end pile and increase the pile toe bearing capacity significantly. The plug should not be removed unless the pile is to be filled with concrete. For open-ended pipe piles not filled with concrete, the formation of soil plug should not be considered in computing pile end bearing capacity. Behavior of the plug during and after driving is a function of pile size and soil type and consistency. Only preliminary design guidance is available, which should always be confirmed by field observations and measurements.

This type of pile is also common in the installation of offshore oil platforms, whether driven from the surface or underwater. In these applications, they primarily are designed for uplift loads due to wave or wind action on the structure. Unless the pile plug generated during driving creates drivability problems, the plug is generally not removed. An illustration of this application is shown in Figure 2-4.

Figure 2-4 Pile Piles for an Offshore Oil Platform

Open ended pipe piles are recommended where the pile or pile group is to be subjected to horizontal loads and bending moments such as vessel impact and scour on large structures such as bridges. With a constant radius of gyration, pipe piles are also the most efficient columns and should be considered where freestanding columnar strength is important (such as open-platform marine piers and docks). This is advantageous in seismic situations, where liquefaction and several other factors have a strong influence on the design of deep foundations. In all of these applications, the pile size can range up to 3000 mm in diameter. Since such applications can require considerable length, this frequently requires adding-on to pipe piles, which is shown in Figure 2-5.

Figure 2-5 Welding an Add-On to Pipe Pile

An example of this kind of application was the Jamuna River Bridge in Bangladesh, built in the mid-1990's. The river is capable of scouring to a depth of 50 m, with a flood discharge of 100,000 m^3/sec. To deal with this, groups of high yield strength piles 2500 – 3150 mm in diameter up to 80 m long with a wall thickness of 45 – 60 mm were installed. After driving, the plug was removed and the toe of the pile was sealed with concrete, then the pile was grouted.[2]

2.1.1.2.3.RR Piles

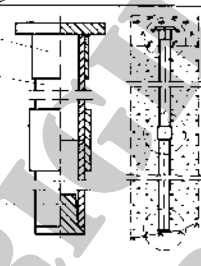
A special type of pipe pile is the RR pile, manufactured by Makela Metals. These can be formed into sectional pile systems by mechanical joints. RR piles are type approved in Finland. They are used as toe-bearing piles in the repair of buildings, as supports under machine bases, and for house foundations. Light installation equipment, the cost-effective use of material and versatility of application are benefits offered by RR piles.

For the determination of bearing capacities and installation information, refer to the design instructions published by Makela Metals and approved by the Finnish Ministry of the Environment. For the technical properties and structure of RR piles, see Table 2-6.

Table 2-6 Technical Properties of RR Piles

DIMENSIONS					
Type of pile	Diameter D mm	Wall thickness t mm	Mass kg/m	Steel grade 1993	Yield strength R_{eH} N/mm²
RR60	60,3	6,3	8,0	S355J2G3	355 [1]
RR75	76,1	6,3	10,4	S355J2G3	355 [1]
RR90	88,9	6,3	12,8	S355J2G3	355 [1]
RR115	114,3	6,3	16,8	S355J2G3	355 [1]
RR140/6	139,7	6,3	20,7	S355J2G3	355 [1]
RR140/8	139,7	8,0	26,0	S355J2G3	355 [1]
RR140/1	139,7	10,0	32,0	S355J2G3	355 [1]
RR170	168,3	10,0	39,0	S355J2G3	355 [1]
RR220	219,1	10,0	51,6	S355J2G3	355
RR270	273,0	10,0	64,9	S355J2G3	355
RR320	323,9	10,0	77,4	S355J2G3	355

DETAIL DRAWING



[1] The load-bearing capacities have been calculated using the characteristic value 430 N/mm².
Piles RR60...RR170 are available in lengths of 1...6 m, piles RR140...RR320 in lengths of 1...16 m.
On piles RR60...RR170, the splice is fixed at the works. Spare splices are available for piles RR140...RR320.

RR piles are spliced using friction joints, so no welding is required for splicing. The Finnish Ministry of the Environment under decision number 282/533/87 and 10/5331/93 has approved the splices.

The pile toe is protected with either an RR sand shoe or RR rock shoe. The pile is furnished with an RR pile cap that is fixed to the pile body by means of sleeve connection.

The connections between the piles and superstructure are designed as flexible joints. However, the connections of piles shorter than 3 meters are preferably made rigid.

The permissible bearing capacity of an RR pile is determined by selecting the lowest of the following values:

- Maximum permissible centrally structural compression load;
- Permitted bearing capacity in respect of buckling;
- Geotechnical bearing capacity.

In accordance with the Pile Driving Instructions LPO-87 section 3.4231 of the Finnish Geotechnical Association, the maximum permissible structural compression load for RR piles is 33 to 58% of the yield point of the pile steel depending on the piling class. This has been considered in the permissible load ratings of Table 2-7.

Table 2-7 Permissible Bearing Capacities with Respect to Buckling, RR Piles

Type of pile	Piling class	Initial radius of curvature R m	Permissible bearing capacity with respect to buckling kN Closed shearing strength of the soil s (u) kN/m² 7	10	15	20
RR60	III	70	76	99	107	107
RR75	IB II	150 100	150 125	187 163	205 188	216 197
RR90	IB II	200 150	208 186	237 223	256 234	267 234
RR115	IB II	200 150	296 296	320 302	343 306	256 306
RR140/6	IB II	200 150	330 277	354 298	377 313	391 313
RR140/8	IB II	200 150	402 337	437 367	471 397	491 407
RR140/10	IB II	200 150	439 380	571 500	637 596	645 626
RR170	IB II	300 200	680 550	738 599	789 631	789 631
RR220	IB II	350 300	740 673	785 716	828 758	854 783
RR 270	IB II	400 350	922 845	972 893	1020 939	1049 968
RR320	IB II	450 400	1095 1011	1150 1063	1202 1114	1234 1145

R represents the initial radius of pile curvature after mounting, but prior to loading.
Corrosion allowance is 1 mm.

Where the pile is embedded in cohesionless soil layers, buckling must be taken into account as a possible determinant for its bearing capacity. Table 2-7 depicts the permissible load ratings of RR piles in respect of buckling. The initial radius of curvature R may be checked on the driven pile by illuminating it with a flashlight.

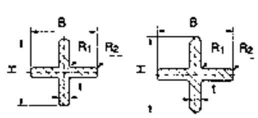
2.1.1.1. X-Piles

Makela Metals supplies the X piles presented in Table 2-8. X piles are mainly toe-bearing piles that are used for earth retaining applications. When used as driven piles, their X-shaped cross section minimizes soil disturbance and displacement. Their high rigidity allow X piles to be driven into hard-to-penetrate site conditions, including landfills.

Table 2-8 Dimensions and Installation, X-Piles

Dimensions

X130-X180 | X200

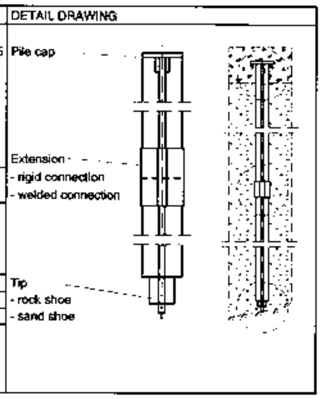


Steel grade:
- S275JR EN 10025
- R_{eH} = 275 N/mm²

X pile	H mm	B mm	t mm	R_1 mm	R_2 mm	Mass kg/m
X130	130±2	130±2	16±0,5	6	2	30,8
X155	155±2	155±2	23±1	8	3	52,1
X180	180±3	180±3	24±1	9	4	63,6
X200	199^{+3}_{-1}	198^{+3}_{-1}	30±1	10	5	85,0

	Permitted geotechnical bearing capacity, sand shoe, kN		
	Piling class		
	IB	II	III
X130	393	275	157
X155	664	465	266
X180	811	567	324
X200	1072	751	429

DETAIL DRAWING



X piles are predominantly used near existing structures in order to avoid damage and reduce ground vibrations. Typical applications include embankment foundation support, bridge structures, supports under machine bases and underpinning.

X piles have been approved in Finland and Sweden. In both cases the grantor's decision on each type approval is supplemented by design instructions, which are to be followed in the design and use of X piles.

The pile body functions satisfactorily for sand sites without special details. Rock shoes are attached at the fabrication location. The pile cap is fitted on the pile head by means of a sleeve connection or by welding. Piles can be spliced by welding or by means of extensions made of steel plate.

A corrosion allowance is taken into consideration in the design of piles. The average rate of corrosion in natural soil is 0.02 mm/year or 1 mm/50 years.

The permissible bearing capacity of an X pile is determined by selecting the lowest one of the following ratings:

- Permitted structural axial capacity;
- Permitted structural lateral capacity (especially buckling with very deep soft soil layers);
- Permitted geotechnical bearing capacity.

The specified geotechnical bearing capacity of the X pile is achieved by driving the pile to a point of sufficient resistance by soil. Steel piles usually function as retaining piles, which means that the geotechnical bearing capacity is equal to the toe-bearing capacity. The geotechnical bearing capacity of a pile with sand shoe is presented in Table 2-8.

The necessary soil analysis for the design of X piles includes the penetration depth and, in cohesionless soil, the shearing strength of the soil.

2.1.1.1. Corrosion of Steel Piles[3]

Corrosion of steel occurs where electric current leaves metal and enters a surrounding moist medium. Seawater at the splash line, where steel is alternately wet and dry is especially aggressive. Most fresh water corrodes steel only slowly unless there are pollutants. Piling driven into the ground so oxygen does not get to it suffers very little, unless there are stray currents. Piles generally are far enough apart that stray currents do not migrate between them.

Cathodic protection, use of a sacrificial anode, can be helpful but may not be effective in the splash zone where the steel is not always wet. Concrete jacketing may be needed in that area. Cathodic protection requires frequent maintenance.

Paint can provide protection if a proper material is selected; the steel is cleaned so paint will adhere and application is made with the steel dry and preferably warm. Cleaning means removal of all scale by mechanical means such as sandblasting. Be sure to follow the manufacturer's recommendations. For example, some bitumastics will not adhere to red oxide primer; they will stay on zinc chromate.

Metallized aluminum coatings have been helpful in protecting steel piling in seawater. About 6 to 12 mils of aluminum sprayed on steel cleaned to white metal and is then vinyl coated has been reported in excellent condition after 12 years of exposure.

Coatings can be applied commercially in specialty plants, usually near the rolling mills. Piles reach the job in good condition with only minor touch-up required.

Cast steel is naturally rust-resistive, so cast steel toe protection for H, sheet or pipe piles almost never rusts to any degree. Metal corrodes only when oxygen is present. Points of driven piles are usually well protected in the ground and protective coatings are unnecessary.

2.1.2. Concrete Piles

Concrete piles utilize concrete as the main structural material for compressive loads; however, concrete is deficient in resistance to tensile load. Therefore, when a concrete pile is subject to direct tension or bending, steel must be added to resist these stresses.

Concrete piles are classified as pre-cast or cast-in-place depending on the method of manufacture.

Pre-cast piles are formed in a casting bed, cured, and then driven into place. There are several ways of manufacturing pre-cast piles:

1. Conventional steel reinforcing bars are used for tensile stresses and placed prior to casting the concrete;
2. High tensile rods or wires are pre-tensioned and the concrete shape cast around them (pre-stressed piles);
3. Hollow concrete cylinders are precast in manageable lengths, high strength rods or wire is strung through ducts in the several pre-cast sections and post-tensioned to form a complete pile.

Cast-in-place piles are, as the name implies, cast in a pre-formed excavation at the project site and hence the concrete is not subjected to driving forces.

2.1.2.1. Cast-In-Place Concrete Piles

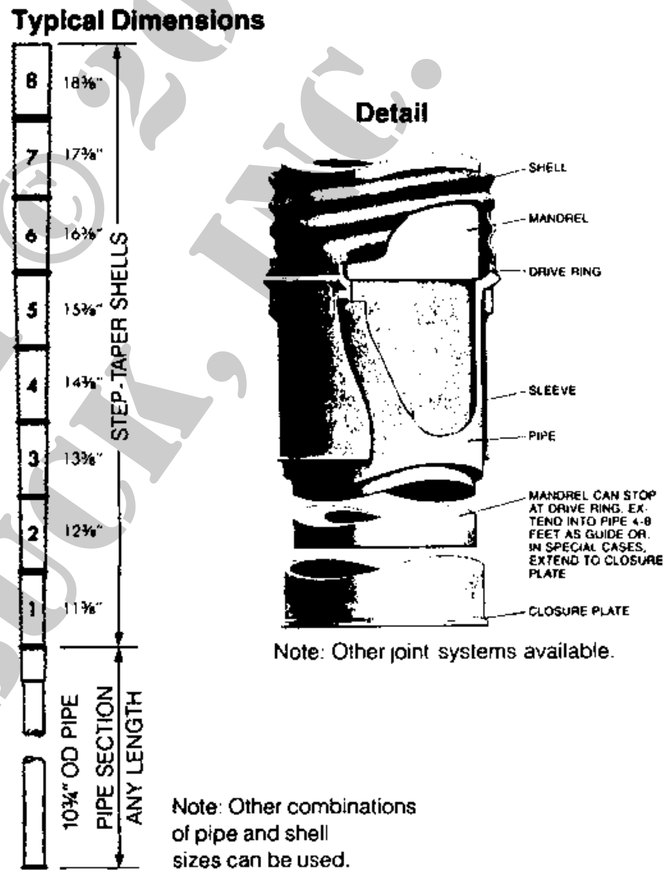
In general, cast-in-place concrete piles are installed by placing concrete in an excavated hole in the ground. In some cases the hole is lined with a steel shell or casing which may be temporary or permanent. Steel pipe piles, when filled with concrete, can be classified under this category. Predetermination of pile lengths is not as critical as for precast concrete piling, since required pile lengths can be easily changed during installation.

Cast-in-place concrete piles can be installed with or without a mandrel[4], depending upon the wall thickness of the pile. Use of a mandrel allows piles with wall thicknesses of 0.02-0.13" (0.5-3.3 mm) thick, while those driven without a mandrel have wall thicknesses of 0.109-2.5" (2.8-63.5 mm) thick. With the latter, concrete is placed into the driven shell and is the primary basis for the structural strength of the completed pile. The steel in head-driven piles is generally of sufficient thickness to be included in the load capacity calculations. Contractors using this method avoid the expense of mandrels and long leads but pay more for the heavier shell. When the wall thickness exceeds about 0.1" (2.54 mm) (depending on building code requirements) the allowable load may be calculated in a way similar to closed-end pipe piles.

2.1.2.1.1. Raymond Step-Taper Piles

The best known of the mandrel-driven type piles is the Raymond Step-Taper® pile. In 1897, Alfred Raymond received a patent for a novel pile, which would consist of a tapered steel shell to be installed with the aid of an internal mandrel. After withdrawing the mandrel, the shell was filled with concrete to complete the pile. The maximum length was 37' (11.3 m). Until then, timber piles had dominated the market. This pile was the basis for forming the Raymond Concrete Pile Company, which fabricated and installed these piles as a general contractor. In the early 1930's, the modern Step-Taper® shape was introduced which was a marked improvement over the earlier design. The configuration for Raymond Step-Taper® piles is shown in Figure 2-6.

Figure 2-6 Raymond Step Taper Pile Configuration

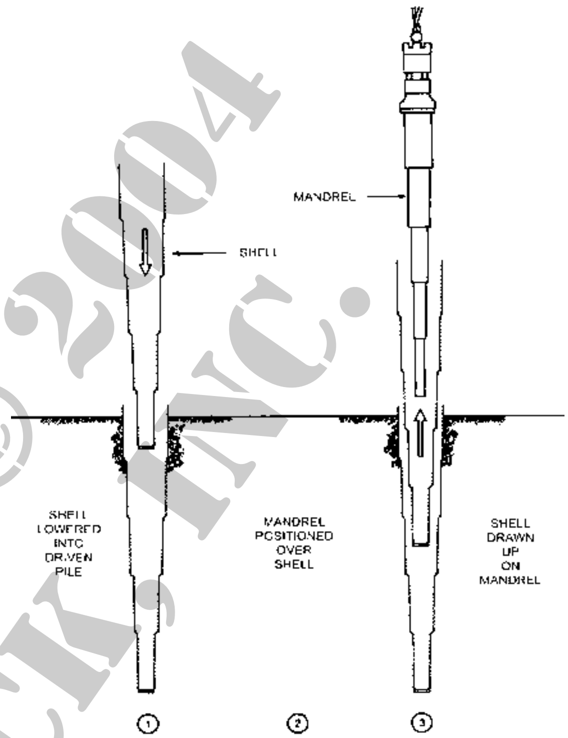


Where the original taper shell was a one-piece design, the Step-Taper® is assembled from short lengths of helically corrugated steel shells from 4' (1219mm) to 16' (4.88 m) in length. Nominal diameters of the sections range from 8" (203.2 mm) to 18" (457.2 mm); when assembled the pile diameter increases in increments of 1 inch per section and the rate of taper varies depending on the section lengths. Obviously if constant lengths are used, the rate of taper will be constant. The shells are made up from 10 to 18 gage steel with the heavier gages used in the lower portion of the pile assembly. At the project site, the combined shell lengths are pulled up over a heavy, steel, tapered mandrel. The mandrel is stepped to match the shell. Driving on the head of the mandrel drives both the mandrel and the shell into the ground. After driving is complete, the mandrel is withdrawn and the shell inspected and filled with concrete. The steel acts as a form for the concrete and is not assumed to carry any portion of the applied load. Reinforcing steel is added when necessary for lateral or tension loading. Lengths of 120’ (36.6 m) are possible but not always practical since very long driving leads must be used.

Step-Taper® piles offer a wide selection of cross-sectional dimensions and length combinations for different loading and soil-bearing conditions. Being displacement piles, they function efficiently as friction piles and particularly in granular soils. By varying the toe diameter, or in combination with a pipe bottom, Step-Taper® piles can function as essentially end-bearing piles when driven to rock or compact strata overlying rock. Their efficiency as friction piles generally would result in a smaller transfer of load to the toe than a non-displacement type pile. The shape and drivability of this pile is especially effective for developing high individual capacities.

To install Raymond step-taper piles, metal shells are assembled at the project site by screwing lengths together. Joints are sealed with a neoprene ring and a bottom closure piece added. The problem of placing the shell over the mandrel can be easily addressed by dropping the shell into a previously driven shell and pulling it up onto the mandrel from the hole (see Figure 2-7). Driving on the mandrel transmits energy to the toe of the shell and the drive rings at the joints. Under certain conditions, such as stiff clays (soil heave) or dense overlying strata, predrilling is sometimes specified.

Figure 2-7 Shell-up Procedure for Step Taper Piles



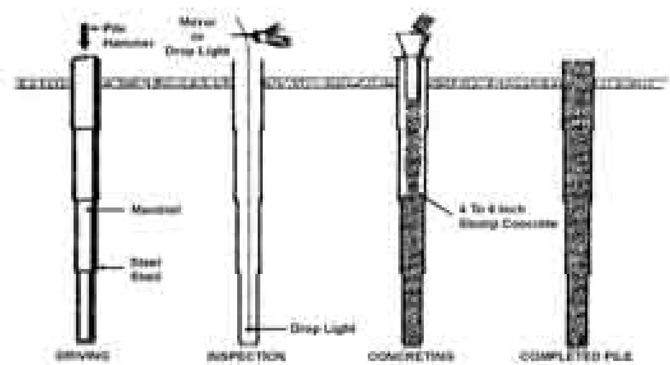
Continuing with Figure 2-8, after the shell has reached the required toe elevation, the mandrel is

Table 2-9 Advantages and Disadvantages of Raymond Step Taper Piles

Advantages	Disadvantages
Versatility, a wide range of configurations and variations are possible to accommodate different loads and soil conditions.	Displacement piles are particularly vulnerable to pile heave in plastic soils. This condition should be monitored closely.
Drivability, the heavy mandrel permits the use of lighter hammers for more effective driving and development of the geotechnical capacity.	Thin gauge shells are vulnerable to damage where underground debris or boulders are encountered.
Internal inspection is possible after driving and before concreting.	Splicing to extend lengths is difficult.
Installation is made without damage to the working pile since driving is done on the mandrel and not on the concrete.	Shells are vulnerable to collapse from excessive earth or hydrostatic pressure, and special measures must be taken in those situations.
A range of pile capacities is possible from medium to very high.	
Shape characteristics: the configuration is that of a true displacement pile combined with the taper to develop capacity of the soil-pile system in shorter lengths than other types, particularly in loose granular soils.	
The pile shell insures that the hole is secure against soil intrusion.	

withdrawn and the shell inspected with a mirror or droplight. Water, should be removed at this time. Concrete is poured in a continuous operation through a drop chute. Generally, vibration is not required but Raymond suggested rodding the "top" 6' to 8' (1.8-2.44 m) of concrete. They also state that concrete may be placed in shells adjacent to driving since the driving has no detrimental effect on the new concrete. Raymond normally utilizes a concrete mix of their own formulation, chiefly based upon larger quantities of small sized coarse aggregate (a special mix to minimize aggregation.) If ground heave conditions are present, the levels of the pile heads should be monitored to see if they have risen. Step-Taper® piles that have heaved may be redriven if proper techniques are used.

Figure 2-8 Installation Sequence for Raymond Step-Taper® Piles



2.1.2.1.2. Other Types of Mandrel Driven Piles

In addition to the Raymond Step-Taper®, there are various straight sided shell piles. Steel companies Armco and Republic market helically corrugated shells, which are driven with proprietary or commercially available expanding mandrels. These grip the sides of the pile shell by pressure and friction in addition to bearing on the boot plate. Installation is somewhat like the Step-Taper® except long shells must be dropped down a specially drilled over-sized hole to be pulled up onto the mandrel. These piles can also be combined with a pipe tip or occasionally with a timber pile to create a composite pile. Other aspects are similar to the Step-Taper®. The Step-Taper® might be fundamentally more economical because of the tapering shape with less concrete and perhaps shorter lengths to develop the same capacity. These piles would have wall thicknesses less than 0.200" but heavier gauge piles might also be driven this way if especially hard driving and possible installation problems dictated this method. The steel in these pipe sections can be used in design calculations as an addition to concrete.

2.1.2.1.3. Monotube Piles

Monotube piles are a proprietary pile shell, which is rigid enough to be head driven. The rigidity is obtained by use of heavy gauge steel (3 to 9 gauge), which is longitudinally ribbed or "fluted" during the cold forming process. The basic shell is tapered with tips of about 8" (203.2 mm) diameter and butts 12" (304.8 mm) to 18" (457.2 mm). Lengths range from 10' (3.05 m) to 75' (22.9 m). Extensions to the tip sections are made with straight-sided tubes up to 40' (12 m) long. After installation, the shell is filled with concrete. Monotube pile configurations are shown in Figure 2-9.

Monotubes compete with lighter wall pipe piles, and mandrel-driven cast-in-place piles for both friction and end-bearing applications. They are designed assuming both the concrete and steel support the applied load.

2.1.2.1.4. Compacted Concrete Piles

This method was developed by the Franki Foundation Co. and was proprietary with them for many years. Recently the general process has become available from others, and there are variations on the Franki pile concept, such as the bulb piles that Raymond installed. The method utilizes a heavy, removable pipe shell and a charge of special mix concrete. Special equipment has been devised to handle the pipe and a heavy drop hammer, which rams the dry-mix concrete into the soil inside the pipe. As the mix descends it pulls the pipe with it. When the desired elevation is reached, the pipe is restrained and the concrete mix is pounded out the base where it forms a compact bulb. The pile shell is then rammed in on head of the bulb terminating at the surface.

This pile is most suited for granular soils and has developed working load capacities of over 300 kips (1334 kN). These piles experience the same general problems as augered piles and they generally are no longer than 40' (12 m).

2.1.2.1.5. Composite Piles

Piles, which combine two types of piles in a single length, are classified as composite piles. The most common of these have been briefly described in the cast-in-place section:

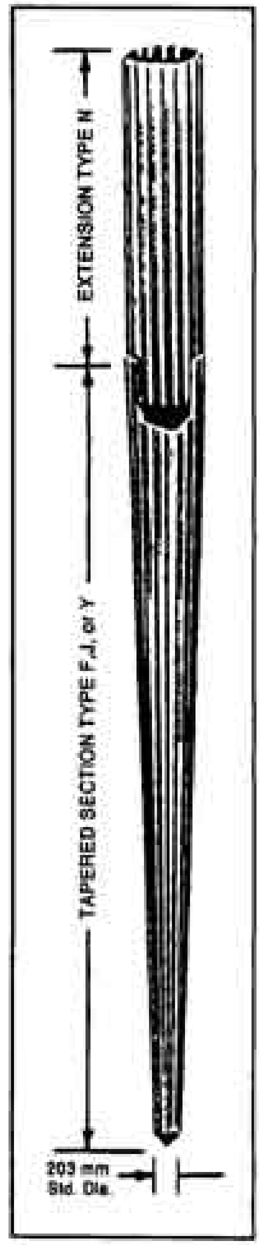
- A light metal shell filled with cast-in-place concrete is combined with a timber pile

Figure 2-9 Monotube Piles

TYPE	SIZE POINT DIAMETER x BUTT DIAMETER x LENGTH	Weight (N) per m				EST. CONC. VOL. m^3
		9 GA.	7 GA.	5 GA.	3 GA.	
F Taper 3.6 mm per Meter	216 mm x 305 mm x 7.62 m	248	292	350	409	0.329
	203 mm x 305 mm x 9.14 m	233	292	336	394	0.420
	216 mm x 356 mm x 12.19 m	277	321	379	452	0.726
	203 mm x 406 mm x 18.29 m	292	350	409	482	1.284
	203 mm x 457 mm x 22.86 m	-	379	452	511	1.979
J Taper 6.4 mm per Meter	203 mm x 305 mm x 5.18 m	248	292	336	394	0.244
	203 mm x 356 mm x 7.62 m	263	321	379	438	0.443
	203 mm x 406 mm x 10.06 m	292	350	409	467	0.726
	203 mm x 457 mm x 12.19 m	-	379	438	511	1.047
Y Taper 10.2 mm per Meter	203 mm x 305 mm x 3.05 m	248	292	350	409	0.138
	203 mm x 356 mm x 4.57 m	277	321	379	438	0.260
	203 mm x 406 mm x 6.10 m	292	350	409	482	0.428
	203 mm x 457 mm x 7.62 m	-	379	452	511	0.657

Extensions (Overall Length 0.305 m Greater than indicated)

TYPE	DIAMETER + LENGTH	9 GA.	7 GA.	5 GA.	3 GA.	m^3 /m
N 12	305 mm x 305 mm x 6.10 / 12.19 m	292	350	409	482	0.065
N 14	356 mm x 356 mm x 6.10 m / 12.19 m	350	423	496	598	0.088
N 16	406 mm x 406 mm x 6.10 m / 12.19 m	409	482	569	671	0.113
N 18	457 mm x 457 mm x 6.10 m / 12.19 m	-	555	642	759	0.145



base providing the economy of timber below the ground water table and the durability of concrete above. These piles are generally utilized for light to low-medium loads.

- Shell pile head and pipe pile bottom, combining the length and penetrating ability of the pipe with the economy of the cast-in-place concrete head for medium to high capacity applications.

A very common type of composite pile is a prestressed concrete pile combined with an H-pile "stinger." This provides both toe protection and penetration assistance for the pile. Such a pile is shown in Figure 2-10.

Figure 2-10 H-pile "Stinger" on Concrete Pile

If required a very high capacity composite pile can be formed from a pipe pile that is driven or drilled to rock, cleaned out and socketed into the rock. A steel core section is added and the pipe filled with concrete. These piles are quite expensive but some building codes permit very high loads on this pile because of the controlled conditions under which it is installed. New York City, for example, has allowed a load up to 3000 kips (13.3 MN) on properly designed and installed piles of this type.

2.1.2.1.1. Drilled-In Caissons

Drilled-in Caissons are drilled shafts, which use a driven casing, either permanently or more typically temporarily. The caisson can be driven with an impact or vibratory hammer, depending upon the soil conditions. Use of a vibratory hammer simplifies removal of the casing. Design considerations are the same as those for drilled shafts.

2.1.2.2. Precast and Prestressed Concrete Piles

This general classification covers both conventional reinforced concrete and prestressed concrete piles. Both types can be manufactured by various methods and are available to a number of different cross sections. Frequently such piles are cast with a hollow core to reduce weight, in which case the head and toe of the pile are solid. The hollow core may be used for placing instrumentation during construction or for determining pile damage. Precast concrete piles are usually of constant cross section but may have a tapered tip. Concrete piles are considered non-corrosive but can be damaged by direct chemical attack (e.g., from organic soil, industrial wastes to organic fills), electrolytic action (chemical or stray direct currents), or oxidation. Concrete can be protected from chemical attack by use of special cements and by special coatings.

Requirements for precast concrete piles generally apply equally to prestressed units, except reinforcement. Such piles must be designed and installed in accordance with the general provisions for piling. Precast piles must be proportioned, reinforced, cast, cured, handled and driven to resist the stress induced by handling and driving as well as by structural loads. Design details should indicate suitable points of pickup and support for each length of pile. Handling equipment shall be constructed to equalize the reactions on multiple lines of pile pickups.

2.1.2.2.1. Reinforced Concrete Piles

These piles are manufactured from concrete and have reinforcement consisting of a steel rebar cage consisting of several longitudinal bars and lateral or tie steel in the form of individual hoops or a spiral. Reinforced concrete piles as compared to prestressed piles are more susceptible to damage during handling and driving because of tensile stresses. They are rarely used in current U.S. practice. These piles are easier to splice than the prestressed piles and are used where possibilities of variable pile lengths exist. These piles are best suited for friction piles in sand, gravel and clays. Typically, the maximum length allowed is 50'.

2.1.2.2.2. Prestressed Concrete Piles

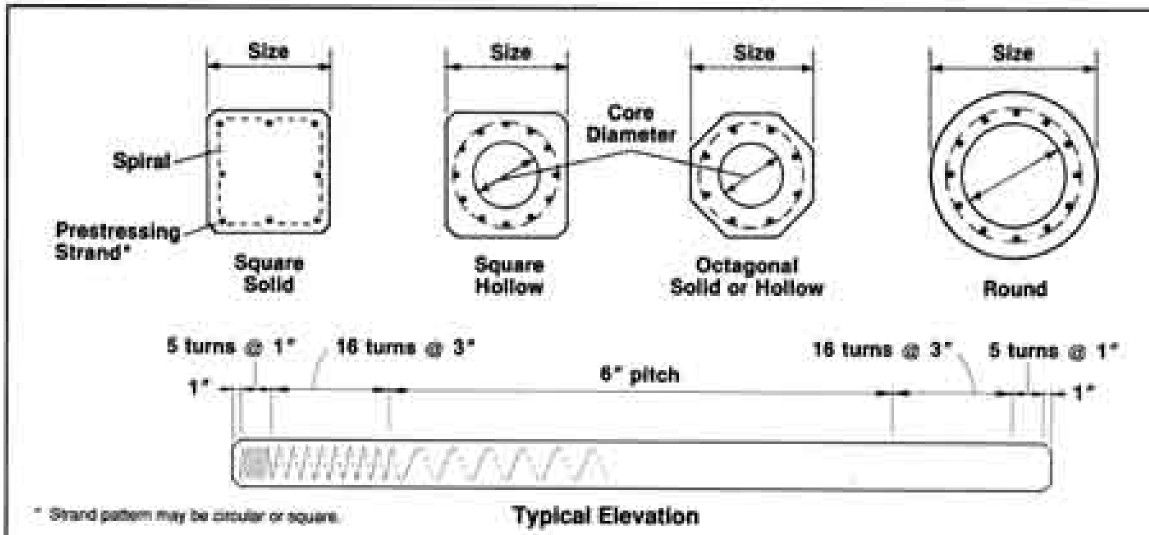
This pile consists of a configuration similar to a conventional reinforced concrete pile except the prestressing steel replaces the longitudinal reinforcing steel. The prestressing steel may be in the form of strands or wires and is placed in tension. The prestressing steel is enclosed in a conventional steel spiral. Such piles can usually be made lighter and longer than normally reinforced concrete piles of the same rigidity.

Prestressed piles can either be pretensioned or post-tensioned. Pretensioned piles are usually cast full length in permanent casting beds. Post-tensioned piles are usually manufactured in sections and assembled and prestressed to the required pile lengths at the manufacturing plant or on the job site. Table 2-10 shows typical prestressed concrete piles, along with data for typical prestressed concrete pile sections. Figure 2-11 shows typical details of pile reinforcement.

The minimum lateral dimensions of precast concrete piles should be 10" (254 mm) except for taper at the toe. For piles designed with voids, the minimum wall thickness of concrete should be 4" (101.6 mm). The maximum departure of the pile axis from a straight line, measured before installation while the pile is not subject to bending forces, should not exceed 1/8" (3.2 mm) in 10' (3.05 m), 3/8" (9.5 mm) in 40' (12 m), or 0.1% of the pile length.

Concrete preferably should have a higher strength than the usually specified minimum of 5 ksi (34.5 MPa) at 7 days if steam cured or at 28 days if cured by other means. The mix should have a cement content of 6 to 8 bags per cubic yard. Type II cement may be used where moderate sulfate resistance is required. Air entraining cement or suitable admixtures may be used to increased workability of the concrete. Calcium chloride may not be used, except for a trace in formulations used to accelerate strength gain and

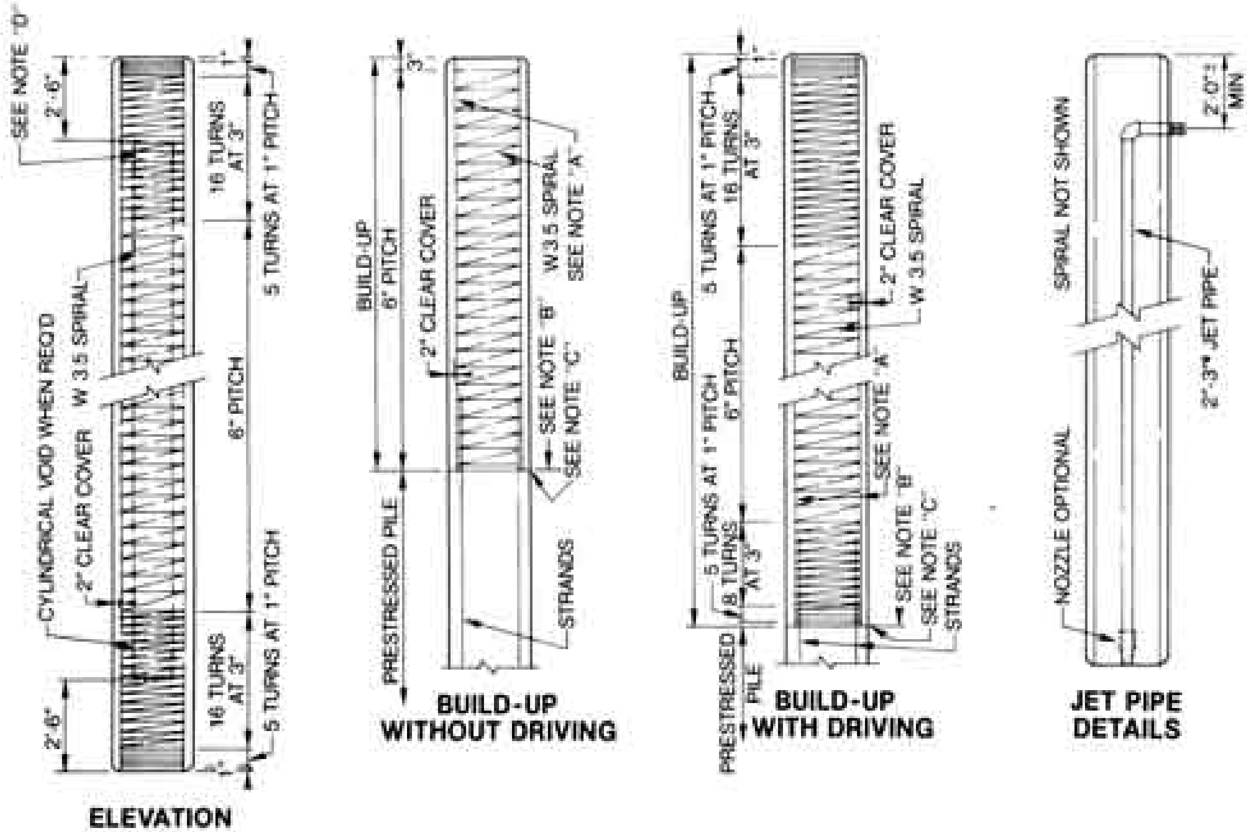
Table 2-10 Section Properties and Allowable Service Loads of Prestressed Concrete Piles



Size (in.)	Core Diameter (in.)	Section Properties[1]: Area (in.²)	Weight (plf)	Moment of Inertia (in.⁴)	Section Modulus (in.³)	Radius of Gyration (in.)	Perimeter (ft)	Allowable Concentric Service Load, Tons[2] f'_c: 5,000	6,000	7,000	8,000
Square Piles											
10	Solid	100	104	833	167	2.89	3.33	73	89	106	122
12	Solid	144	150	1,728	288	3.46	4.00	105	129	152	176
14	Solid	196	204	3,201	457	4.04	4.67	143	175	208	240
16	Solid	256	267	5,461	683	4.62	5.33	187	229	271	314
18	Solid	324	338	8,748	972	5.20	6.00	236	290	344	397
20	Solid	400	417	13,333	1,333	5.77	6.67	292	358	424	490
20	11 in.	305	318	12,615	1,262	6.43	6.67	222	273	323	373
24	Solid	576	600	27,648	2,304	6.93	8.00	420	515	610	705
24	12 in.	463	482	26,630	2,219	7.58	8.00	338	414	491	567
24	14 in.	422	439	25,762	2,147	7.81	8.00	308	377	447	517
24	15 in.	399	415	25,163	2,097	7.94	8.00	291	357	423	488
30	18 in.	646	672	62,347	4,157	9.82	10.00	471	578	685	791
36	18 in.	1,042	1,085	134,815	7,490	11.38	12.00	761	933	1,105	1,276
Octagonal Piles											
10	Solid	83	85	555	111	2.59	2.76	60	74	88	101
12	Solid	119	125	1,134	189	3.09	3.31	86	106	126	145
14	Solid	162	169	2,105	301	3.60	3.87	118	145	172	198
16	Solid	212	220	3,592	449	4.12	4.42	154	189	224	259
18	Solid	268	280	5,705	639	4.61	4.97	195	240	284	328
20	Solid	331	345	8,770	877	5.15	5.52	241	296	351	405
20	11 in.	236	245	8,050	805	5.84	5.52	172	211	250	289
22	Solid	401	420	12,837	1,167	5.66	6.08	292	359	425	491
22	13 in.	268	280	11,440	1,040	6.53	6.08	195	240	283	328
24	Solid	477	495	18,180	1,515	6.17	6.63	348	427	506	584
24	15 in.	300	315	15,696	1,308	7.23	6.63	219	268	318	368
Round Piles											
36	26 in.	487	507	60,007	3,334	11.10	9.43	355	436	516	596
42	32 in.	581	605	101,273	4,823	13.20	11.00	424	520	616	712
48	38 in.	675	703	158,222	6,592	15.31	12.57	493	604	715	827
54	44 in.	770	802	233,373	8,643	17.41	14.14	562	689	816	943
66	54 in.	1,131	1,178	514,027	15,577	21.32	17.28	826	1,013	1,199	1,386

(1) Form dimensions may vary with producers, with corresponding variations in section properties.
(2) Allowable loads based on $N = A_c\,(0.33\,f'_c - 0.27\,f_{pc})$; f_{pc} = 700 psi. Check local producer for available concrete strength.

Figure 2-11 Typical Details of Pile Reinforcement



Notes on Build-up

Note A: The minimum area of reinforcing steel shall be 1½ percent of the gross cross section of concrete. Placement of bars shall be in a symmetrical pattern of not less than four bars.

Note B: Method of attachment of pile to build-up may be by any of the methods given in the notes on alternate pile heads. If mild reinforcing steel is used for attachment, the area shall be no less than that used in the build-up.

Note C: Concrete around top portion of driven pile shall be bush-hammered to prevent feather edges in the cast-in-place build-up.

Note D: End fitting or form may be flat or tapered with proper taping to prevent leakage.

Note E: Additional mechanical and other types of splices are available to designers. Refer to PCI JOURNAL two-part series, "Splicing of Precast Prestressed Concrete Piles," September-October and November-December 1974.

reduce shrinkage.

The minimum amount of longitudinal reinforcement should be at least 1.5 to 2% of the concrete section, made up of a minimum of four bars symmetrically placed. For a length equal to at least three times the minimum lateral dimension at each end of the pile lateral tie reinforcement should be spaced 3" (76.2 mm) on centers, increased elsewhere to a maximum of 12" (304.8 mm). Lateral reinforcement should be No. 5 gauge or equivalent spiral. For piles designed with voids, the 3" (76.2 mm) spacing of ties or laterals can be extended for a distance of 12' (3.66 m) or one-third the length of the pile, whichever is smaller. Closely spaced ties or spirals improve the ductility of a pile. If hard driving is expected, spacing of 4" (101.6 mm) minimum is recommended.

Current practice is to cover longitudinal reinforcing steel with a minimum of 1-1/2" (38.1 mm) of concrete.[5] Voids, when used, shall be located within 3/8" (9.5 mm) of the position shown on plans. Voids may extend through either or both ends of the pile. If the void extends through the lower end of the pile, the pile head must be vented to prevent build-up of internal hydraulic pressure during driving. Paper or fiber used to form a void in the pile has been known to decompose and develop destructive gas pressures, so it should be removed or the pile permanently vented.

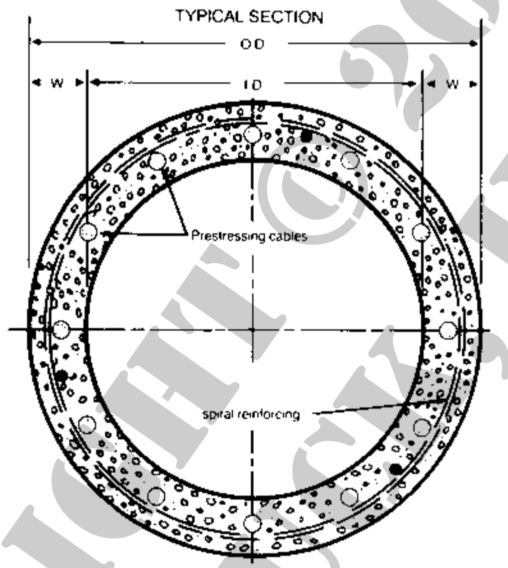
If prestressed piles are used, the minimum working net prestress in the pile should be 700 psi (4.83 MPa). Prestressing strands are of the ungalvanized seven-strand type conforming to the general requirements of ASTM designation A 416 and may be either regular or high-strength. Strand properties, manufacture and installation should conform to guidelines of the Prestressed Concrete Institute.[6]

The primary advantage of prestressed concrete piles versus conventional reinforced concrete piles is durability. Since the concrete is under continuous compression, hairline cracks are kept tightly closed and thus prestressed piles are usually more durable than conventionally reinforced piles. Another advantage of prestressing (compression) is that the tensile stresses, which can develop in the concrete under certain driving conditions, are less critical. These piles are best suited for friction piles in sand, gravel, and clays.

2.1.2.2.3. Prestressed Cylinder Piles

Prestressed cylinder piles, originally developed by Raymond, are post-tensioned piles that are spun cast in sections, bonded with a plastic joint compound, and then post-tensioned in lengths containing several segments. Special concrete is cast by a process unique to cylinder piles that achieves high density and low porosity. The pile is virtually impervious to moisture. Results of chloride ion penetration and permeability tests on prestressed cylinder piles

Table 2-11 Dimensions and Properties of Prestressed Cylinder Piles



CYLINDER PILE DESIGN PROPERTIES

SIZE O.D.	SIZE I.D.	SIZE W	A_c	I	S	r	CIRCUM-FERENCE	POINT AREA	WEIGHT PER FOOT (a)	STRESS ON CONCRETE DUE TO EFFECTIVE STRESS PER CABLE (b) Wire (c)	Strand (d)
in.	in.	in.	in.²	in.⁴	in.³	in	ft	ft²	lb	lb/in.²	lb/in.²
36	27	4½	445	56,360	3,130	11.3	9.43	7.07	479	116.1	110.5
* 36	26	5	487	60,000	3,330	11.1	9.43	7.07	524	106.1	100.9
42	32	5	581	101,300	4,820	13.2	11.00	9.61	625	89.0	84.6
48	38	5	675	158,200	6,590	15.3	12.57	12.57	726	76.6	72.8
* 54	44	5	770	233,400	8,640	17.4	14.14	15.90	829	67.1	63.8
54	42	6	905	264,600	9,800	17.1	14.14	15.90	973	57.1	54.3
60	49	5½	942	353,200	11,770	19.4	15.71	19.63	1014	54.9	52.2
* 66	54	6	1131	514,000	15,580	21.3	17.28	23.76	1217	45.7	43.5
72	60	6	1244	683,000	18,970	23.4	18.85	28.27	1339	41.5	39.5
78	65	6½	1460	940,700	24,120	25.4	20.42	33.18	1572	35.4	33.7
84	70	7	1693	1,265,300	30,130	27.3	21.99	38.48	1823	30.5	29.0
90	76	7	1825	1,582,900	35,180	29.5	23.56	44.18	1964	28.3	26.9

*STANDARD SIZES

NOTES:

(a) The tabulated weights, intended for design purposes, are based on a unit weight of concrete of 155 lbs/ft³ and the nominal wall thicknesses. For handling purposes, allowance should be made for manufacturing tolerance in extra wall thickness with corresponding increase in weight per foot.

(b) Number of prestressing cables ranges from 8 to 16 for 36" piles, 12 to 24 for 54" piles, and 16 to 32 for 66" piles.

(c) Each prestressing cable consists of twelve 0.192"-diameter stess-relieved wires with initial stress of 175,000 psi (60,801 lbs) and effective stress of 148,750 psi (51,681 lbs).

(d) Each prestressing cable consists of two ½"-diameter 270 ksi 7-wire strands with initial tension of 57,820 lbs and effective tensionof 49,150 lbs.

indicate that the spun cylinder piles have excellent resistance to chloride intrusion. Table 2-11 shows the typical configuration of prestressed cylinder piles and provides appropriate engineering design data. Figure 2-12 shows typical details of cylinder pile reinforcement. Generally, cylinder piles are used for marine structures or dry land trestles. The piles typically extend above ground and are designed to resist a combination of axial and lateral loads. They are available in diameters of 36" (914.4 mm) to 90" (2286 mm).

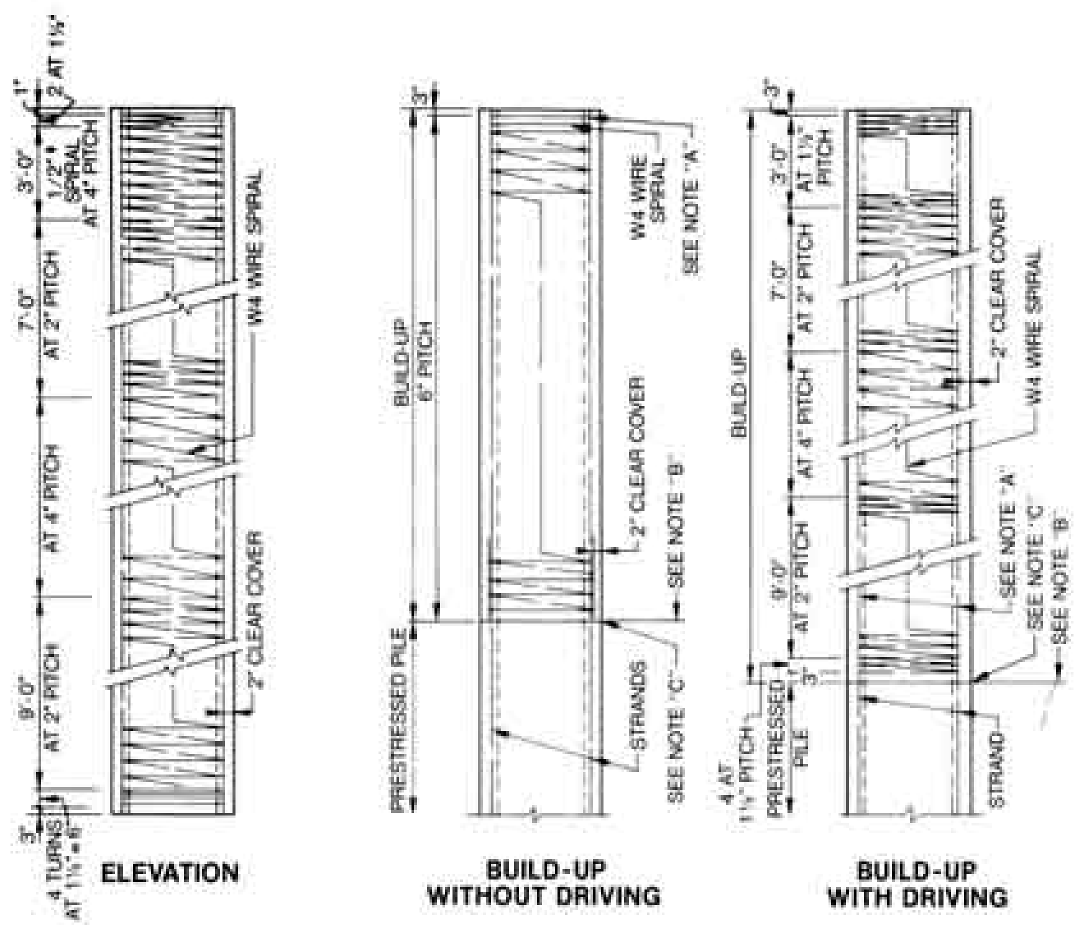
2.1.2.2.3.1. Pretensioned Spun Concrete Piles

A relatively new type of concrete pile is the pretensioned spun concrete pile, a cylindrical pile with a void. It is geometrically similar to cylinder piles but the manufacturing process has some differences.

These piles are manufactured as follows:

1. The strands are straightened from coil and cut to the desired length. Their ends are button headed for the prestressing machine. The spiral wire is automatically wound around and welded to the strands. The cage is then placed into the bottom half of the mould.
2. Concrete is fed into the bottom half mould, after which the top half of the mould is bolted to its mate.
3. The longitudinal strands are then prestressed against the mould through a central shaft. This operation insures uniformity of stress in all of the bars and contributes to the straightness of the pile.
4. The pile is then spun in the mould. While forcing the concrete to the sides of the mould and thus giving the pile its tubular shape, this also squeezes water out of the concrete,

Figure 2-12 Typical Details of Cylinder Pile Reinforcement



Notes on Build-up

Note A: The minimum area of reinforcing steel shall be 1½ percent of the gross cross-section of concrete. Placement of bars shall be in a symmetrical pattern of not less than eight bars.

Note B: Method of attachment of pile to build-up may be by any of the methods given in the notes on alternate pile heads. If mild reinforcing steel is used for attachment, the area shall be no less than that used in the build-up.

Note C: Concrete around top portion of driven pile shall be bush-hammered to prevent feather edges in the cast-in-place build-up.

increasing the strength of the pile.

5. The pile is removed from the mould using a vacuum lifter.
6. The pile is cured in an autoclave, which advances curing further and prevents the driving of uncured piles.

Pretensioned spun concrete piles can be obtained in diameters from 250 mm (9.8") to 1000 mm (39.4"), and in lengths up to 46 m (151'). They include a provision for splicing and can be cut off with the usual methods.

2.1.2.2.1. Material Specifications

2.1.2.2.1.1. Aggregates

Concrete aggregates should conform to "Specification for Concrete Aggregates" (ASTM C 33) or to "Specifications for Lightweight Aggregates for Structural Concrete:" (ASTM C 330); except that aggregates failing to meet these specifications, but which have been shown by special test or actual service to produce concrete of adequate strength and durability, may be used with the approval of the governing authority. [7]

2.1.2.2.1.2. Water

Water used in mixing concrete should be clean and free from injurious amounts of oils, acids, alkalis, salts, organic materials, or other substances that may be deleterious to concrete or steel. Mortar cubes made with nonpotable mixing water should have 7- and 28-day strengths equal to at least 90% of the strengths of similar specimens made with potable water.

2.1.2.2.1.3. Admixtures

Air-entraining admixtures should be considered where concrete piles are exposed to conditions of freezing and thawing. When used, air-entraining admixtures should conform to "Specification for Air-Entraining Admixtures for Concrete" (ASTM C 260).

The amount of air entrainment and its effectiveness depend on the admixture to be employed, the size and nature of the coarse aggregate, its moisture content, and other variables. Too much air will lower the strength of the concrete and too little will reduce its effectiveness. It is recommended that the air content of concrete is to be in the range of 4 to 7%, depending on the size of the coarse aggregate.

Air-entraining admixtures are less effective when used with low slump, high strength concrete. Furthermore, the need for air entrainment is reduced in high strength concrete because of its high density and low porosity. For this reason, the designer should carefully evaluate the site conditions compared to the pile quality specified before making a decision regarding air entrainment.

When used, water-reducing admixtures, retarding admixtures, accelerating admixtures, water reducing and retarding admixtures, and water reducing and accelerating admixtures should conform to "Specification for Chemical Admixtures for Concrete" (ASTM C 494). Calcium chloride or admixtures containing calcium chloride should not be used.

2.1.2.2.1.4. Concrete Quality

Concrete in precast prestressed piles and build-ups to be driven should preferably have a minimum compressive cylinder strength (f'_c) of 5000 psi at 28 days. Economy in handling and driving along with higher load capacity can be achieved with concrete strengths up to 8000 psi. Designers should check with local pile manufacturers to determine optimum strengths.

For acceptable durability, concrete piles should have at least six sacks of cement per cubic yard of concrete. The water-cement ratio (by weight) should correspond to the least water that will produce a plastic mix and provide the desired workability for the most effective placement of the concrete.

2.1.2.2.1.5. Reinforcement

All steel wires, prestressing strands and reinforcements, unless otherwise stipulated, shall conform to applicable ASTM standards.

2.1.2.2.1.6. Grout

Cement grout where used in prestressed piles should be of materials which conform to the requirements stipulated herein for cement, sand, admixtures, and water. Approved expanding admixtures or expansive cements may be used. Sand and cement grouts are generally used when grouting dowels into holes in heads of piles, sometimes with expanding admixtures.

Some expanding admixtures contain calcium chloride and should be avoided. Neat cement grout is frequently used to grout dowels in pile heads[8].

2.1.2.2.1.7. Anchorages

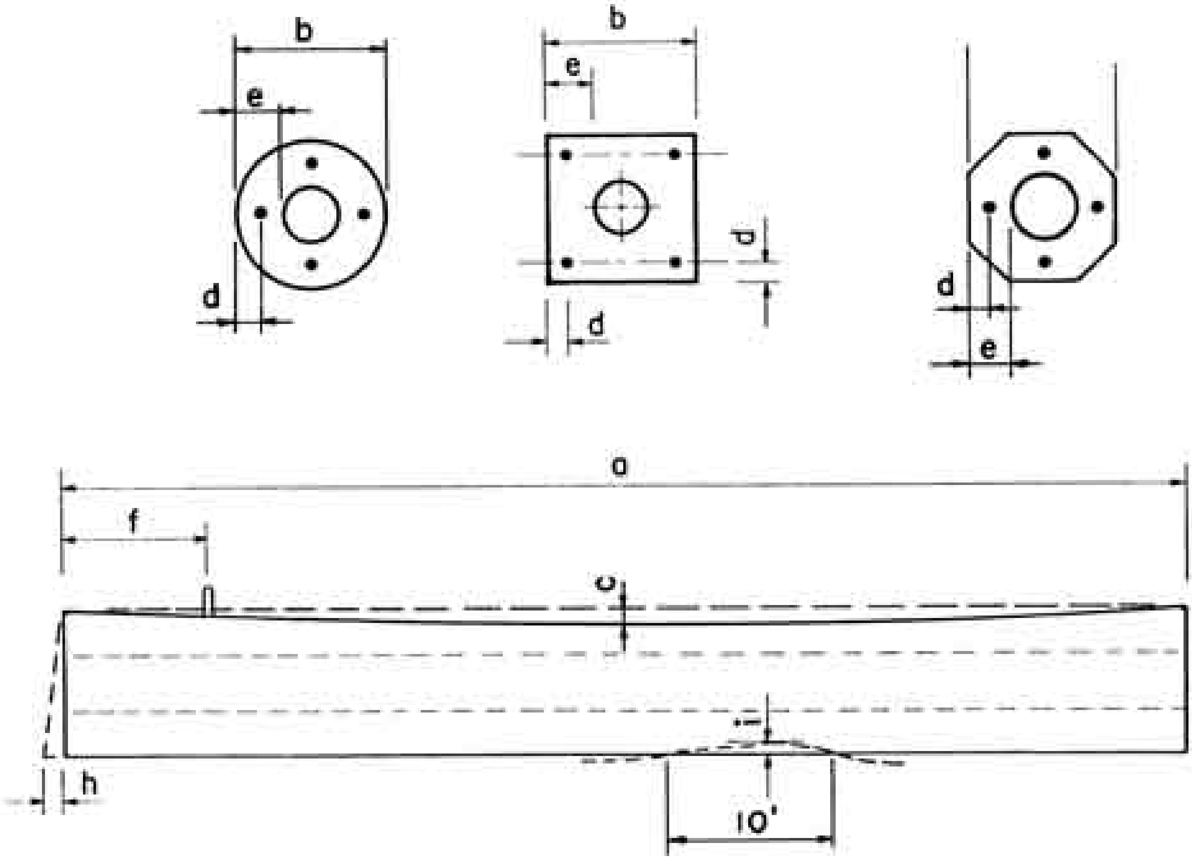
Anchorage fittings for post-tensioning assemblies should conform to the latest ACI 318, Building Code Requirements. ACI post-tensioning specifications may also be used for guidance.

2.1.2.2.2. Forms and Casting

Precast and prestressed concrete piles are usually cast at off site yards and hauled to the site by truck or barge. They are made in forms 400-600' (122-183 m) or more in length. This has the advantage of good manufacturing control; it has the problem of moving long, heavy units some distance through congested areas. Prestressing wires are pretensioned across this length by hydraulic jacks. Bulkheads are set in the form to make the desired length of pile; prestressing wires go through the bulkheads, which serve as spacers. Spiral reinforcing is slipped over the strands during stringing and distributed before placing the bulkheads. Forms for casting piles are preferably relatively permanent and made of steel or other reusable material. Provision should be made to chamfer edges and corners of the piles, except where reinforcement may protrude through an end. Reinforcement must be spaced away from the pile faces by small cement blocks or by metal chairs with plastic tips. Lateral bars must be effectively tied to the longitudinal steel. Figure 2-13 shows tolerance dimensions for concrete piles.

Hydraulic jacks must stress prestressing strands uniformly. An accurately calibrated gage incorporated in the system permits stress computation at any time. Elongation should be measured at completion

Figure 2-13 Tolerance Dimensions for Precast and Prestressed Concrete Pile



a = Length* .... ± 1 in.

b = Width or diameter .... ± 3/8 in.

c = Sweep (variation from straight line parallel to centerline of member) (considered to be a form tolerance) .... ± 1/8 in. per 10 ft

d = Position of tendons .... ± 1/4 in.

e = Wall thickness .... – 1/4 in., +1/2 in.

f = Position of handling devices .... ± 6 in.

g = Position of steel driving tips .... ± 1/4 in.

h = Variation from specified end squareness or skew .... ± 1/4 in. per 12 in., ± 1/2 in. max.

i = Local smoothness any surface .... ± 1/4 in. per 10 ft

j = Longitudinal spacing of spiral reinforcement .... ± 1/2 in.

* In most cases, controlling pile length to + 6 in., – 2 in. is functionally acceptable.
Note: 1 ft = 0.305 m; 1 in. = 25.4 mm.

of stressing and at time of placing concrete; it should conform to elongation tables furnished by the manufacturer of the strand. Strands must be kept free of oil and other substances harmful to the concrete bond. Some discoloring of the strand may not be harmful but corrosion must be prevented.

Concrete should be compacted by high frequency internal or external vibrators; contact of vibrators with prestressing strands should be kept to a minimum. Full tension on the strands shall be maintained until test cylinders, cast and cured under the same conditions as the piles, indicate strength of at least 4,000 psi. Pretension in the strands or wires must be released from the anchorage gradually and uniformly. Burning strands in alternate locations, rather than all strands across one side does this. When released from elongation strands expand and grip the concrete; full tension may not be achieved for the initial 50 diameters of the strand length at both pile ends.

Points at which piling are to be lifted or supported should be clearly apparent. When other picking methods are used (inserts, slings, vacuum pads) suitable markings to indicate correct support points should be provided. When not specified otherwise, the two pick-up points on a precast concrete pile should be 21% of the length from both head and toe.

For long columns for bridge piers and for offshore towers large diameter, open-centre piles are centrifugally cast in about 16’ (4.88 m) lengths. Post-tensioning wires are inserted through openings formed in the 4 or 5” (127 mm) thick walls to develop the required lengths, which may be over 200’. Additional information is available from PCI and from the producers.

2.1.3. Timber Piles

Evidence of structures supported by timber piles can be traced back to Switzerland some six thousand years ago. Timber piles have been used in North America since the mid-eighteenth century and even to this day, are still very important to the foundation designer despite the inroads made by manufactured materials. An historical application of timber piling – that of major bridges – is shown in Figure 2-14.

Figure 2-14 Timber Piling Driven for a Bridge

Historically, almost all types of wood have been employed for piling purposes at one time or another. Two species however, now account for over 90% of the usage and are the basis for which most standards concerning timber piles are written. These species are Southern pine and Douglas fir.

Southern pine is grown mainly in the southern United States and consists of four sub-species: longleaf, loblolly, slash and short leaf. Douglas fir is a product of the Northwest Coast with the preferred product for piling identified as "Coastal" Douglas fir.

Some specialty timber is imported from the tropics for marine piling applications. Greenheart, imported from South America, is one such species. It features high strength and superior resistance to decay and to attack by marine borer organisms.

Timber piles are processed as clean-peeled (all outer bark and 80% of inner bark removed) rough peeled (all outer bark removed) and un-peeled (all bark retained). Piles that are to be further treated with preservatives must be clean-peeled.

Timber piles are frequently installed un-peeled and untreated. These are generally for use in temporary structures or installations with a planned short-service life. However, the majority of timber piles are now treated with wood preserving chemicals to extend their life.

Sawed timbers are very rarely used for piling, therefore timber piles are always round and tapered, which is an efficient shape for a pile.

2.1.3.1. Sizes of Timber Piles

Table 2-13 and Table 2-14 relate circumference at the toe of the pile to head circumference for ten-foot length increments up to 120' (36.6 m).

- Table 2-13 is to be used when the toe dimension is specified and the minimum circumference of the head is desired.
- Table 2-14 is used when the head dimension is specified and the corresponding toe dimensions are needed.

In the case of end-bearing timber piles, the toe dimension is more important since most of the load will be transferred to the toe. In the case of a true friction pile, the head dimensions are more critical since most of the load will theoretically be transferred to the soil long before reaching the toe. By utilizing the two charts, the timber industry can more efficiently match timber shapes to the requirements of the design.

Circumferential dimensions are used since it is difficult to accurately measure diameters of a tree trunk. Head dimensions listed are for a location 3' (914 mm) from the true head (since the butts are trimmed for driving and cut-off later.

2.1.3.1. Quality

Timber for piling should be of sound wood and free from decay and insect damage. Other possible defects are identified as follows:

- A check is a separation of the wood extending across the growth rings from the surface toward the centre but not completely across the section. A check should not extend any further than the pitch (centre core).
- A shake is a circumferential separation of the rings of growth. The lengths of shakes in the head of the pile are limited.
- A split is a lengthwise separation of the wood across the growth rings but extending from one surface to the other. Splits may not be any longer than the diameter of the head.
- Knots are, of course, the source of limbs, which have been trimmed from the trunk. Restrictions are imposed on the sizes and depth of knots based on being classed as "sound" or "unsound."
- Straightness requires that a straight line from center of head to center of toe must lie entirely within the pile body.

2.1.3.1. Preservative Treatment

In the past, timber piles, which have remained continually wet due to their location below the ground water table, have proven to have a practically indefinite service life. Conversely, timber piles subject to a fluctuating water table or exposed to attack by insects, fungi or marine woodborers have shown rapid deterioration. The subject of proper and effective preservation treatment for timber piles is therefore very important to a potential owner or specifier of timber piles.

Attempts to prevent deterioration by surface treatment can be traced to ancient engineers who used various oils or pitch for surface treatment of some of their structures. Modern wood preserving began in England in 1832 with a process using mercuric chloride.

Pressure injection of creosote began in England in 1838. A plant was opened in Massachusetts, using imported creosote, in 1865. The usage of creosoted timbers for railroad ties and pile-supported structures grew rapidly with the expansion of the railroads. Thus, so did the number of creosote treating plants. In 1904, the American Wood Preservers Association was founded. This group, composed of timber growers, industry representatives, engineers, educators, and piling users has been responsible for developing wood preservation into an effective and reliable science.

2.1.3.2. Environmental Concerns

There are no materials that are immune to attack by at least some elements of the environment. Timber, in its natural state, is attacked by insect pests, fungi, decay and disease. Once trees are cut and converted to products for the building trades, wood is still vulnerable to most of the same problems in addition to some new ones. These problems have been identified and protection for each developed and improved over the years. An important task of the piling designer is to identify potential deterioration mechanisms and

Table 2-12 Advantages and Disadvantages of Timber Piles

Advantages	Disadvantages
Low cost, per ton of capacity.	Cannot be spliced to extend lengths.
Dependable, renewable supply – available in a range of lengths and sizes.	More vulnerable to driving damage.
Long history of successful application to low and medium unit loads.	Vulnerable to deterioration from a number of natural sources unless effective protection is provided.
Easily handled and driven with conventional equipment.	Restrictive properties regarding strength, sizes and lengths.
Tapered shape and full displacement characteristics advantageous for developing soil capacity in shorter lengths.	
Strength in tension and bending applications.	

Table 2-13 Specified Butt Diameters with Minimum Tip Circumferences[9]

Specified Butt Diameters, in.	7	8	9	10	11	12	13	14	15	16	18
Required Minimum Circumference 3 ft from Butt	22	25	28	31	35	38	41	44	47	50	57
Length, ft	Minimum Tip Circumferences (in.) and Corresponding Diameter in Italics										
20	16.0	16.0	16.0	18 0	22.0	25.0	28.0				
	5.0	5.0	5.0	5.7	7.0	8.0	8.9				
30	16.0	16.0	16.0	16.0	19.0	22.0	25.0	28.0			
	5.0	5.0	5.0	5.0	6.0	7.0	8.0	8.9			
40				16.0	17.0	20.0	23.0	26.0	29.0		
				5.0	5.4	6.4	7.3	8.3	9.2		
50					16.0	17.0	19.0	22.0	25.0	28.0	
					5.0	5.5	6.0	7.0	8.0	8.9	
60						16.0	16.0	18.6	21.6	24.6	31.6
						5.0	5.0	5.9	6.9	7.8	10.0
70						16.0	16.0	16.0	16.2	19.2	26.2
						5.0	5.0	5.0	5.1	6.1	8.3
80							16.0	16.0	16.0	16.0	21.8
							5.0	5.0	5.0	5.0	6.9
90							16.0	16.0	16.0	16.0	19.5
							5.0	5.0	5.0	5.0	6.2
100							16.0	16.0	16.0	16.0	18.0
							5.0	5.0	5.0	5.0	5.8
110										16.0	16.0
										5.0	5.0
120											16.0
											5.0

Table 2-14 Specified Tip Diameters with Corresponding Minimum Butt Circumferences

Specified Tip Diameter in.	5	6	7	8	9	10	11	12
Tip Circumference, Required Minimum	16	19	22	25	28	31	35	38
Length, ft	Minimum Circumferences 3 ft from Butt in. with Diameter in Italics.							
20	22.0	24.0	27.0	30.0	33.0	36.0	40.0	43.0
	7.0	7.6	86	9.5	10.5	11.5	12.7	13.7
30	23.5	26.5	29.5	32.5	35.5	38.5	42.5	45.5
	7.5	8.4	9.4	10.3	11.3	12.2	13.5	14.5
40	26.0	29.0	32.0	35.0	38.0	41.0	45.0	48.0
	8.3	9.2	10.2	11.1	12.1	13.0	14.3	15.3
50	28.5	31.5	34.5	37.5	40.5	43.5	47.5	50.5
	9.0	10.0	11.0	11.9	12.9	13.8	15.1	16.0
60	31.0	34.0	37.0	40.0	43.0	46.0	50.0	53.0
	9.8	10.8	11.8	12.7	13.7	14.6	15.9	16.8
70	33.5	36.5	39.5	42.5	45.5	48.5	52.5	55.5
	10.6	11.6	12.6	13.5	14.4	15.4	16.7	17.7
80	36.0	39.0	42.0	45.0	48.0	51.0	55.0	58.0
	11.4	12.4	13.4	14.3	15.3	16.2	17.5	18.4
90	38.6	41.6	44.6	47.6	50.6	53.6	57.6	60.5
	12.2	13.2	14.2	15.1	16.0	17.0	18.3	19.2
100	41.0	44.0	47.0	50.0	53.0	56.0	60.0	
	13.0	14.0	15.0	15.9	16.8	17.8	19.0	
110	43.6	46.6	49.6	52.6	55.6	61.0		
	13.8	14.8	15.7	16.7	17.7	19.4		
120	46.0	49.0	52.0	55.0	58.0			
	14.6	15.6	16.6	17.5	18.4			

specify appropriate protection.

Timber foundation piles are used extensively on land to provide support for buildings, floor systems, machinery, equipment, retaining walls, storage tanks and bridge piers. This usage results in the pile being driven into the soil, with (the toe and part of the pile generally below the water table) and the head end "encased" with a concrete slab or footing. Piles for these applications are generally the least affected by the environment. A fluctuating water table however, could contribute to decay of untreated wood. Furthermore, the interface of pile to concrete and the disturbed area directly below is a potential site for fungi. It is now common practice to treat the entire pile with at least the minimum treatment shown in AWPA Standard C1 and C3 which lists creosote, creosote-tar solution, creosote-petroleum, pentachlorophenol, ammonical copper arsenate, and chromated copper arsenate as preservatives for selection. The purpose of this treatment is to prevent moisture from reaching the wood that would inhibit decay from wetting and drying cycles, and also provide an inhospitable environment for wood-destroying organisms.

Timber piles are used extensively in fresh water as well as on land for marina piers, railroad and highway trestle bents, supporting buildings above the flood plain, shear fences, and other applications. These piles are partially embedded in soil and partially exposed to water, air, or both, Timber piles in fresh water have no organic enemies as long as the pile is continuously wet. Splash and fluctuating water levels will result in wetting and drying periods that could result in deterioration at those locations. Untreated timber piles exposed to air are vulnerable to inspect attack; on land, the interface between ground and atmosphere is also a potential problem area. In any case, when one comes in contact with any of these situations, timber piles should probably be treated 100% (the full length) as spot treatment would prove impractical.

Land and fresh water piles should be treated in accordance with the requirements of AWPA Standard C1. Table 2-15 shows the difference between retention quantities intended for land and fresh water foundations and marine piling applications

Table 2-15 Minimum Retention, Pounds per Cubic Foot for Various Types of Timber Piling

	RETENTION PCF (MIN.) Southern Pine			Douglas Fir		
	Foundation	Land and Water	Fresh Marine	Foundation	Land and Water	Fresh Marine
Creosote and creosote solutions						
Creosote	12.0	12.0	20.0	17.0	17.0	20.0
Creosote-coal tar Creosote-petroleum	12.0	12.0	20.0	17.0	17.0	20.0
Oil-borne Preservatives						
Pentachlorophenol	0.60	0.60	N.A.	0.85	0.85	N.A.
Water-borne Preservatives						
ACA	0.80	0.80	2.50 (a) 1.50 (b)	1.00	1.00	2.50
CCA	0.80	0.80	2.50 (a) 1.50 (b)	1.00	1.00	
Penetration in inches of wood, min. and/or sapwood.	3.0 or 90	3.0 or 90	3.5 or 90	0.75 (c) and 85	0.75 (c) and 85	Variable see C3

(a) Zone 1
(b) Zone 2
(c) Up to Max of 1.60

2.1.3.3. Marine Applications

Timber piles are used extensively along the coasts in salt and brackish water for marine construction, commercial docks and piers, navigation devices, trestle bent bridge construction, mooring and turning posts, bridge protection and others. In addition, timber in marine environments are exposed to a variety of organisms which either feed directly on the wood or drill into it for nesting purposes. Woodborers are divided into two families, mollusks related to the clam, and crustaceans related to crabs or shrimp. Mollusks include teredinids (shipworms). These feed on and live in untreated wood. Within a year of infestation, they may grow to an inch in diameter and four feet long. Attack is generally heaviest near the mud line. Pholads, another mollusk, resemble minute clams and do not burrow as deep. Teredinids, including teredos and bankia, can be found along the entire coastline regardless of temperature or salinity. The crustacean branch includes Limnoria, of which there are many species and Sphaeroma, which use the wood only for shelter. Limnoria are responsible for the hourglass shape of piling as seen along the coast. Limnoria lignorum are colder water species found in coastal waters of the northeast and northwest. Limnoria tripunctata favors warmer water from Virginia southward on the East coast, San Francisco southward on the West Coast and all of the Gulf Coast. In the warmer water, this borer is very tolerant of creosote and therefore other means of discouragement have had to be employed. Sphaeroma is reported to be widespread on the Florida and Gulf coasts, particularly in brackish waters, however this borer is normally not the source of severe damage.

The AWPA has especially focused on piles for marine environments, having published their "Standard for Pressure-Treated Material in Marine Construction," C18 and also Standard C 2-85, "Lumber, Timbers, Bridge Ties and Mine Ties – Preservative Treatment by Pressure Processing," Table 2-16 summarizes the type treatment suggested for the four most common marine borers.

Table 2-16 Preservative Treatment for Lumber and Timber Exposed to Marine Borers

Marine Borer	Preservative Type and Retention (pcf)		
	CREOSOTE	CCA-ACA-ACZA	DUAL
Teredinids	25	2.5	1.5 & 20
L. Quadripunctata or Lignorum	25	2.5	1.5 & 20
L. Tripunctata	NR	2.5	1.5 & 20
Pholads	25	NR	1.5 & 20
Spaeroma	25	NR	1.5 & 20

CCA = Chromated Copper Arsenate
ACA = Ammoniacal Copper Arsenate
ACZA = Ammoniacal Copper Zinc Arsenate
NR = Not Recommended
Duel = Combined Treatment

Creosote is and will probably remain the predominate treatment for wood piling. It is sometimes combined with coat-tar in solution. Pentachlorophenol (Penta) is combined with oil to provide an alternative to creosote. However, Penta cannot be used in salt-water applications. Metallic salts identified as CCA (chromated copper arsenate,) ACA (ammoniacal copper arsenate, and ACZA (ammoniacal copper zinc arsenate) which are water-borne preservatives and are commonly used for protection of marine piling against borers or in combination with creosote in a dual treatment process. Some embrittlement of the wood fiber is a disadvantage of the metallic salt treatment.

Timber piles to be treated are clean-peeled, then dried and conditioned by steaming. Douglas fir is not steamed, but conditioned by another process. Preservative is forced into the wood under pressure. The retention of preservative is the key to adequate performance and the standards are very explicit about this quantity for various applications.

Dual treatment combines water-borne metallic salts (which deter certain specific marine borers that are immune to creosote) with creosote that deters other types.

It is obvious that unprotected timber piles are in jeopardy when installed in salt or brackish water. In addition, there have been effective means developed to prolong their life. The identification of the problems and the specification of protection is a part of the design process for these structures. Local experience and practice combined with the recommendations of those who know preservation treatment best is an appropriate method of handling the problem.

2.1.3.4. Specialty Woods

While the main theme of this chapter concerns foundation piling, timber has been used extensively for waterfront construction involving piles that function as foundation piles but also as part of the structure itself. Examples of this are timber piers and docks, trestle bents, shear fences, groins, jetties, dolphins, fenders and others. It was considered important to include some discussion of the specialty woods, particularly Greenheart. There are several origins for wood with this name.

Demerara Greenheart (Nectandra Rodioei) is so named because of the place where it is grown, which is the Demerara River area of Guyana, South America. The wood is characteristically very dense and consequently up to 3 times as strong as Douglas fir and Southern pine in bending and compression. The wood exhibits a very good resistance to marine borers and decay. This wood contains an alkaloid substance that deters marine organisms from attacking, but if attacked, the very dense heartwood is an additional deterrent to the borer. Demerara Greenheart piles are available in lengths up to 75' (22.9 m) Greenheart piles have not been commonly used for pure foundation pile because of cost, supply limitations and the fact that the longevity advantage is not generally a factor in underground installations.

It is said that the cost of Greenheart is about equal to properly creosoted conventional piling timbers. The resistance of Greenheart to attack by some of the more ferocious borers, particularly in warm or tropical waters is not well documented at this time.[10]

The service life of all wood piles can be expected to be curtailed in tropical waters, as is the case of most piling materials.

Other specialty woods, some bearing the general name "greenheart" are also imported for marine piling application and fendering systems. The designer who is contemplating the use of specialty piling woods should consult the supplier to insure that the wood he will get will fulfill the requirements of his design.

For reference, Table 2-17 shows test results of tests of Demerara Greenheart performed in 1987 in accordance with ASTM D-143.

Table 2-17 Test Results for Demerara Greenheart[11]

Property	Ultimate Strength, ksi	Allowable Strength, ksi
Bending Strength	8.3	3.943
Tension Parallel to Grain	7.55	3.586
Compression Parallel to Grain	10.75	5.403
Compression	8.85	2.159
Shear Parallel to Grain	0.95	0.634
Modulus of Elasticity	2990	2990
Unit Weight, kips/ft^3	0.0654	0.0654

2.1.4. Plastic Piling

Although, as shown above, both concrete and wood piling have features to prevent both decay and environmental degradation, both have limitations in this regard. To address these problems, especially for use with dock piling and marine fender systems, round recycled plastic piles have been developed. These range in diameter from 8” (203 mm) to 23 1/4” (590 mm), and can be made in lengths up to 120’ (36.6 m). They are manufactured from recycled plastic but, like concrete piles, have a reinforcing cage that can be steel, fiberglass, or a combination of the two. A pipe in the centre of the pile, in which case the pile is hollow, can also reinforce them. Their usual applications are marine piling, marine camels and marine lumber. Newer versions of these piles can also have a square cross section. They are designed to withstand both axial and lateral loads, including ship impact. They can be installed with any type of impact hammer.[12] An example of these piles in use is shown in Figure 2-15.

Figure 2-15 Plastic Composite Piling in Marine Application

2.1.5. Selection of Pile Type

General guidelines for the selection of a pile type are shown in Table 2-18, and Table 2-19. Table 2-18 provides pile type recommendations for various subsurface conditions. Table 2-19 shows the placement effects of pile shape characteristics. These are only general guidelines; specific project conditions and requirements may alter these substantially.

In addition to the considerations provided in the tables, the problem posed by the specific project location and topography must be considered in any pile selection process. The following are some of the problems usually encountered:

- Driven piles may cause vibration damage.
- Remote areas may restrict driving equipment size and, therefore, pile size.
- Local availability of certain materials may have decisive effects on pile selection.

Table 2-18 Pile Type Selection
Subsurface Conditions and Recommended Pile Characteristics

Typical Problem	Recommendations
Boulders overlying bearing stratum.	Use heavy nondisplacement pile with a point and include contingent pre-drilling item in contract.
Loose cohesionless soil.	Use tapered pile to develop maximum skin friction.
Negative skin friction.	Use smooth steel pile to minimize drag adhesion, avoid battered piles. Use bitumen coating for piles.
Deep soft clay.	Use rough concrete piles to increase adhesion and rate of pore water dissipation.
Artesian Pressure	Caution required for using mandrel driven thin-wall shells as generated hydrostatic pressure may cause shell collapse: pile heave common to closed-end pile.
Scour	Do not use tapered piles unless large part of taper extends well below scour depth; design permanent pile capacity to mobilize soil resistance below scour depth.
Coarse Gravel Deposits	Use prestressed concrete piles where hard driving is expected in coarse soils. Use of H-piles in these deposits often results in excessive pile lengths.

Table 2-19 Pile Type Selection
Pile Shape Effects

Shape Characteristics	Pile types	Placement Effect
Displacement	Closed end steel pipe	Increase lateral ground stresses.
	Precast concrete	Densify cohesionless soils, remolds and weakens cohesive soils temporarily. Setup time for large pile groups in sensitive clays may be up to six months.
Nondisplacement	Steel H	Minimal disturbance to soil.
	Open End Steel Pipe	Not suited for friction pile in coarse granular soils because piles have a tendency to "run"
Tapered	Timber Thin-Wall Shells Monotubes	Increased densification of soil, high capacity for short length in granular soils

- Waterborne operations may dictate use of shorter pile sections due to pile handling limitations.
- Steep terrain may make the use of certain pile equipment costly or impossible.

Although one pile type may emerge as the only logical choice for a given set of conditions, more often several different types may meet all the requirements for a particular structure. In such cases, the final choice should be made based on a cost analysis that assesses the over-all cost of alternatives. This would include uncertainties in execution, time delays, cost of load testing programs, as well as differences in the cost of pile caps and other elements of the structure that may differ among alternatives. For major projects, alternate foundation designs should be considered for inclusion in the contract documents if there is a potential for cost savings.

2.2. Sheet Piles

Sheet piles are by definition, structural units which when connected one to another, will form a continuous wall, generally for retaining earth or excluding water. Interlocking devices formed as part of the manufactured product provide the wall continuity. Sheet piling has been made of steel, concrete, wood, aluminum and other materials. Steel is by far the dominant choice, due to ready availability, relative strength, and ease of handling, storage and installation, although the use of other materials is increasing.

- Bridge Protection Cells – to protect bridge piers from shipping collisions.

2.2.1. Steel Sheet Piling

Steel sheet piling is generally delivered to the project from the mill or from field-stocks in preordered lengths and stacked, ready for use. Individual pieces or pre-interlocked pairs are installed by driving using impact hammers, vibrators or by water jetting. Sheets are "threaded" one to another during the setting and driving operation so that a continuous, relatively soil and watertight wall is formed.

In functioning as a wall, the sheet piling acts as a beam under load and therefore must resist bending. In certain applications, ability to resist bending is not as important but strength of the interlock is.

Sheet pile shapes have evolved over the years from simple channel sections with crude fabricated locks, to "U" shapes with integral, rolled-on interlocks, to today's wide range of high strength "Z" shapes.

A successful sheet piling may be ideally described as one having shape and strength to stand up under impact driving, containing free-sliding interlocks which permit one sheet to be continuously connected to its neighbor, durable in order to provide the desired life, and having the structural capacity to safely resist the service loads anticipated.

2.2.1.1. Applications

Steel sheet piling applications include the following:

- Artificial Islands
- Bulkheads-including dock walls for marine terminal facilities in water
- Cofferdams – temporary, in water or on land to permit excavation for and construction of permanent works
- Cut-off Walls – in connection with earth or concrete dams or dikes to retard seepage
- Dry Dock Walls
- Retaining Walls
- Seawalls, Flood Walls, Dikes, Jetties, Groins
- Navigation Lock Walls and other large navigation structures
- Mooring and Turning Cells, Dolphins.
- Barge Docks – Consisting of Individual Cellular Structures

2.2.1.1. Types

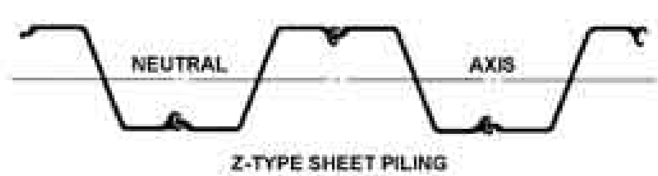
Steel sheet piling is manufactured in three basic configurations – "Z", "U" and "straight" (flat). Historically such shapes have been "hot-rolled" products of structural mills. Like other shapes such as beams or channels, they are formed during a succession of passes through different roll stands of the mill. In the case of sheet piling, the rolled-on clutch or interlock is an additional special feature of sheet piling production.

Some producers use a cold-forming process in which hot-rolled sheet steel is fabricated into traditional sheet piling shapes manufactures some sheet piling shapes. These new additions to product availability contain interlocks that are considerably different from the hot-rolled products. Cold-formed sheeting is manufactured from a hot-rolled coil of steel, and then is slowly fed through a series of rollers, which gradually bends or forms the steel into its designated shape.

2.2.1.1.1. Z-Type Shapes

The Z type configuration for sheet piling is the strongest and most efficient. These shapes resemble wide-flange beams, having a web and two flanges. The interlocks are located out on the flanges at maximum distance from the neutral axis, and this provides a high section modulus for resisting bending moments. Because of this, Z-shapes have traditionally been used for heavier construction projects. However, they are now complemented by the arch or U shapes for lighter work, and lightweight Z-shapes have been also introduced into the marketplace.

Figure 2-16 Z-Type Sheet Piling



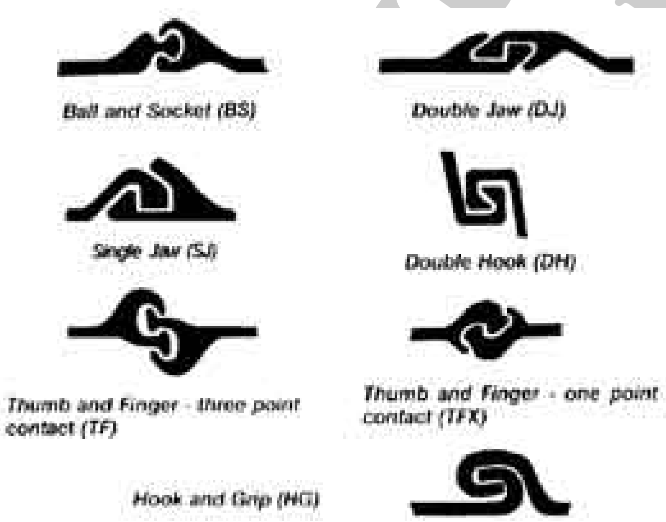
2.2.1.1.1.1. Interlocks

The interlocks of hot-rolled Z-type sheet piling are designed for free sliding and integrity during driving. Since most Z-piles are used to construct straight walls, there is generally no need for any guaranteed swing or deflection between sheets although there is almost always some attainable if needed, except perhaps in very long sheets. Sheet piling produced in the United States has been rolled with a "ball and socket" interlock design. Historically, it has been recommended that these be driven so that the ball of the interlock was leading. The socket then had a pre-cleared path into the ground. The importance of this recommendation has been properly questioned and many walls have been successfully installed without following this procedure. These inter locks are not designed for applications where resistance to tension is important. There are other shapes and interlocks specifically designed for tension applications, which will be discussed later in this chapter.

Although there are some general similarities in the styles, the interlocks provided on Z-piling available from European and Japanese producers vary with the producer. One manufacturer describes his lock as a "double jaw," each lock having a finger, a thumb and a socket formed by these elements. When interlocked, one thumb engages and is held in position by the fingers. Other manufacturers have designed "single-jawed" interlocks where one thumb engages the adjacent socket, and is restrained by the finger, similar to the ball and socket.

The interlocks of the cold-formed series of Z-Type shapes are best described pictorially in Figure 2-17. The forming process produces an interlocking structure on the end of each web, termed a "hook and grip."

Figure 2-17 Types of Interlocks for Sheet Piling



In general, whether the piling be foreign or domestic, the user should not assume sheets can be mixed on the job simply because the locks "look" the same. Tolerances may vary from producer to producer.

The interlocks of the heavier piling sections may not interlock with lighter ones from the same producer. The manufacturer should be consulted for accurate information. Specially fabricated pieces may be needed to change shapes or types in a run of wall.

Because of their inherent strength, Z-piles can be handled and shipped with less exposure to possible damage than some other style sheets. These interlocks do not lend themselves well to splicing and splices should be avoided if possible. Lengths up to 100' (30.5 m) have been produced and installed. However, these are difficult for the mills to process and ship and the manufacturer should be consulted regarding any requirement for lengths over approx. 65' (19.8 m)

Interlocks should be reasonably free sliding, that is, the pile should run to grade of its own weight when interlocked with its neighbor. The mills check interlock clearances and tolerances with templates and gauges as part of the inspection procedure prior to shipment. When "stickers" are encountered in the field, combinations of minor deficiencies such as camber or sweep in the piling length and interlocks, which may be on the edge of acceptable tolerance, could create a problem in installation.

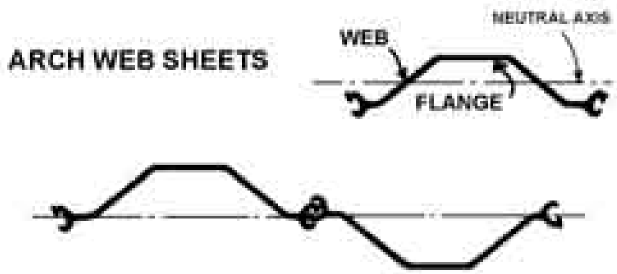
Domestic sheet piles have been typically identified by their weight per square foot. For example, PZ-27 is a Z-type weighting twenty-seven pounds per square foot of projected wall. This is obtained by dividing the piling weight, which is 40.5 pounds per foot, by the width of each sheet, which in this case is 1.5'.

Z-piles are generally used in constructing straight wall structures – cofferdams, bulkheads and retaining walls. Sheet piling can be pulled after temporary use, the interlocks cleaned and reconditioned and the sheets used again for similar applications. There is a large business in rental sheet piling and such considerations as delivery requirements, project duration, number of uses, re-sale values must be evaluated in order to affect the decision to rent or purchase.

2.2.1.1.2. Arch Web and U-Shape Piling

These shapes resemble the hot-rolled channel sections produced on structural mills. The interlocks are formed on the web ends and interlock with their opposing mate along the centerline of the wall. These shapes are not nearly as efficient as the Z-type for the equivalent weight. For example a typical arch web piling wall constructed of PDA-27 sheets weighs the same (per square foot) as a PZ-27 wall but has only about one-third the strength based on section modulus per foot of wall. The reason for this is the location of the interlocks on the centerline of the wall. Since shear transfer across the interlocks cannot be guaranteed, the wall strength is generally based on the properties of a single sheet, which greatly reduces the strength available for design purposes.[13]

Figure 2-18 Arch Web Sheets



Except for very shallow-arch shapes used primarily in circular cells, hot-rolled arch web sheet piling is no longer produced in the U.S. Some arch web profiles are available from the cold-formed producers, and European and Japanese makers still offer a complete line of hot-rolled U-shapes. Despite their inefficiencies, these shapes have survived because they are somewhat easier to work with in the field than the Z-sheets. The interlocks are looser and more swing per lock can generally be obtained when needed.

2.2.1.1.2.1. Interlocks

Interlocks of domestic arch-web sheet piling were of the "thumb and finger" design. The thumbs of opposing sheets were threaded into the sockets formed by the thumb and curved finger providing a strong grip and one of relatively good water and soil tightness. The standard installation procedure calls for reversing every other sheet. Occasionally either accidentally or to save space, contractors have laid the sheets up in singles by using the fingers rather than the thumbs to run in the slots. It is almost impossible to hold a straight line in this manner and those who have attempted it have had mixed success.

The German engineer Larssen based interlocks of foreign U-type piling on an historical interlock design. This interlock is best described as a "double-clutch" design and is considerably less complex than the thumb and finger design of American manufacture. There has not been much recent experience with foreign U-type sheet piling in this country. This is probably attributed to the ready availability of the more efficient Z-type shapes and the refusal of domestic engineering firms to recognize shear transfer across the locks, and thus the higher published strengths claimed by some producers.

Figure 2-19 Larssen Type Interlock

Arch web and U-type sheets may be somewhat easier to splice for extending lengths than Z-sheets. In addition, since these locks are somewhat looser, there is a smaller chance of binding during the setting and driving operation when dealing with extremely long lengths.

The interlocks of the series of arch web shapes produced by cold forming are of the "hook and grip" type previously described.

Arch-web shapes have been used primarily for lighter construction, for example, trench shoring, shallow cofferdams in water or on land, light bulkheads for marinas or river port facilities, shallow retaining walls and cut-off walls (where strength is less important than interlock integrity). Large "U" shapes have traditionally been popular in other parts of the world for all classes of construction, probably because Z-type sheets are a more recent addition overseas.

2.2.1.1.3. Flat and Shallow Arch Web Types

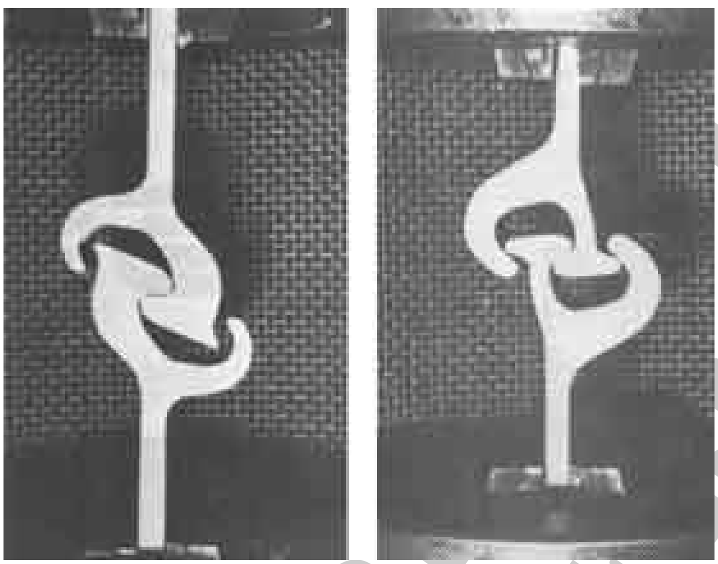
Whereas the Z-type and Arch-web type piling are used in applications where their resistance to bending is the "primary" consideration, there is another series of piling shapes that find their application in circular, freestanding structures called Filled Cells.

The sheets used in these applications are subjected to hoop tension from internal pressure exerted by the retained soil, rather than bending. As a result, the ability to transfer this stress across the interlocks is most important and these sheet pilings have interlocks specifically designed for such loads. When used to build these large, barrel-like structures, the individual sheets strongly resemble barrel staves. They are purposely designed as flat profiles so that they will not elongate and flatten across the arch as would be the case with the arch-web or Z-sheets.

2.2.1.1.3.1. Interlocks

The interlocks of this group are of the thumb and finger type, as shown in Figure 2-20. Opposing thumbs are threaded into the slots formed by the thumb and finger and under hoop tension. The sheets then form a continuous circular wall that is earth tight and relatively watertight. (Hoop tension is a function of the internal soil pressure and the cell radius). The manufacturer guarantees the strength between interlocked sheets so that designs can be prepared which will provide adequate safety factors against failure. It has been found that a three-point contact interlock is somewhat stronger than the one-point contact produced by some European producers. This may be important only when striving for higher than normal interlock strengths to meet special design requirements.

Figure 2-20 Straight Web Sheet Piling Interlock Types



There are two basic profiles produced for these circular applications. A shape having a slight arch and identified as PSA23 by its domestic manufacturer is recommended for smaller diameter cells. The interlocks are the lightest produced for these applications but are said to provide an ultimate strength of at least 12 kips per inch. The manufacturer suggests that design stresses be held to 3 kips per inch since the sheet may stretch under additional loading.

This piling section weighs only 23 pounds per square foot and is extremely economical if it can be used. Since interlock pull is a function of cell diameter, this sheet finds application for diameters up to about 45' (13.7 m).

Several heavier sections are available with higher interlock strengths. A domestic manufacturer offers one weighing 27.5 pounds per square foot with ultimate interlock strength of 16 kips per inch of interlock. A similar shape but with slightly thicker web for corrosion allowance or hard driving is also offered at 31 pounds per square foot. An interlock with a pull of 28 kips per inch was developed several years ago to meet the demand for larger cell construction. Using high strength steel and thickening the restraining finger accomplished this. The limited market and the difficulty of manufacture apparently contributed to the decision to abandon production several years ago. Sheet piling of this grade is still available from at least one foreign producer. It should be noted that it is possible to special order interlock strengths over the standard 16 kips.

In order to turn arcs and close circles, flat or shallow arch piling is manufactured to provide a "swing" of approx. 10° between sheets. This available swing may be reduced when working with longer sheets, however, chances are if you're working with longer sheets, the cell is probably of a large diameter, and 2 or 3° may be all that is needed. Where swing between sheets will exceed the manufacturer's recommendation, bent sheets must be used to insure closing the arcs.

2.2.1.1.3.2. Applications

Filled cells built of sheet piling become large, free standing gravity structures capable of withstanding large overturning moments and sliding forces from external loads. An example of this is shown in Figure 2-21.

The flat sheets are threaded to continuously connect with each other around a circular guide template. This "barrel" is then filled with select material such as sand, sand-gravel or rock. Filled cells generally must be built on rock, hard clay or driven into sand or gravel. When used as single cells in diameters from about 15' (4.6 m) to 65' (19.8 m) they can function as artificial islands, dolphins, mooring structures and navigational lock walls.

Their primary application however is for deep-water cofferdam construction and in bulkheads, piers or other waterfront construction where the water is deep and the loads are high. In this case, individual cells are built and connected to each other with intermediate connector cells. The result is a continuous wall of steel and fill. Temporary cofferdams can be dismantled and the piling reused many times. It should be pointed out that manufacturer warranties extend to the first use only. The sheets of one manufacturer should not be randomly interlocked with another's even though they thread easily. Interlock strength is a function of the interlock dimensions. Tolerance gauges are used by the mill in their inspection procedures and are backed by laboratory pull tests on representative samples. If any sheets seem loose or sloppy with any tendency to separate, even for a short length, then all sheets should be closely inspected before use.

Figure 2-21 Cellular Cofferdam

The cold-formed process does not produce flat sheets since the required strength in tension cannot be attained with the typical "hook and grip" interlock.

2.2.1.2. Grades of Steel Sheet Piling

In the United States, sheet piling is specified by reference to the ASTM standard. The basic grade is A-328. This requires that the yield strength be a minimum of 38.5 ksi. Higher strength steels are available in ASTM Grades 50 and 60 which have minimum yields of 50 ksi (345 MPa) and 60 ksi respectively. This permits possible economies in meeting calculated bending moments by combining lighter sections with higher strength steel.

An additional grade of steel for piling has been developed for possible use where corrosion from salt water is a consideration. This grade is ASTM A-690 which is a 50 ksi (345 MPa) yield steel and also of a formulation which has demonstrated increased life in salt-water splash zones compared to regular grades.

Allowable stresses for design of sheet pile structures are generally based on about 65% yield (25 ksi for the standard A 328 grade). Proportionately higher allowable stresses of 32 ksi and 38 ksi respectively are allowed for the higher strength grades. Some increase is generally allowed for temporary stresses.

2.2.1.3. Other Wall Systems

Economic considerations as well as mill facility limitations dictate just how big a sheet piling shape can be produced and marketed, regardless of short-term demand. The mills have done a good job of keeping up with the need for sheet piling for deeper port facilities – as well as larger and deeper cofferdams. The strongest Z-type shape offered by any manufacturer (European) currently has a published section modulus of 78 cubic inches per foot of wall.

One domestic manufacturer offers a Z-type having a section modulus of 60.7 cubic inches per foot of wall. A pile this large combined with high strength steel could be expected to handle all but the most severe design requirements. To address exceptional situations, one European producer has developed a wall system employing wide-flange beams with interlock devices rolled into the flange edges. These are combined with Z-shapes to form a wall, which benefits from the use of a very efficient wide-flange beam to provide higher section moduli at less weight per foot of wall. Various combinations are offered which give a wide selection of solutions.

Traditionally, producers of U-shaped sheets have offered fabricated master piles to stiffen deep bulkhead walls and provide very large moments of inertia at the expense of weight and fabrication costs. In the United States, deep construction was generally designed around wide flange beams with the wall continuity maintained by welding pieces of piling interlocks to the beams. These structures were sometimes difficult to build although with more experience, some recent structures have turned out very well for both owner and contractor.

2.2.1.4. HZ Walls

Wide flange beams are the most efficient structural units for handling loads that result in bending moments developing. A wall constructed entirely of interlocking wide-flange beams would be very difficult to construct and would be inefficient from the standpoint of wall face coverage. A system has been developed which combines wide flange beams with Z-type sheet piling to provide a wider range of section moduli. The basic layout combines one wide flange with two light Z-shapes as the basic unit as shown in Figure 2-22 and Figure 2-23. By including wide flange in the unit, elevated section moduli, well above anything attainable from plain sheets, can be realized. The system is not quite as efficient as a conventional wall when bending moments are less than about 2 million inch-pounds, since these can be handled with "as-rolled sheets" and high strength steel. An alternate to the proprietary HZ system for deep-water design is to utilize wide flange beams to stiffen a conventional Z-pile wall. Either the beams are welded to pairs of Z-sheets or portions of the Z sheet are slit and welded to the beam flanges to provide an interlock. Very high section modulus can be obtained using these methods.

Figure 2-22 Master Pile Section

Figure 2-23 Master Pile Wall

2.2.1.5. Anchor Systems

The top support for the sheet pile wall is provided by the anchor system. Typical anchor systems are shown in Figure 2-24. The reaction obtained during the design is transferred from the wall to the anchors by structural steel wales generally fastened to the rear of the wall by bolting. Occasionally, wales are located on the outboard face of the wall but for working bulkheads, they are best placed on the inside face. Wales generally consist of two channels, back to back, with spacers.

Tie rods, spaced at regular intervals, extend from the face wall through the wales to an anchor wall or anchor piles to the rear. Depending on the loads per rod, tie rod spacing is generally an even multiple of the driving distance (width) of a pair of sheet piles to facilitate installation. Tie rods are fabricated from steel bars, the ends upset to provide additional metal at the threads, and assembled on the job with holding plates, washers, nuts and turnbuckles. Tie rods should be located as close to the low water elevation as possible to reduce the span between supports, but should be above water to facilitate installation. The dead man or rear anchor wall should be located well outside the influence of the active failure zone of the soil against the front wall. Tie rods should be coated and wrapped to protect them from corrosion losses and protected from overstressing due to ground settlement.

Other methods of anchoring bulkheads include rock or earth anchor systems and H-pile tension piles. Earth anchors are useful where there is not sufficient space behind to install a more conventional tie rod system. Earth anchors utilize slant-drilling techniques to install high strength steel rods or cable between the wall and rock or stable soil at some lower elevation. The anchor is grouted in place and a pre-test of its capacity is possible during the prestressing or post-tensioning phase. Steel H-piles may be driven on a batter and fastened to the wale system. They function as tension piles.

2.2.1.6. Temporary Cofferdams

Steel sheet piling is virtually the only means for a contractor to keep water out of a construction site while the permanent structure is built in the dry. On land, other methods such as slurry walls and steel soldier beam walls have replaced sheet piling for temporary construction. The exception would be where ground water must be retained or to comply with legal requirements for safety.

Straight wall cofferdams are designed using techniques similar to bulkheads and retaining walls. The cofferdam consists of a closed square or rectangular wall of sheet piling. An internal system of wales and struts provide support. On land, earth or rock anchors keep the inside of the cofferdam clear for working ease. Out in the water however, conventional bracing systems of walers and struts are still necessary.

Figure 2-24 Various Anchorage Systems for Sheet Pile Walls

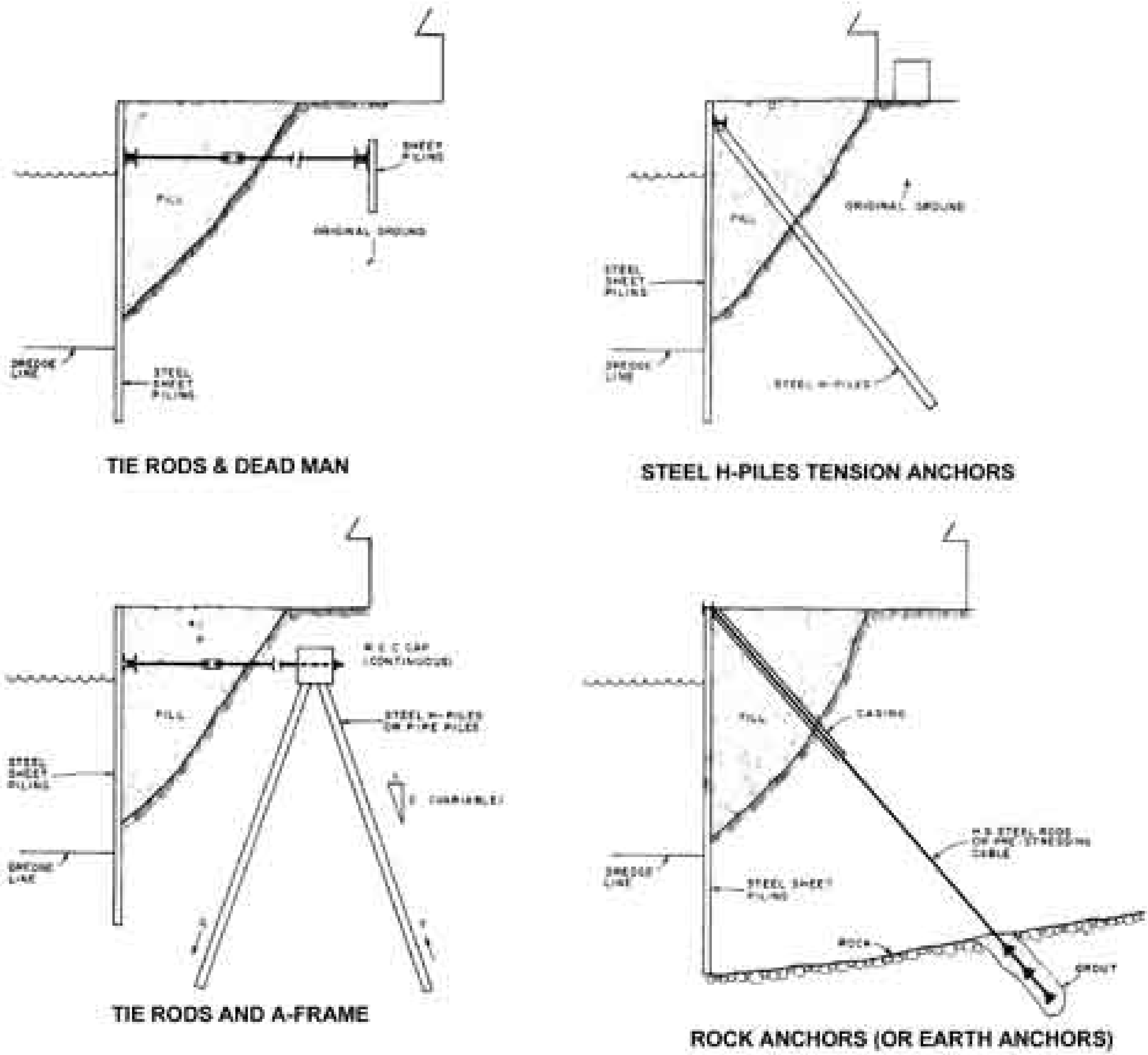


Figure 2-25 Sheet Piling Box Cofferdam

In river cofferdams, external water pressure is the dominant load and removes a lot of uncertainty from the load assumptions since the loading is triangular at 62.4 pounds per foot of depth. Below excavated elevation, the pressure consists of submerged soil and water, which increases the pressure. The sheeting is designed as a beam on multiple supports. Loading conditions both during construction of the cofferdam and after dewatering must be considered. Stability of soil under and in front of the wall should also be examined for seepage effects. Internal bracing is spaced so that the sheet piling will not be overstressed. Moment calculations can be based on continuity over the supports. Reactions from the sheeting provide loads on the wales, which are designed as beams on supports. Loads on wales should include end thrust from the other members in the tier. Cross struts are designed as columns and located so that they do not seriously interfere with the work inside.

Circular cofferdams with internal ring wales and no cross struts have sometimes been constructed where it has been necessary to keep the interior clear. Wales have been fabricated of steel or have been of cast in-place reinforced concrete.

Several serious collapses of steel ring-wale braced cofferdams in water have occurred due to incorrect assumptions regarding the nature of stress distribution in the wales. Experienced designers should work on these applications.

2.2.2. Aluminum Sheet Piling

2.2.2.1. Introduction

Aluminum sheet piling has been available since 1969 in various forms and has had an excellent success rate during this period in both salt and fresh water environments. As many as seven different companies have produced piling sections in various sizes, shapes and thicknesses. Examples of aluminum "Z" sections are shown in Figure 2-26.

Figure 2-26 Aluminum "Z" Sections

There are several important questions to be addressed when the choice of an aluminum sheet pile wall is being considered:

- It is strong enough?
- How long will it last?
- Will it look good?
- Is it functional?
- What are its initial costs and total costs over its life?
- Is it acceptable to the owner?

One of the most significant advantages of aluminum sheet piling systems is its light weight. It has one of the most efficient strength to weight ratio of any type of building material. The ease of handling the relatively lightweight sheets, cap and hardware is a pleasant surprise to most contractors who are new to the use of aluminum piling. It allows the installer to work in tight spots that otherwise might be impractical from a cost standpoint with other types of piling materials.

Historically, almost 90% of all aluminum piling applications have been in a saltwater environment, and generally without protective coatings. If care is taken in properly applying the material to the site, protective coatings will normally not be required.

There are five important areas, which should be thoroughly addressed when considering aluminum sheet piling.

1. Material Specification,
2. Corrosion,
3. Construction Suggestions,
4. Design Principles, and
5. Engineering Data.

2.2.2.1. Material Specifications

The following material specification covers the mechanical properties of the aluminum allows used in the sheeting, wale, cap, tie rods, anchors, corner extrusions and fasteners in marine retaining wall applications.

2.2.2.1.1. General

Tolerances should conform to the specifications listed in "Aluminum Standards and Data", Fifth Edition. Typical safety factors, except for anchor rods and clips, as recommended in the Aluminum Association's "Specifications for Aluminum Structures – Section 1" are 1.95 for ultimate strength or 1.65 for yield strength.

The welding filler used on all wall system welds shall be alloy 5356 in conformance with the American Welding Society's Specification A5.10 and with chemical composition in accordance with "Aluminum Standards and Data".

2.2.2.1.2. Sheeting, Bracing Assemblies, Wales, Cap, Backing Beams, Shims, Tie Rods, Rod Shims, Wale Clips

All material shall be made from aluminum alloy 6061-T6. The chemical composition shall conform to American Society for Testing Materials, ASTM, designation B 221 alloy 6061-T6, shown in Table 2-23. The mechanical properties as given in Table 2-20 shall be met.

Table 2-20 Aluminum Alloy ASTM B221 6061-T6

Thickness, Inches	Minimum Ultimate Tensile Strength, ksi	Minimum Yield Tensile Strength, ksi	Minimum Elongation in 2 inches, percent
< 0.125	38	35	8
0.125 - 1.000	38	35	10

The sheeting shall be furnished in standard sizes to permit assembly in uniform increments as shown on the plans. The sheeting shall have a minimum section modulus of _____in³/LF of wall and shall have a minimum constant thickness of _____ inches.

2.2.2.1.3. Tie Rods, Bolts and Nuts for Connections

Tie rods and bolts for connections shall be of the diameter specified by the Engineer. Threads shall be American Standard Course Thread Series, Class 2, Free Fit.

Aluminum bolts and nuts material shall conform to either the chemical requirements of the ASTM designation B 221 alloy 6061-T6, as provided in Table 2-20, or to the ASTM designation B 211 alloy 6061-T6, as provided in Table 2-21. The allowable design tensile stress shall be 18,000 psi on the root area. The bolts may be sampled and tested before erection or may be accepted on the manufacturer's certification.

Stainless steel type 18-8 (300 series) bolts and nuts, of the same diameter as the aluminum bolts and nuts may be substituted in lieu of aluminum bolts and nuts. This material shall meet ASTM specification A 193B8.

Table 2-21 Aluminum Alloy ASTM B211 6061-T6

Thickness, Inches	Minimum Ultimate Tensile Strength, ksi	Minimum Yield Tensile Strength, ksi	Minimum Elongation in 2 inches, percent
0.125 - 8.000	42	--	10

2.2.2.1.4. Alternate Sheeting, Cap Insert, Corner Extrusions

Alternate anchor sheeting sections and any alternate sheet piling sections specified by the engineer, cap inserts and corner joints shall be furnished in aluminum alloy 6063-T6. The chemical composition shall conform to ASTM designation B 221 alloy 6063-T6, shown in Table 2-23. The mechanical properties as given in Table 2-22 shall be met.

Table 2-22 Aluminum Alloy ASTM B221 6063-T6

Thickness, Inches	Minimum Ultimate Tensile Strength, ksi	Minimum Yield Tensile Strength, ksi	Minimum Elongation in 2 inches, percent
< 0.125	30	25	8
0.125 - 1.000	30	25	10

2.2.2.1.5. Anchor Plates

The anchor plates shall be fabricated from sheeting and backing beams as required in the plans.

2.2.2.1.6. Field Inspection and Acceptance of Parts

The field inspection shall be made by the Engineer, who shall be furnished by the manufacturer of all the wall parts, an itemized statement of the number and size of the parts in each shipment. Each part included in a shipment shall meet fully the requirements of these specifications.

2.2.2.1.7. Methods of Testing

Unless otherwise provided, chemical analysis, when required, shall be in accordance with Standard Method E34 of the ASTM except when suitable spectrographic analysis may be employed.

Table 2-23 Chemical Composition Limits of Aluminum Materials

Chemical Element	Alloy 6061-T6, Percent	Alloy 6063-T6, Percent
Si	0.40 - 0.80	0.20 - 0.60
Fe	0.70	0.35
Cu	0.15 - 0.40	0.10
Mn	0.15	0.10
Mg	0.80 - 1.20	0.45 - 0.90
Cr	0.25	0.10
Zn	0.15	0.10
Ti	0.05	0.05
Other Alloys	Each 0.05	Total 0.15

2.2.2.2. Corrosion

Probably the most common question asked about aluminum sheet piling is "will it work in this environment?" The following information regarding aluminum's corrosion resistance is provided below and should be helpful in determining if your site is suitable for the use of aluminum piling.

2.2.2.2.1. Introduction to Marine Aluminum

Aluminum alloys have been selected as materials of construction in many fields because of their ability to resist corrosion. Aluminum's ability to resist corrosion by atmospheric weathering has been well demonstrated by its application in agriculture, industrial and residential roofing, siding and other building materials for many years. The use of aluminum for storage tanks, tank cars, heat exchangers and other process equipment is ample evidence of its resistance to corrosion by chemicals and food products. Aluminum's resistance to corrosion both by fresh and salt waters can be shown by its many applications in ships, pleasure boats, irrigation pipe, heat exchangers, sewage disposal plants, rain carrying equipment, etc. Experience has also been gained over the years from installations of culvert sheeting and buried pipelines, which indicate that aluminum will perform satisfactorily in contact with many soils.

2.2.2.2.2. Why Is Aluminum Corrosion Resistant?

In order to have knowledge of and thoroughly understand proper installation and maintenance suggestions it is first necessary to know the mechanism by which aluminum derives it resistance to corrosion.

Although aluminum is an active metal, its behavior is stable because of the protective, tightly adherent, invisible oxide film on its surface. Even when disrupted, this film begins to re-form immediately in most environments when oxygen or air is present. The oxide is present on the surface of the cast ingot and continually reforms after being disrupted by rolling, forging, drawing, extruding or other fabricating processes.

As long as this oxide film is intact and continuous or can reform, if damaged, the aluminum metal will maintain its high resistance to corrosion. The oxide film is tenacious, hard and relatively insoluble and is therefore able to endure under a wide variety of environmental conditions. There are, however, some conditions that can lead to a breakdown or dissolution of the oxide film. Many years of study by the aluminum industry have been devoted to defining these conditions and developing means of minimizing their effect.

2.2.2.2.3. Causes of Corrosion

In most environments, the corrosion of aluminum (like that of other common structural metals) is associated with the flow of electric current between various anodic and cathodic regions. The electrochemical corrosion produced depends on the electrical potentials of these regions.

In order to investigate the electrochemistry of aluminum corrosion compared to other metals, scientists have developed a test solution, which can be used to establish the potential difference between aluminum, its alloys and dissimilar metals. Table 2-24 presents the potential difference of aluminum, its alloys and other metals.

Table 2-24 Electrode Potential of Several Metals Measured under Different Conditions

Metal	Standard Electromotive Series (volts)	Static Seawater (volts)	Flowing Seawater 13 ft. per sec. (volts)
Magnesium	−2.34	−1.45	
Aluminum	−1.67	−0.74	
Zinc	−0.76	−0.80	−1.03
Iron	−0.44	−0.5	0.61
Hydrogen/Platinum	0.00	0.00	
Copper	+0.34	+0.80	−0.36
Silver	+0.80	+0.12	−0.13
Stainless Steel Type 316			−0.05
Platinum	+1.20	+0.4	+0.15

Although the potential differences shown are useful in predicting the possibility of galvanic corrosion, they are only a guide. To establish the actual potential difference between aluminum and some dissimilar metals under actual project conditions, a potential measurement in the solution actually used in the intended application must be made because the potential difference depends upon the electrolyte, as the table indicates. Furthermore, the amount of galvanic corrosion is determined, not only by the potential difference, but also by the overall electrical resistance in the galvanic circuit. Special resistances to current flow, called polarization, can exist at the metal-liquid interfaces that are relatively large compared to the resistance of the solution.

The phenomenon of polarization accounts for the fact that even though an aluminum-stainless steel couple has a greater potential difference that does an aluminum-copper couple, the resistance at the metal-liquid interface on stainless steel is greater than on copper. Hence, the stainless steel causes less galvanic current flow from anodic regions on the aluminum than does copper. In actual practice this means that aluminum is quite compatible with stainless steel but problems can and do arise when aluminum is coupled to copper or copper-bearing alloys in certain electrolytes.

Corrosion of aluminum (as well as other structural metals) is electrochemical in nature and involves the flow of electric current between various anodic and cathodic regions. Several major factors basic in determining this flow of current and the resulting corrosion are:

- Alloy constituents
- Metallurgical and thermal treatments

- Effect of pH
- Galvanic corrosion (dissimilar metals)
- Stray currents
- Soil resistivity

2.2.2.2.3.1. Alloy Constituents

Virtually all of the aluminum used commercially today are alloys in which the primary ingredient is aluminum metal but include additions of other metals, usually for the purpose of increasing strength and/or workability without sacrificing corrosion resistance.

The variables that influence the amount and distribution of corrosion are:

2) Composition of the micro-constituents and their location;

3) Quantity of the micro-constituents and their location;

4) Continuity of the micro-constituents and their location; and

5) Electrical potential relative to the aluminum solid solutions.

Table 2-25 shows the electrode potentials of aluminum solid solutions and constituents. Note that iron (Fe), for example, forms constituents that are cathodic to aluminum. These constituents, because they form cathodic points over which the oxide film is weak, may promote electrochemical attack of the surrounding aluminum. The same analogy may also be drawn in the case of alloys containing various amounts of copper constituents. For this reason, alloys containing these metallic additions are rarely used when resistance to corrosion is of paramount importance.

Table 2-25 Electrode Potential of Aluminum Solid Solutions and Constituents

Solid solution or constituent	Potential, v(a)	Solid solution or constituent	Potential, v(a)
Mg_2Al_3	−1.24	99.95 Al	−0.85
Al + 4 $MgZn_2$(b)	−1.07	Al + 1 Mg_2Si(b)	−0.83
Al + 4 Zn(b)	−1.05	Al + 1 Si(b)	−0.81
$MgZn_2$	−1.05	Al + 2 Cu(b)	−0.75
$CuMgAl_2$	−1.00	$CuAl_2$	−0.73
Al + 1 Zn(b)	−0.96	Al + 4 Cu(b)	−0.69
Al + 7 Mg(b)	−0.89	$FeAl_3$	−0.56
Al + 5 Mg(b)	−0.88	$NiAl_3$	−0.52
Al + 3 Mg(b)	−0.87	Si	−0.26
$MnAl_4$	−0.85		

(a) 0.1*N* calomel scale, measured in an aqueous solution of 53 g per liter NaCl + 3 g per liter H_2O_2 at 25 C. (b) Solid solution.

From these data it would appear that silicon additions could produce alloys, which would be very cathodic and cause corrosion. Conversely, when silicon and magnesium are both used as additions in the proper amounts, magnesium silicide (Mg_2Si) forms as a constituent, which, in solid solution, has very little effect on the electrode potential. Alloys 6061 and 6063, which are used exclusively in the major manufacturers' wall systems, are alloys of this type and are well known for their corrosion resistance in seawater.

Aluminum alloys containing magnesium in amounts up to about 5 % are also known to have good corrosion resistance in marine environments. Alloys 5052, 5083, 5086, and 5154 are examples of this alloy type.

2.2.2.2.3.1. Metallurgical and Thermal Treatments

Metallurgical treatments of aluminum alloys that can be used to develop desired mechanical properties also could influence resistance to corrosion. Thermal treatment and cold work processing influence the quantity and distribution of the constituents and the magnitude of residual stresses. Thus, these factors are very important influences on the type and rate of corrosion.

Commercial treatments used in aluminum producing plants assure that the alloy specified will exhibit the properties attributed to that alloy. However, subsequent working or thermal treatments applied by the customer can and often do alter the properties of the alloy. One result can be a lowering of the alloy's natural corrosion resistance. If one portion of an alloy surface receives a thermal or mechanical treatment different from the remainder of the alloy, differences in potential between these regions can result and resistance to corrosion lowered (For example, the heat due to welding). Careful selection of welding filler material must be made in order to avoid or minimize corrosion problems that might result from the heat of welding.

2.2.2.2.3.2. Effect Of pH

Generally, the protective oxide film is stable in aqueous solutions in the pH range of 4.5 to 8.5. Usually the oxide film is readily soluble in strongly acid or alkaline solutions; consequently, such solutions may attack aluminum. However, as with all general rules there are exceptions.

Aluminum alloys are used in environments such as ocean, lake, river and municipal waters. No significant correlation is known between the corrosiveness of waters on aluminum and such factors as chloride content, sulfate content, total solids, total hardness, or total alkalinity. Some generalizations can be made but a sufficient number of exceptions are found to necessitate caution in applying them.

In water with a pH of 8.5 or more, the resistance of aluminum depends primarily on the nature of the compounds causing the high pH. Service experience has demonstrated that many natural alkaline waters are compatible with aluminum.

Similarly, the extent of corrosion of aluminum in acid water depends to a large degree on the nature of the compounds causing the low pH. Acid waters containing chlorides are particularly corrosive to aluminum. Sulfate waters of low pH are also corrosive, but less severe than chloride waters of the same pH.

These general statements are not valid if the waters contain traces of heavy metals. Copper, lead, tin, nickel, mercury and cobalt compounds generally referred to as heavy-metal compounds, promote localized corrosion attack.

2.2.2.2.3.3. Galvanic Corrosion – (Contact With Dissimilar Metals)

Corrosion currents of substantial magnitude may be caused by contact between different metals in the presence of an electrolyte. In general, the behavior of the various metals can be predicted from their electrode potentials as shown in Table 2-24. The less negative metal is likely to stimulate attack of the more negative.

Although Table 2-24 can be used to predict which metal or alloy in a couple would suffer galvanic attack, the extent of this special attack cannot be predicted from the table. For instance, as cited previously, although the difference in potential between an aluminum alloy and stainless steel is greater than that between the aluminum alloy and copper, the current with the former couple is less than the latter because of polarization of the stainless steel. The table does suggest that unless the materials are plated or coated in some manner, contact of aluminum with mild steel, copper or copper bearing alloys should be avoided where possible. When it is not possible to avoid the use of these metals, they should be electrically separated from the aluminum by the use of non-metallic materials.

2.2.2.2.3.4. Stray Current Corrosion

Electric currents (either AC or DC) caused by externally generated potentials can be responsible for severe corrosion, particularly in marine and underground structures. Such stray currents can be associated with the track-return of street railways, grounding of electric generators and welding equipment or buried pipelines having induced cathodic protection. The attack occurs at the point where the stray current leaves the aluminum retaining wall to enter the soil or electrolyte. The magnitude of such stray currents and possibilities of encountering them are subjects of speculation because few factual data are available. Such corrosion is becoming less prevalent because of improved design and installation practices.

Aluminum piling has been used successfully in many marinas. Proper design of the electrical system of course is the key to prevent stray current corrosion from affecting any metals at marine installations.

2.2.2.2.3.5. Soils

The corrosion performance of unprotected, buried aluminum alloys varies considerably with the type of soil. No satisfactory classification of soils with regards to their corrosive action on aluminum has been developed. It has been assumed that the "safe" range of pH values for soil is the same as for aqueous solutions, pH 4.5 to pH 8.5, but this has not been adequately substantiated. As in aqueous solutions, the particular compounds in the soil that are causing the high or low pH is undoubtedly a factor. Some data indicate that soils in the "safe" pH range, which have a resistivity greater than 500 ohm-cm, have proven to be compatible with aluminum. Testing of soil samples and resistivity determinations can be only used as guides. Further studies are underway by various companies to further address this issue.

2.2.2.2.3.6. Clay Soils

In general, clay and organic soils are corrosive to aluminum and should be avoided. Protective coatings or cathodic protection should be added to the aluminum to provide a longer service life, if aluminum is to be used in these types of soils. The least expensive and most commonly used method is to coat the material that is in contact with the clay soils with a coal tar epoxy coating. The decision to use aluminum or not is generally left to the user when dealing with these types of soils.

2.2.2.2.4. Types of Corrosive Attack

The aluminum alloys used for all components of the system are highly corrosion resistant. It is possible, however, that under extremely adverse environmental conditions some corrosion could occur. If corrosion does occur, it most probably would be either the uniform or pitting type. These types of corrosion will be discussed briefly to aid in recognition.

2.2.2.2.4.1. Uniform Attack (Etching)

During uniform attack, the metal corrodes evenly. Such attack usually occurs in the presence of strongly acid or strongly alkaline electrolytes that simply dissolve the oxide film and prevent its reformation. The appearance of the metal being uniformly attacked may range from superficial etching and staining to rapid dissolution of the metal. Uniform attack is easy to evaluate by a measurement of weight loss or decrease in thickness. The rate of attack usually is expressed in mils per year (mpy). Etching may be a serious problem if it continues at a lineal rate.

2.2.2.2.4.2. Pitting Attack

Pits, the most common form of corrosive attack on aluminum, may form at localized discontinuities in the oxide film when aluminum is exposed to weather, fresh or salt water, or other neutral electrolytes. Depending upon the alloy composition, the quality of the oxide film and the nature of the corrodent, the pits may be minute and concentrated or can vary in size and be widely scattered. Pitting type corrosion often appears to be more severe than it actually is because the build-up of corrosion product occupies many times the volume of the metal from which it was formed. Removal of this corrosion product will often reveal corrosion of only minor significance.

The evaluation of pitting corrosion is difficult. Weight losses are of little value and tension tests can be misleading. Measurements of depth and distribution of pits made at several time intervals provide a means of determining whether the rate of penetration changes with time.

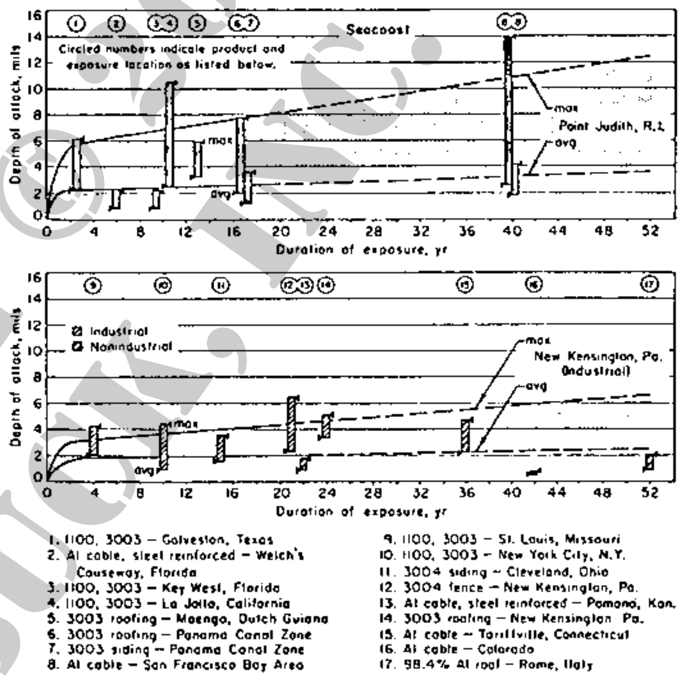
2.2.2.2.5. General Resistance To Corrosion

Since laboratory exposure tests, such as salt spray or immersion in electrolytes, are only useful for comparative information and do not necessarily predict actual service performance, actual long-term atmospheric exposure and weathering tests have been necessary.

In the past 30 to 35 years, thousands of specimens have been exposed throughout the U.S. and elsewhere. Test reports published in the literature demonstrate convincingly the excellent atmospheric weathering characteristics of aluminum alloy products in industrial, chemical, seacoast, tropical and many other environments.

One obvious phenomenon that has emerged from these long-term exposure tests is that corrosion of aluminum in these environments is "self-limiting." Whereas corrosion during the early months and years of exposure may appear to be severe, this rate of weathering decreases with time. The tendency is for the attack to proceed laterally along the surface rather than to become progressively deeper. The decreased rate of attack, as evaluated by losses in tensile strength as well as depth of attack measurements, indicates that corrosion diminishes with time over the entire surface to a very low rate. The curves in Table 2-26 show test data from many exposure sites, which demonstrate this effect.

Table 2-26 Comparison of test data and service for atmospheric exposure at seacoast and industrial sites



Curves for Point Judith and New Kensington are based on data obtained on aluminum alloys 1100, 3003, and 3004, extrapolated to 52 years. Data obtained on test specimens at other exposure stations and on related aluminum alloys from a variety of service conditions are shown as vertical bars on the charts. Comparison shows that performance of aluminum alloys at Point Judith and New Kensington can be used with confidence to predict performance in most seacoast and industrial regions.

2.2.2.2.6. General Suggestions

There is no absolute "safe" method for testing soils. On a "normal" homeowner lot, one can easily miss an "unsafe" area of bad soil. The best suggestion is to take soil samples at the left, centre and right sides along the intended bulkhead installation line. One sample in the centre back from the wall line should also be taken. Two water samples should be taken also at the one-third points. These suggestions assume the natural ground to be homogeneous throughout the property. If the natural soils are not homogeneous, the same procedures should be followed for each type of soil present. Heavy metals should be tested for if you suspect their presence.

If the test results show either the soil or water to be outside the "safe" ranges, as discussed previously, the decision is then left to the designer to either use protected aluminum, non-protected aluminum or no aluminum.

If time permits while applying for a Corps of Engineers permit, install a section of sheeting in the ground along the intended bulkhead line and remove the sample in 2 to 3 months time. This should provide sufficient evidence of corrosion for one to make a reasonable conclusion as to the suitability of aluminum for that site. Aluminum, if unsuitable for a site, will normally react adversely in that 2 to 3 month period.

It is unnerving to some potential users but there is really no safe method of testing for soils. Potentially corrosive areas can be missed during the normal testing procedures. Nothing is 100% sure in any occupation but when pH and resistivity are checked and are found within the suggested general safe guidelines, the user will find the odds in favor of a successful application to be very good.[14]

2.2.3. Vinyl Sheet Piling

2.2.3.1. Introduction

Vinyl sheet piling is a relatively new type of sheeting that can be applied in a wide variety of applications. It is lightweight, simple to set and install, resistant to environmental attack and can be configured in various colors. It was designed to be:

- Weatherable
- Corrosion Resistant
- Unaffected by Fungi and Marine Borers
- Environmentally Friendly
- Easy to Install
- Cost Effective

It is ideal for the lighter bulkheads that are typical with residential, recreational and marina construction. Vinyl sheeting can also be used for Navy walls as well.

2.2.3.1. Configuration

Vinyl sheet piling is generally manufactured by continuous extrusion. This is the same process used to form PVC pipe. The raw material, plastic resin compound, is melted and pushed through a die. This die shapes the plastic into the desired cross section. The shape is then cooled and cut to the desired length.

The individual sheets have interlocking male and female edges. The interlocking edges are extruded as part of the sheet to insure continuity.

Vinyl sheeting is available in a number of configurations. The most common configuration is a Z-sheet type of configuration, which is similar to steel piling. Such sheets are made to be driven two at a time and, as is the case with their steel counterparts, offer a high section modulus. Since it is extruded, vinyl sheet piling can have a wider variety of sections than rolled steel sheeting. Vinyl sheet pile manufacturers take advantage of this advantage and frequently include stiffening ribs and/or thickened corners. The configuration of these stiffening elements varies with the manufacturer.

Another configuration that is common with vinyl sheet piling is an "AWL" configuration as shown in Figure 2-27. This configuration combines the high section modulus of Z-sheeting with the ease of interlock alignment of flat and U-type sheeting – in fact, it is in effect two U-sections put together. AWL sections also eliminate interlocks and thus potential leakage. When installed by vibratory drivers, however, setting the clamp arrangement for multiple sheet driving can be difficult due to the physical layout of the sheeting.

Figure 2-27 "AWL" type sheeting

As is the case with other sheeting, vinyl sheeting requires transition pieces such as corners and intersections. These are customized for the other sheeting the manufacturer makes.

2.2.3.2. Material

Vinyl sheeting is made of a modified polyvinyl chloride (PVC), which makes it suitable for most marine environments and not subject to leaching, corrosion or similar deterioration mechanisms. The technology that has brought us vinyl siding for homes, plastic automotive parts such as bumpers and dashboards, and durable home appliances, is now being utilized to produce a sheet piling for marine retaining walls, sea walls or bulkheads. The vinyl also includes a UV stabilizer to reduce deterioration due to sunlight. Tensile strength for this material is approximately 6-7 ksi[15] (41.3-48.3 MPa), with an initial modulus of elasticity of 350-400 ksi (2.41-2.76 GPa.) It cannot be overemphasized, however, that with plastics of any kind material properties cannot be applied as simplistically as with metals. Tensile strength of the material, for instance, can vary both with the way the sheeting is loaded (purely tensile vs. flexural loads) and with time. Time variation is also significant with the modulus of elasticity. It is important to follow the manufacturer's recommendations on loading, and in many cases the manufacturer will specify a maximum moment per foot or meter of sheeting wall as opposed to allowing the designer to compute the maximum fiber stress in flexure.

The relatively low values of strength and modulus of elasticity given above are very important to consider in the design of vinyl sheet walls. Not only is it important to consider the strength of the material but also that it is subject to greater deflection than other types of sheeting as well. Designers will realize that, as support spans increase, wall deflection will

become the controlling aspect of the design.

2.2.3.3. Design

The design of vinyl sheet piling is similar to that of other types of sheet piling. Since vinyl sheeting is light and commonly used in residential or other light applications it is tempting to assume that one can shortcut the design as well. Vinyl sheet piling, however, is an engineered marine product and should be treated as such. Most manufacturers of vinyl sheet piling have engineering specifications and recommendations that should be followed during the application.

The following presents several key points related to the design of vinyl sheeting:

- The type and compaction of backfill is very critical to the success of a vinyl sheet pile wall. Ideally, backfill should be free draining cohesionless soil, compacted in layers or "lifts," with an angle of internal friction of 34° or more. Cohesive soils should be avoided as backfill to avoid rupturing the sheets as they both expand with changes in water content and have very low permeability. Expansive soils or soils with high plasticity indices (such as fat clays) should be avoided as backfill.
- Weep holes should be considered to allow for drainage behind the sheets during rapid changes in the groundwater level. The success of these weep holes depends on the permeability of the soil.
- Vinyl sheet walls are almost always tied back; they are seldom cantilevered. Tiebacks must be sufficiently long to carry the load. Make sure the tieback spacing is not excessive or the purpose of the tiebacks will be defeated.
- Consider the long-term properties of the material, as they will change with time. A factor of safety of at least 1.5 should be used when designing vinyl sheet pile walls, taking creep effects into consideration.
- Walls are generally capped with wood or concrete, although occasionally steel caps are used.
- Although sheet piling does not generally work against rock, it is especially important to avoid rock with vinyl sheet piling. As with any vinyl product, it is subject to rupture and will damage severely during installation if rock is hit.
- Use of a proper waling system is very important for a successful vinyl sheet pile wall. Single waling is suitable for lower walls while multiple waling is necessary for taller ones.
- Design should take into consideration wave and ice loading.
- The layout of vinyl sheeting is also similar to other types of sheeting. Careful consideration should be made to the sheet geometry and corner details.

2.2.3.1. Installation

Vinyl sheet piling can be installed using a variety of equipment types, which include:

- Vibratory hammers, either excavator or crane mounted. Vibratory plate compactors are also used, but these are exclusively excavator mounted. It is important when using a plate compactor to keep a steady, downward force on the pile and vibrator during driving.

- A portable air-compressor or hydraulic jackhammer with a sheet shoe. This is only suitable for short sheets and is generally used by occasional installers.
- A drop impact hammer, either land-based or barge-mounted.
- A water jet fed by a high output pump, either held by hand or suspended from a crane.

As with other types of sheet piling, vinyl sheet piling is best set before being driven. Because it is lightweight, when safety conditions permit it can be set by hand. It can also be installed with a crane or excavator if the conditions require.

The selection of an installation method is a matter of both jobsite conditions and contractor preference. However, as with any driven pile, the preparation before driving is frequently as important as the driving itself. The following is an outline of a technique for installing vinyl sheet piling, in this case a single wale design.

The optimum method of installation is to set the sheets first, then driven them. Manufacturers' recommendations for sheet pile wall installation in terms of sheet alignment, panel driving and other techniques apply to vinyl sheeting as well.

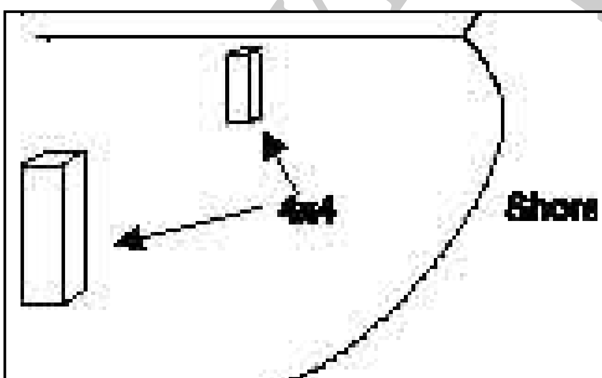
2.2.1. Pultruded Fiberglass Sheeting

2.2.1.1. Introduction

Pultruded sheet piling is another relatively new product. It has two distinct characteristics:

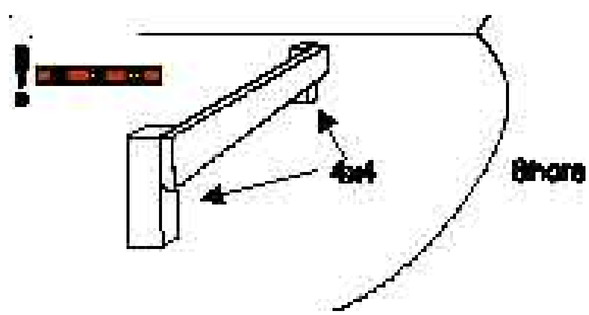
- It consists of very strong fiberglass roving (long extended fibers) and mat that are cured into a high performance resin. The roving imparts most of the longitudinal strength with tensile strength in excess of 500 ksi and an elastic modulus of 10,000 ksi. The tensile strength of the roving is greater than most steel. The continuous strand mat provides the material its transverse (longitudinal) strength.
- It is pulled through the die that forms its shape, not pushed through like extruded aluminum and vinyl profiles. The continuous manufacturing process makes the parts very consistent in tolerances and properties from one piece to the next.

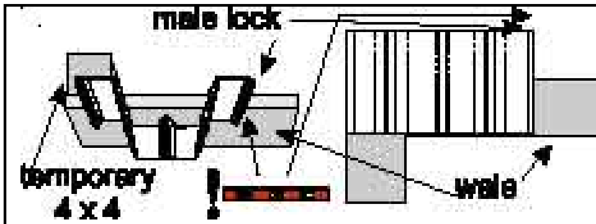
The pultrusion manufacturing process allows for producing continuous lengths of reinforced plastic structural shapes with constant cross-sections. The process involves pulling the raw materials through a heated steel forming die using a continuous pulling device. The reinforcement materials are in continuous forms. As the reinforcements are saturated with the resin mixture ("wet-out") in the resin bath and pulled through the die, heat from the die initiates hardening of the resin. A rigid, cured profile is then formed that corresponds to the shape of the die. In the forming



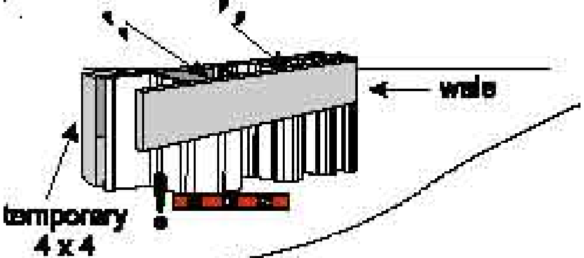
Drive 4x4 piling on 14' centers along the outside (waterside) line of the finished wall. These pilings are temporary and will be removed at the end of the project.

Attach what is to be the top wale of the structure. This beam will also be part of the total cap system, therefore, be sure to mount the beam at the proper elevation and check for alignment.

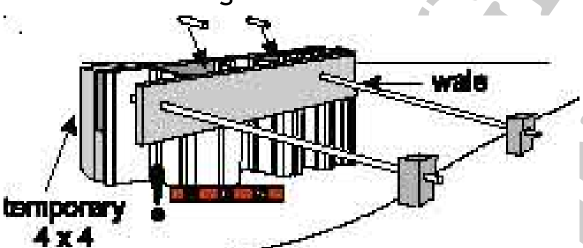




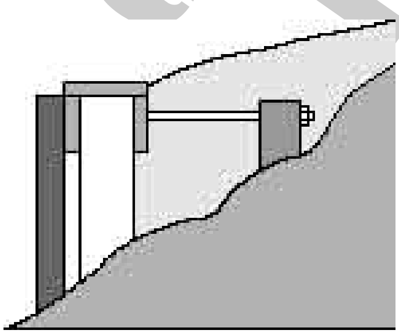
Once the panel is driven to grade, check the leading male edge for alignment. When you are satisfied that the panels are properly aligned, attach the leading panel to the wale using stainless steel lag screws. Do not overtighten. Repeat this process until you are finished. At this point, all panels should be aligned.



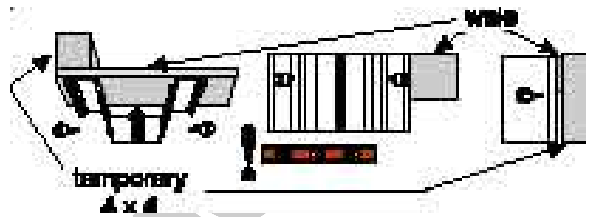
Attach the tie rods to anchors. The rods should be long enough so that the anchors can be placed in stable soils. The distance between the rods is dependent on the strength of the wale and the applied load. Consult your local contractor or engineer.



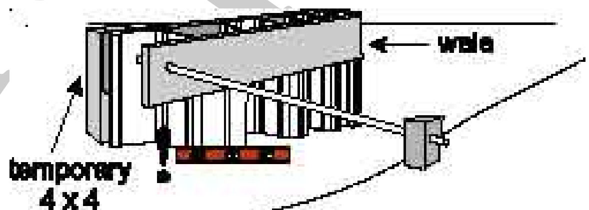
Mount the 2” (50.8 mm) x 12” (304.8 mm) cap board flush with the back wale.



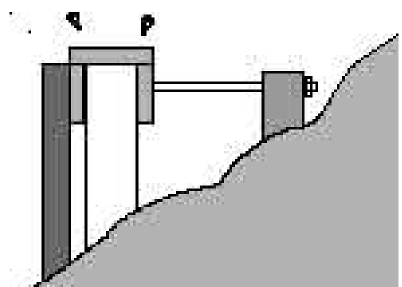
Connect the two panels and set them into driving position, leading with the male lock. Install the panels, driving them to grade with a drop hammer, vibratory hammer or water jet. Throughout driving, check the panels for alignment.



Once all panels are driven, attach the back wale beam. Panels that are not lagged to the front wale should be lagged to the back wale.

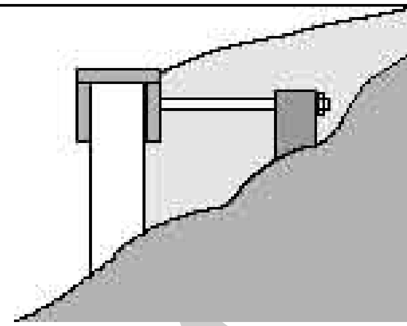


Place the stainless studs between the rods.



Backfill in 1’ lifts using granular or small, light aggregate backfill.

Remove temporary piling.



and curing die, the thermosetting reaction is heat activated and the composite is cured (or hardened.)

On exiting the die, the hot product must be cured to prevent cracking and deformation before the pull blocks grip it. The final product can then be cut to any length.

Other properties of Pultruded sheet piling include the following:

- Resistant to corrosion.
- Resists attack of marine borers and other destructive elements in the marine environment.
- Resists UV degradation.
- Lightweight – allows for easier installation, even setting by hand in many cases.

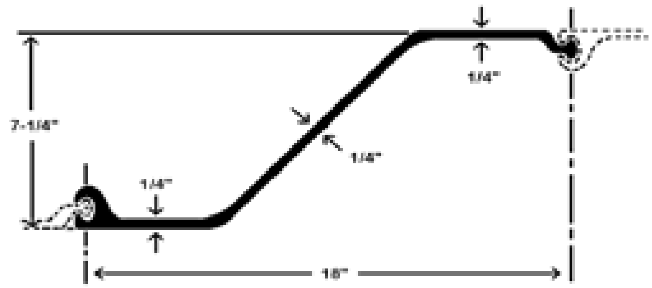
2.2.1.1. Material Specifications

Typical material specifications for pultruded sheet piling are shown in Table 2-27.

2.2.1.2. Sheeting Profiles

Pultruded sheeting comes in a wide variety of profiles and shapes. A typical profile is shown in Figure 2-28.

Figure 2-28 Typical Sheeting Profile for Pultruded Fiberglass Sheeting



2.2.1.3. Design of Pultruded Sheet Walls

Pultruded sheet pile walls are designed using the same principles as other sheet piling materials. There are some special design considerations of these walls that need to be noted:

- Deflection. Although stiffer than other non-metallic sheeting, Pultruded sheeting is still more susceptible to deflection than steel sheeting. Designers should insure that excessive deflections do not occur. Also, the deflections shown here – and those of most methods used to compute deflections of sheet piling – do not take into consideration shear deflection, which is significant in short sections and more important in fiberglass than in materials such as steel.
- Local Buckling and Transverse Bending. In

Table 2-27 Typical Material Specifications for Pultruded Sheet Piling

Mechanical Property	ASTM Test	Property, Parallel to Fibers	Property, Perpendicular to Fibers
Tensile Strength	D638	30 ksi	7 ksi
Tensile Modulus	D638	2,500 ksi	800 ksi
Compressive Strength	D695	30 ksi	15 ksi
Compressive Modulus	D695	2,500 ksi	1,000 ksi
Flexural Strength	D790	30 ksi	10 ksi
Flexural Modulus	D790	1,800 ksi	800 ksi
Full Section Modulus of Elasticity		2,800 ksi	
Notched Izod Impact	D256	25 ft-lbs/in	4 ft-lbs/in

addition to the flexural stresses computed by conventional analysis methods, Pultruded fiberglass shapes – both the sheeting and the H-piles used in the wales – are subject to both compression flange buckling and lateral-torsional buckling. The former is a function of the shape geometry and the properties of the material; the latter includes the unsupported length of the sheeting. Although both of these can generally be avoided through the limitation of conventional deflection and bending stresses, the designer should check these conditions. If H-piles are used in the wales, these elements can be included in the design by use of the property tables available from the manufacturers of Pultruded H-piles, along in some cases with discussions of these conditions in general.

- Interlock strength. The transverse strength of the material is considerably less than the longitudinal strength. Applications such as cofferdams where interlock strength is critical should be avoid with Pultruded sheeting.
- Compaction. The type and compaction of backfill is very critical to the success of a Pultruded sheet pile wall. Backfill should be free draining cohesionless soil, compacted in layers. Cohesive soils should be avoided as backfill to avoid rupturing the sheets when they expand with changes in water content.
- Weep holes should be drilled into Pultruded sheeting to allow for drainage behind the sheets during rapid changes in the groundwater level. Weep holes are more effective if the soil is cohesionless and has high permeability.
- Factors of safety should be similar to those used with other sheet pile materials.
- Although no sheet piling does really well against rock, it is especially important to avoid rock with Pultruded sheet piling.

The layout of Pultruded sheeting is also similar to other types of sheeting. Careful consideration needs to be made to the sheet geometry and how it comes out in corners.

2.2.1.1. Modifying Pultruded Sheeting

Pultruded sheeting is furnished cut to specified length. In most cases, however, it will be necessary to cut, drill or tap the material to complete the installation.

2.2.1.1.1. Important Notes when Cutting on Pultruded Sheeting

1. Observe common safety precautions. For example, the operator of a circular power saw should wear safety glasses to protect his eyes as well as an OSHA approved dust mask.
2. A coverall or long sleeved shirt will add to the operator’s comfort during sawing, machining or sanding operations. Although the dust created is non-toxic and presents no serious health hazard, it can cause skin irritation. This can be reduced or eliminated by use of a protective cream and/or the wearing of proper attire when cutting.
3. Always provide adequate support to keep the material from shifting when making a cut. Without adequate support fiberglass reinforced profiles can shift and may cause chipping at the cut edges. Proper support will also prevent any warping.
4. When cutting and drilling, use light evenly applied pressure. (Avoid excessive pressure!) Heavy pressure tends to clog the blade teeth with dust particles shortening the cutting life of the blade. In addition, cutting speed is a critical variable. If the edges begin to fray, slow the cutting speed. In addition, too much force can rapidly dull the tool. Diamond or carbide grit edge saw blades, carbide tip drill bits and carbide router bits are recommended.
5. Water-cooling is desirable when cutting numerous pieces or when thick cross sections are being sawed. With cooling, cutting speeds increase, smoother cuts result, and dust is often eliminated.
6. Do not generate excessive heat in any machining operation. Excessive heat softens the bonding resin in the fiberglass – resulting in a ragged rather than a clean-cut edge. Excessive heat can also burn resin and glass.
7. Shearing and/or punching are not recommended.

2.2.1.1.1. Sawing or Cutting

The cutting or sawing of pultruded sheet piling, cap or walers can be accomplished quickly and accurately with a circular power saw. A table or radial model is better than a portable hand model because of the built-in rigidity and guides, which insure accurate cuts. However, a hand model utilized by a capable individual is effective.

For infrequent cutting with a circular power saw, a metal blade with coarse, offset teeth can be used satisfactorily. For frequent cutting, a masonry saw blade – preferably carbide tipped – will give accurate cuts and reasonably long blade life. For production cutting, use a 60 to 80-grit diamond tipped blade for best results.

When sawing relatively few pieces, a disposable-blade hacksaw (24 to 32 teeth per inch) is suitable. Although an ordinary carpenter's saw can be used, frequent resharpening makes this tool less desirable.

One problem that may be encountered with a circular power saw is that larger pultruded sections (e.g. walers/H-piles) cannot be cut in one pass due to the blade vs. wale size. This problem does not exist with Composite Z™ Sheet Piling. However, larger wale sections can be sawed in two passes by cutting halfway through from one side, inverting the material or saw and cutting from the opposite side. Obviously this would be best performed prior to placement of the waler however can be accomplished in place by a skilled carpenter.

If the cross section is too large for the circular saw "two-pass method," or if large sections are being sawed in quantity, use a power band saw with a carbide or diamond tipped blade – preferably a machine with automatic feed to insure a light, even pressure on the blade.

2.2.1.1.2. Drilling

Any standard twist bit is a good tool for drilling pultruded sheet piling, caps and walers. Carbide tipped drills are recommended when cutting large quantities. Drill speeds should be approximately equivalent to those used for drilling hardwood. When drilling large holes, a backup plate of wood will prevent the hole from breaking out on the backside.[16]

2.2.1.1.3. Threading and Tapping

Threading and Tapping of fiberglass reinforced material is not recommended as a means of fastening when high strength is required, and should be avoided in the design of fabricated components whenever possible. The threading operation cuts the continuity of the glass fibers and leaves only the sheer strength of the resin component to provide the strength of the thread. Although threaded connections have been used satisfactorily where strength is not an important consideration (e.g. mounting of "signs" or lightweight "lighting components", etc.) it generally requires a bonding of the threaded connection with an epoxy or urethane in to improve the strength of the connection.

2.2.1.1.4. Sanding

Open grit sandpaper on a high speed sanding wheel gives best results. Use very light pressure – do not force the sander against the fiberglass surface because heavy pressure may heat up and soften the resin. Wet sandpaper applied by hand or with an orbital sander will produce a high gloss finish if desired.

2.2.1.1.5. Grinding

Grinding is generally not recommended on composite shapes. In ordinary grinding operations, the dust tends to load the stone and stop the grinding action. If grinding is required, use a coarse grit wheel and water as a coolant.

2.2.1.2. Mechanical Fastening[17]

2.2.1.2.1. Bolted Connections

Using standard bolts, nuts, and washers can make satisfactory connection between pultruded fiberglass sheet piling and composite cap and wale components. In marine applications these are generally galvanized or stainless. Since fiberglass materials can fail under high, localized stress conditions, such as those encountered around a bolt, it is important to use the proper washer. Remember, the strongest joint between pieces of composite shapes is obtained by using properly fitted bolts and a larger diameter washer to help distribute the load. This is extremely important particularly with regard to the wale and tie-rod installation[18].

2.2.1.2.2. Nailed Connections

Nailing is a satisfactory way of fastening Pultruded shapes to wood and to other materials that provide enough grip to hold the nail. Although, common nails can be driven through 1/16" thick composite shapes without re-drilling holes – tempered nails are generally required when penetrating 5/16" thick material. Fiberglass heavier than 5/16" requires pre-drilled holes, slightly oversize, to admit the nail and to allow for expansion and contraction between the fiberglass and the material. It is also advisable to pre-drill slightly oversized holes before nailing long lengths of lighter fiberglass sections. One important note, never nail fiberglass to fiberglass.

2.2.1.2.3. Screwed Connections

Self-tapping screws have been used successfully in many applications involving mechanical connection when high strength fasteners are not required. A better use of self-tapping screws is in combination with adhesives. In this application the screws can serve to hold the adhesive bonded surface of the two parts together while the adhesive cures in addition to contributing limited mechanical strength to the connection. Appropriately sized pilot holes should be provided in the Pultruded shape for the screws. In corrosive environments, galvanized, stainless steel or Monel screws should be used. If corrosion is still a concern, a suitable coating of epoxy or urethane can be applied to the exposed screw heads to aid in the prevention of rusting. Lag screws are not recommended because they do not bite well in the fiberglass.

2.2.1.2.4. Bolting Into Tapped Holes

Mechanical fastening can be accomplished with screws into tapped holes, however, the properties of tapped holes are not good nor will the connection be strong. For removable cover plates, sheet metal screws can be used. The strength of the connection can be improved by use of threaded inserts bonded into place with suitable adhesives.

When removable bolts are required: threaded metal inserts of fasteners should be installed in the fiberglass and preferably bonded in place with a suitable adhesive. Fiberglass threads can wear out quickly and may not provide sufficient strength. Many types of metal inserts and fasteners are commercially available to eliminate this concern.

2.2.1.2.5. Riveted Connections

"POP" Rivets are very effective in joining pultruded fiberglass sections or attaching certain accessories. Rivets are available in various sizes and head styles in aluminum, steel, Monel, copper, and stainless steel. Those materials subject to corrosion should not be utilized in a marine environment. Other types of rivets, such as Drive Rivets, those formed by a rivet gun or the conventional rivet formed with a ball peen hammer, can produce an effective mechanical connection. The strength of the connection can also be improved with suitable adhesives. The riveting of any accessory to a pultruded shape is subject to weight, load and/or strength limitations. As a result only lightweight accessories such as signs, lightweight lighting components or conduit should be attached using a riveted method. Backup washers are recommended for distributing load stresses. As in drilling operations, it is necessary to use a slightly larger drill than the exact diameter of the rivet. For a 1/8" rivet, use a No. 30 drill rather than a 1/8" drill.

2.2.1.3. Wales, Tiebacks and Caps

2.2.1.3.1. Caps

All permanent sheet pile walls should be capped when installation is complete. Although this can be done with wood or concrete caps, a more sensible solution is the use of pultruded sheeting cap that is customized to fit the sheeting profile. A drawing for this is shown in Figure 2-29.

Figure 2-29 Pultruded Sheet Pile Cap

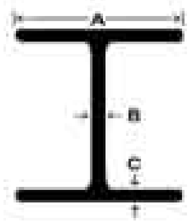
2.2.1.3.2. Wales

Most installations of Pultruded sheet piling will include some type of additional support for the wall. Although this support usually includes a tieback system, it always will include wales. Proper waling is very important in successful use of pultruded sheet pile walls. Low wall heights can be strengthened with single waling but taller walls require multiple waling.

The most suitable waling for this application is pultruded H-piles, which avoid the deterioration and environmental difficulties of wood wales. These H-piles come in several sizes and are configured according to the design requirements. Specifications are shown in Figure 2-30.

Figure 2-30 Pultruded Wale Specifications

SIZE	A, in.	B, in.	C, in.	I_{xx}, in^4	I_{yy}, in^4
12” x 1/2”	12	1/2	1/2	452.45	144.11
10” x 1/2”	10	1/2	1/2	256.20	83.42
10” x 3/8”	10	3/8	3/8	198.53	62.54
8” x 1/2”	8	1/2	1/2	126.96	42.74
8” x 3/8”	8	3/8	3/8	99.19	32.03
6” x 3/8”	6	3/8	3/8	40.17	13.52



Although single wales are sometimes acceptable, in some cases double waling – or more -- is required.

2.2.1.3.3. Tiebacks

Tiebacks are essential to resist wall overturning when the wall is sufficiently tall. There are three recommended options to tie back Pultruded sheet pile walls:

- Conventional galvanized or stainless steel tie-rod, washer and bolt systems anchored into a properly engineered “deadmen”, tieback wall, pile or other anchored device when properly engineered will be suitable. These consist of three basic components;
    - Tieback rod, which is generally a threaded, galvanized stainless steel rod cut to suitable length. For maximum corrosion resistance, an 18-8 stainless steel (300 series) should be used for these rods. Remember that these rods are completely buried so they are subject to deterioration due to groundwater, soil pH and other environmental agents.
    - Washers, bolts and other spacers to connect the tiebacks to the wales and thus the wall. These are threaded onto the tieback rods and tightened after suitable holes are drilled in the wall and wales.
    - Anchor for the tiebacks. This can be an anchor plate, pile or other type of anchor, depending upon the soil conditions and tieback pull loads. The tie rods are connected to the anchors.
- Manta Ray Anchor system, manufactured by Foresight Products, LLC: This anchoring system (similar to a “toggle bolt”) has a “hydraulic/load locker” device, which can give an immediate proof test of the installed anchor.
- A.B. Chance Company, a Hubbell Company: The A.B. Chance helical tieback anchor (screw anchor) for tieback applications has been used throughout the industry in retaining wall, seawall, and bulkhead applications. It has a long history of successful applications. As with the Manta Ray system, it also can provide an immediate true load test of the anchor.

The design and spacing of the tiebacks depends upon the loading requirements. Spacing of the tiebacks is also influenced by the rigidity of the wales or top cap. If tiebacks are spaced too far apart, the wales and thus the wall will excessively deflect.

Any of the above three options can provide for a structurally sound tied back anchoring system when properly engineered. A retaining wall, seawall, or bulkhead is only as strong as its properly engineered wale and tieback system.

2.2.1.1. Installation of Pultruded Sheet Pile Walls

Installation of Pultruded sheet piling is similar to that of other types of sheet piling. Pultruded sheet piling can be installed using a variety of equipment types, which include:

- Vibratory hammers, either excavator or crane mounted. Vibratory plate compactors can also be used, but these are exclusively excavator mounted. It is important when using a plate compactor to maintain a steady, downward force on the pile and vibrator during driving.
- A portable air-compressor or hydraulic jackhammer with a sheet shoe.
- A drop impact hammer, either land-based or barge-mounted.
- A water jet driven by a high output pump, either manually held or suspended from a crane.

As with other types of sheet piling, Pultruded sheet piling is best set before being driven. Because it is lightweight, when safety conditions permit it can be set in place by hand. It can also be installed with a crane or excavator if the conditions require.

The selection of an installation method is a matter of both project conditions and contractor preference. However, as with any driven pile, the preparation before driving is frequently as important as the driving itself.

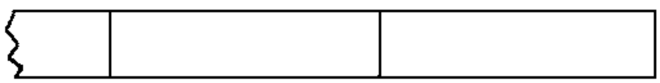
After the sheeting is driven, the wales, tiebacks, caps, etc. are to be installed. Make certain all recommendations in this guide concerning cutting, drilling, tapping and mechanical connections are followed during any or all of these operations.

2.2.1. Wood Sheeting

2.2.1.1. Types of Wood Sheeting

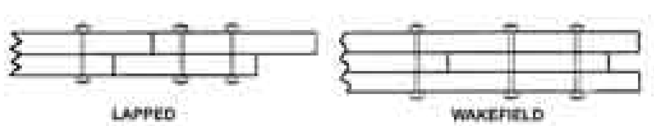
In its simplest form, wood sheet piling can consist of a single line of boards or "single-sheet piling" but it is suitable for only small excavations where there is no serious ground water problem.

Figure 2-31 Single Sheet Piling



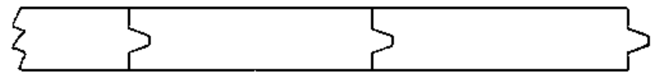
In saturated soils, particularly in sands and gravels, it is necessary to use a more elaborate form of sheet piling which can be made reasonably watertight with overlapping boards spiked or bolted together, such as the "lapped-sheet piling" or "Wakefield" system. Wakefield sheeting consists of three planks 2" (50.8 mm), 3" (76.2 mm) or 4" (101.6 mm) thick and 12" (304.8 mm) or more wide, bolted and/or spiked together with the centre piece an inch or more ahead of the others to form a tongue and groove. For most Wakefield assemblies, timbers should be surfaced on all four faces.

Figure 2-32 Lapped and Wakefield Sheet Piling



In areas where steel sheet piling may not be available, Wakefield Piles are useful; this system was in wide use before the advent of steel sheet piles. For the driving case, the forward bottom edge of the wood can be beveled to force the sheet being added tightly against the in-place units. Wakefield or similar piles may be driven with a small conventional pile hammer or a heavy, hand-held air hammer or "paving breaker." A vibratory earth compactor has been successfully used for vibrating lightweight sheet piling, as have been excavator mounted vibratory hammers. "Tongue and groove" sheet piling is also used as shown in Figure 2-33. This is made from a single piece of timber that is cut at the mill with a tongue and groove shape.

Figure 2-33 Tongue and Groove Wood Sheet Piling



2.2.1.2. Typical Timber Bulkheads

Figure 2-34 shows a conservatively designed, low height bulkhead where the existing grade along the sheet piles is somewhat higher than the low water level. Figure 2-35 shows an intermediate height bulkhead suitable for retaining fill at the site of a marina or for providing a finished waterfront in a housing development. If these bulkheads are located inshore, or if the outside water level variations are less than shown in the figures, the heights of bulkheads and lengths of sheet piles may be reduced based on design computations.

Figure 2-34 Bulkhead Design, Zero-Foot Water Depth

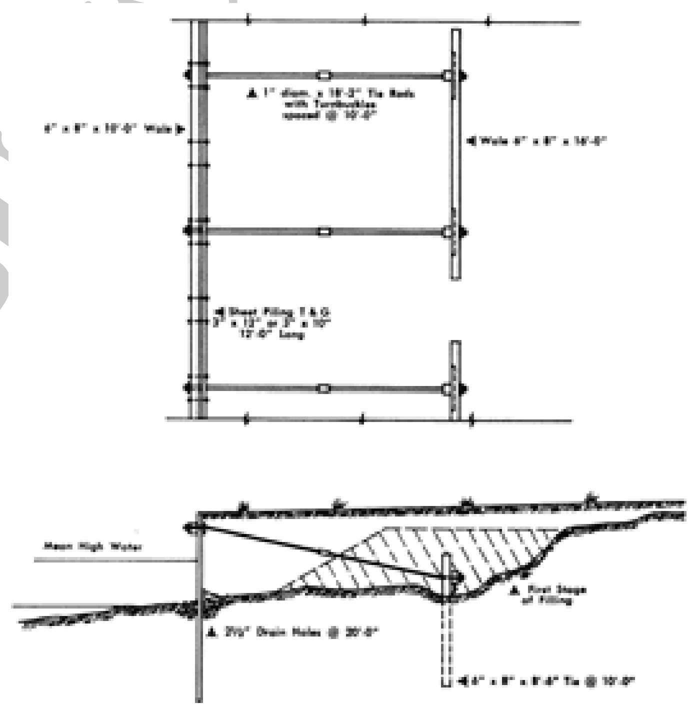


Figure 2-35 Bulkhead Design, Four-Foot Water Depth

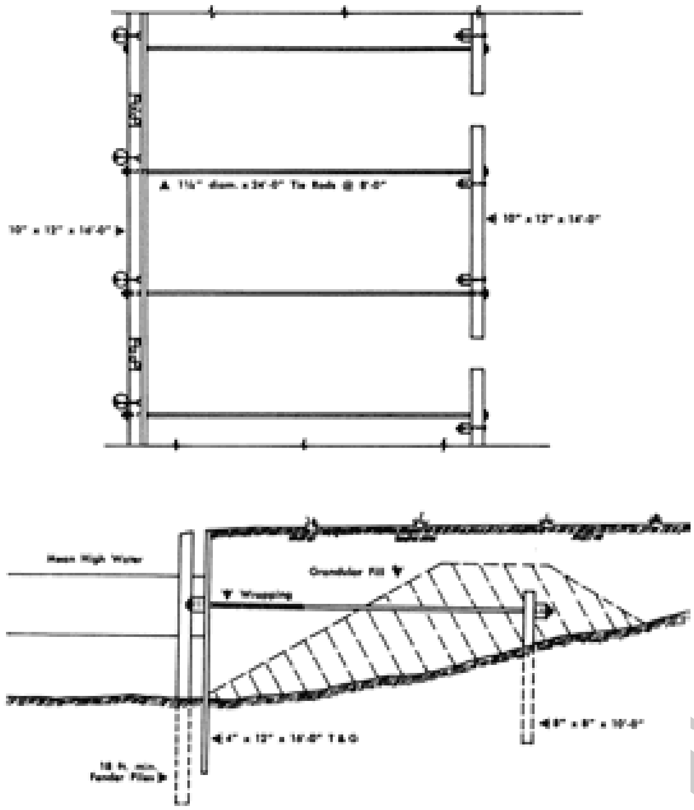
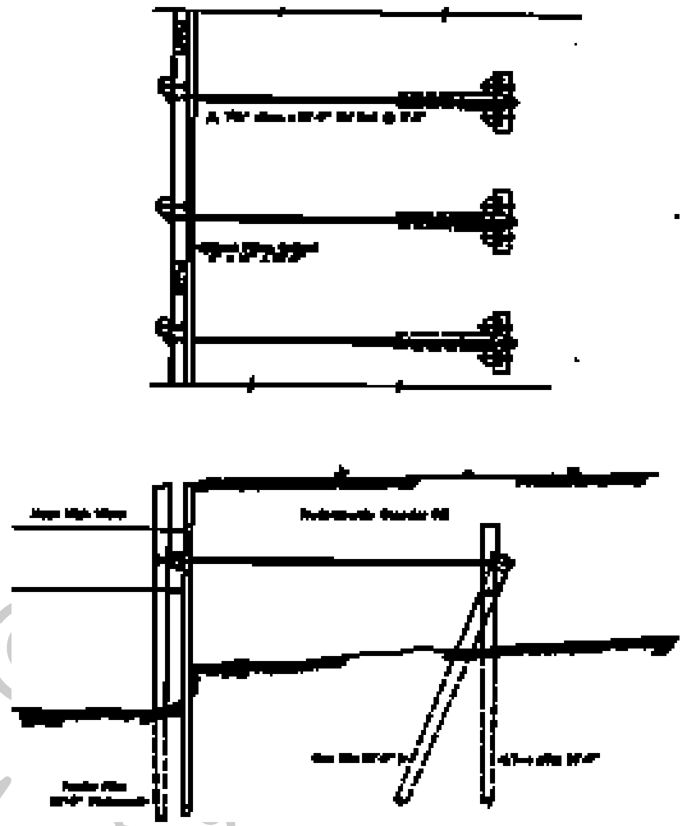


Figure 2-36 Bulkhead Design, Eight-Foot Water Depth



The anchorage systems (Figure 2-34 and Figure 2-35) depend upon the passive resistance of the earth immediately around the anchor post and wales. The theoretical mound required to develop this passive resistance is shown by a dotted line. If backfill is placed directly against the sheet-pile bulkhead before this mound of earth is placed around the anchor system, the resulting forces may displace or fail the bulkhead, resulting in a costly and disastrous failure. After the mound is placed over the anchorage system, backfill can be deposited against the sheet piles by suitable methods.

Figure 2-36 shows a bulkhead suitable for the deepwater marinas, or for locations where the existing water depths are 6 to 8 (1.8-2.4 m) and extensive landfills are desirable. The anchorage system (Figure 2-36) is a self-supporting A-frame that does not depend on passive earth resistance. This anchor system is particularly adaptable to filling by the hydraulic method because the backfill can be raised behind the sheet piles without regard for the placement of backfill at the anchorage location.

To install the A-frame anchorage, a pile-driving rig is required to drive the piles to specified bearing capacity and length. At locations with less water level variation that the 4 (1.2 m) shown, the height of finished grade may be lowered proportionally. For an increase in water level variation, a similar increase in height of finished grade can be made with a corresponding reduction in water depth. The 5 (1.52 m) vertical distance from finished grade to tie rod level should be maintained.

A typical completed timber bulkhead is shown in Figure 2-37.

Figure 2-37 Completed Timber Bulkhead

2.2.2. Concrete Sheet Piles

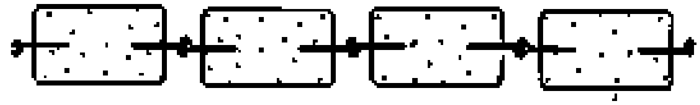
For sea walls, groins and other waterfront structures, precast concrete sheet piles are often economical. They are normally used in situations where the precast members will be incorporated into the final structure or are going to remain in place after they fulfill their purpose. Precast concrete sheet piling is usually made in the form of a tongue and groove section. The individual pieces vary in width from 18" (457.2 mm) to 24" (609.6 mm) and in thickness from 8" (203.2 mm) to 24" (609.6 mm). They are reinforced with vertical bars and hoops in much the same way as precast concrete bearing piles. For seawater contact especially, prestressing is most desirable, as the minor cracks are kept closed so salt does not get to the reinforcing. This type of sheeting is not watertight, but the spaces between the piles can be grouted.

Figure 2-38 Concrete Sheet Piling

Tongue and groove design, or a slot for grouting, will help to make the wall watertight. The slot would have to be washed out after pile installation and grout forced into the opening. For driving, a bevel of about 30º at the bottom on the leading edge of the pile will force the section being added tightly against the wall already in place.

In order to provide a watertight precast concrete sheet pile, two halves of a straight steel web sheet pile, which has been split in half longitudinally, are embedded in the pile, as shown in Figure 2-39.

Figure 2-39 Concrete Sheet Piling with Steel Interlocks



Jetting is frequently used to install concrete sheet piles in sand. The pile must be installed while jetting, as the jetted hole may not stay open.

The Portland Cement Association and the Prestressed Concrete Institute have data on manufacturing and installing concrete sheet piles.

Photo and Figure Credits

- GRL and Associates/Pile Dynamics, Inc.: Figure 2-3, Figure 2-10.
- Plastic Pilings, Inc.: Figure 2-15
- J.A. Rauch Construction Co., Inc.: Figure 2-37.
- Prestressed Concrete Institute: Figure 2-11, Figure 2-12, Figure 2-13, Table 2-10.
- Don C. Warrington, P.E.: Figure 2-2, Figure 2-3, Figure 2-4, Figure 2-5, Figure 2-14, Figure 2-26.

Footnotes

[1] Bethlehem Steel Piles, Bethlehem Steel Corporation, July 1979

[2] Gerwick, B.C., Jr., Bach, P.B., and Fotnos, G. "In the Wet." Civil Engineering, May 1995, pp. 46-48.

[3] A thorough discussion of this topic can be found in the Pile Buck Sheet Piling Design Manual.

[4] Mandrels are discussed in the chapter on installation equipment.

[5] Bengt Fellenius, who has had long experience with precast piles, suggests less cover for greater pile strength. This requires that close positioning tolerance be strictly adhered to. Placing the longitudinal reinforcing accurately so it has a dependable cover of just 1" (25.4 mm) to the outside of the steel will result in a stiffer pile that is better able to withstand driving stress. This will provide greater strength and minimize risk of cracks in the pile.

[6] For some years this was a standard of the American Association of State Highway Officials and PCI. AASHTO has discontinued participation in such joint activities.

[7] ACI recommends a limit of 8% C_3A for sulphate concentrations between 0.1 and 0.2% and a limit of 5% for concentrations over 0.2%. However, for the higher strength concretes (8000 psi and over) employed in the manufacture of prestressed piles, the 8% limit on C_3A is considered

adequate for sulfate concentrations over 0.2% (see ACI Journal, August 1973).

[8]Neat cement grouts used in bonding post-tensioned tendons should follow the "Recommended Practice for Grouting Post-Tensioned Prestressed Concrete" (PCI JOURNAL, Nov.-Dec., 1972).

[9] Where the taper applied to the butt circumferences calculate to a circumference at the tip of less than 16 in., the individual values have been increased to 16 in. to assure a minimum of 5-in. tip for purposes of driving.

Diameters are approximate. Circumferences are the specified requirements.

[10]J. Much (U.S. Coast Guard's "The Engineer's Digest" March-April, 1958) reported greater resistance of Greenheart piling to marine borer attack compared to creosoted yellow pine at the San Juan, P.R. Base. Both species were included in test Dolphins built at the base. After three years, the Greenheart was still in good condition while the pine had revealed some attack. Presumably, these tests were continued and information compiled beyond 1957

[11] The tests were conducted by Shimel and Sor, T.L., for Greenheart Associates-Demerara Inc.

[12] Heinz, R., "Plastic Piling." Civil Engineering, pp. 63-65, April 1993.

[13] This statement reflects design practice in the U.S. In the E.U., the interlocks are frequently ignored as they are along the neutral axis, and two sheets are treated as one section.

[14] An example of a real down-to-earth rule of thumb corrosion check is this: if grass is not growing where you want to place the wall, there probably is a problem with pH. Grass will normally grow in the 4.5 to 8.5 range.

[15] Tensile strength figures such as these do not take into consideration that vinyl is subject to creep. A reasonable figure for creep limited tensile stress is 4,000 psi. With a factor of safety of 2, this would mean an allowable stress of 2,000 psi. A factor of safety of 1.5 (and a corresponding allowable stress of 2,667 psi) can be used only with certain types of materials and with the recommendation of the manufacturer. The industry standard for determining the creep limited stress is ASTM D5262 for a minimum duration of 10,000 hours. This test is done on samples collected from the finished product. Therefore, it not only verifies the performance of a particular vinyl compound, but also the method of manufacture as well.

[16] Important Note for Close Tolerance work: Holes drilled in composite structurals are generally .002" to .004" undersize. Thus, a 1/8" drill will not produce a hole large enough to admit a 1/8" expanding rivet. Instead, a No. 30 drill must be used. This should be noted when drilling for wale and/or tie rod hardware placement. Remember, just as in cutting operations, drilling should be done in a light, evenly applied pressure.

[17] Consider carefully the use and design of fastening devices for mechanical connections of any composite structure.

[18] The proper washer will aid in distributing "load stresses" which is critical in the design of any composite structure.