CURRENT PRACTICE IN DESIGN AND INSTALLATION OF DRIVEN PILES

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Tests have proved that H-piles can dependably carry heavier loads than usually are assigned to them. Concrete and timber piles are being loaded heavier. Prestressed concrete piles benefit from improved splicers. Gaining in use are H-pile extensions for precast. The H end, with cast steel protection, can assure penetration into compact material; it can prevent sliding of sharply battered piles or piles driven on steeply sloping rock; it provides protection to the vulnerable end of a precast pile. An import from Europe is an interlocking deep-web H that can be used with sheet piles for cofferdams or a strong wall. Improved mandrels have increased use of corrugated shell piles. The wave equation is increasingly used for determination of driving stresses and selection of the optimum combination of pile and hammer. Dynamic measurement gives instant pile capacity information at minimum cost. More adequate soils investigation and foundation planning can reduce overall cost.

Recent comprehensive tests have proved that H-piles can dependably carry heavier loads. Use of H-section extensions on precast piles makes it practical to drive on to sloping rock or to penetrate dense materials such as boulder-filled tills. Precast piles--most often prestressed--are gaining in use.

Pipe piles currently are used less than in the past but are preferred by some as the inside of the pile can be checked after driving; especially for waterfront work they can be made large for the loads and lateral strength needed. Corrugated shells, installed with a mandrel and filled with concrete, continue to be a popular design for larger projects where soils are suitable. Timber still is used in quantity for lighter loads. Augering to place concrete as a deep shaft without driving is expanding but is outside the scope of this presentation.

Diesel hammers are used very widely--especially for moderate size bridge projects where a relatively few piles are needed for each of several supports. Steam-air hammers are used extensively in urban areas, following long-established work practices. The heavy ram, and short stroke of the single-acting steam-air hammer has generally been found preferable for driving heavy precast piles. In some soils more rapid strokes may drive even the large displacement piles faster. Diesel hamers require resistance to driving to continue firing. Steam-air hammers may work more satisfactorily where initial driving is through very soft materials. (Ref. 1)

Steam hammers are popular for use on floating rigs where boilers may be part of the equipment for other needs. If a compressor or boiler is conveniently available, it may be preferable to use an on-hand steam-air hammer rather than purchase or rent other equipment. Economy of this should be carefully checked. Drop hammers are not much used in the U.S. but continued satisfactory results elsewhere may result in a resurgence of their use. A Swedish development provides for rapid lifting by hydraulic means, then a free fall for a heavy drop. Load bearing capability of driven piles is being quickly checked by dynamic information fed into a job site computer.

Design loads generally have increased for all types of piles. More dependable subsurface data, more knowledgeable interpretation of test results, plus improved installation methods and inspection procedures have made this practical. This has reduced the factor of safety, which in the past may have been a factor in avoiding unacceptable settlements.

H-piles At 18,000 PSI Working Stress

Under American Iron and Steel Institute (AISI) sponsorship extensive tests on driven long H-piles provided verification for loading A-36 steel to one-half of its 36,000 psi yield strength. This is 248 in SI MPa units. The tests were made at Bethlehem Steel Corp.'s construction of a blast furnace at their Sparrows Point, MD, plant. The tests were planned and conducted under supervision of Thomas D. Dismuke, Chairman of the AISI Subcommittee on Steel Piles and a consultant in the Technical Services Engineering Department of Bethlehem Steel Corp.

Soils under the furnace are sedimentary, mostly sand, gravel, clay and silt. The first dependable bearing strata is at 27 m (88 ft) depth. Test and production piles were driven to 30 to 33 m (100 to 110 ft) to obtain adequate support for the blast furnace. Several piles were test loaded; some were instrumented and a few were pulled. For one, a 560 mm (22 in.) diameter casing was driven to 28 m (90 ft) and cleaned out to 24 m (80 ft) then an HP 360 x 108 (14 x 73) driven inside the pipe to bearing in the sand. This eliminated frictional support of the upper fine-grained soils to give dependable bearing capabilities. Pile tip movement after driving and test loading, to over 450 tonne (500 tons), was roughly twice as much for the pile driven inside the protective casing. But net settlement after removal of load was less than half as much for the protected pile as for the one driven full-length through the soil. (Ref. 2) Conclusions in the referenced article include:

1. The tested piles can be normally driven to safely support loads at stress levels exceeding 0.5 f_y.
2. The current use of the concept "freeze" is not adequate to predict the load capacity difference between results of pile tests and wave equation solutions.
3. The wave equation was very inaccurate in the prediction of the driving stress.

Properly, many codes and jursidictions are cautious about use of half the yield strength of steel as a safe loading for H-piles driven into unknown obstructions in the underground. After considerable study New York City accepted .35 f_y or 86.8 MPa (12,600 psi) on A 36 steel. This has been in effect for a few years. No problems are known to have developed from this if adequate safeguards and inspection are given to installation. But Boston still has 58.6 MPa (8,500 psi) as the upper limit in its code. The American Association of State Highway and Transportation Officials specifies 6.2 MPa (9,000 psi) where test or other means are not used to prove greater strength value.

Bethlehem Steel Corp. used cast steel point protection on piles driven in critical areas. Such points have become quite common for use on H-piles driven into difficult ground. Observation of pulled H-piles and soldier piles where excavated to below their tips, show that point reinforcement can be most helpful in enabling the pile to penetrate to desired strata in dependable bearing conditions. Close observation at two test sites provide details.

Interlocked H-sections For Deep Cofferdams

From Arbed in Luxembourg come interlocking H-piles arranged for use with steel sheet piles. The H-piles can be used as a high section modulus continuous wall with an interlocking bar connection. Or, they can be used as mater piles with a pair or more of Z type sheet piles between them. This reduces the section modulus per linear length but also the amount and cost of the steel.

The interlocking H-sections are available in several configurations at about 0.58 to 1.00 m (23 to 39 in.) web depth and flange widths of 360 to 460 mm (14 to 18 in.). Sections are available in different web and flange thicknesses. Several shapes of sheet piles from Arbed interlock with the deep H-sections to give a wide choice of section modulus and wall strength.

Figure 1. New from Europe is an interlocking deep section H with high section modulus for cofferdams or dock walls. Interlocking Z sections can be alternated to reduce steel weight and cost.

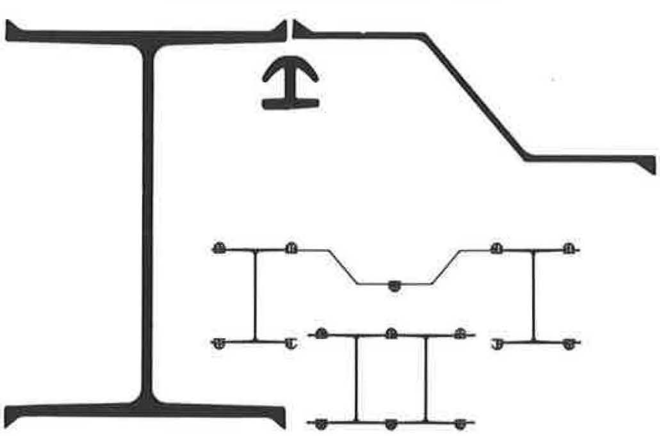


Figure 2. For a bridge over the Columbia River near Portland, cast steel points protect the interlocking H-sections for driving through boulders.

Figure 3. One side of the connecting bar is cut back a little at the top to ease threading of the front and rear interlocks.

Where a continuous H wall is used with the interlocking bar on both face and rear the wall can be exceptionally watertight. For special conditions clays or other materials can be puddled between the H-sections.

Tests Prove H-pile Value

H-piles Replace Caissons

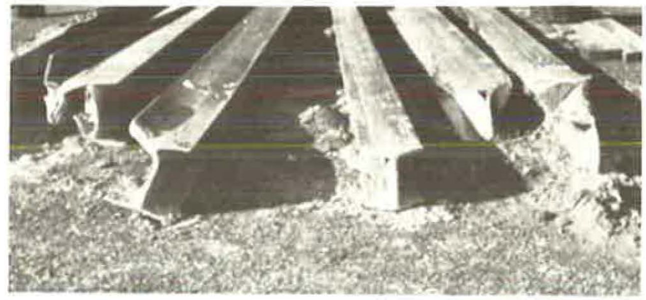
On a project in a mixed limestone area the owner asked that a test be made using H-piles for a parking garage where caissons on a nearby job had far overrun the contract amount. At a shallow area and at a deep area, some 100 m (330 ft) apart, an HP 250 x 62 (10 x 42) was specified to have cast steel point protection. At the deep area a comparison HP 250 x 85 (10 x 57) was required. The contractor for the test installation elected to drive reaction piles to develop the test load. HP 310 x 79 (12 x 53) were used as tension piles--without end protection.

Figure 4. With cast-steel end protection H-piles can be driven into medium hard rock. Note how the contractor utilized salvaged guard rail.

On the test at the shallow area the HP 10 x 42 with point protection and six HP 310 x 79 (12 x 53) reaction piles were driven to a moderately hard limestone with a Link Belt 440 double-acting diesel hammer, rated at 2520 kg-m (18,210 ft lb). After testing the HP 250 x 62 (10 x 42) to the desired load the seven piles were pulled. All six of the unprotected HP 310 x 79 (12 x 53) were damaged, see photo. The HP 250 x 62 (10 x 42) test pile, with a cast-steel point was the only pile not damaged. Significantly, none of the experienced pile driving crew were aware of the damage to the piles.

At the deeper area of the site the test pile and comparison pile were driven to 90 ft depth. The unprotected HP 250 x 85 (10 x 57) was twisted into a "bow-tie" at the tip, with undependable bearing capability. The HP 250 x 62 (10 x 42)--with a 10 kg (23 lbs) cast steel point but some 590 kg (1,300 lb) less steel--was damaged. Some HP 310 x 79 (12 x 53) reaction piles were mangled on small boulders at 7 m (23 ft) depth--above material resisting only four blows on a standard sampling spoon. Several piles could not be pulled, probably because they were badly distorted by driving onto obstructions. (Ref 3)

Figure 5. Test pile HP 250 x 62 (10 x 42), 3rd from right with point protection was unharmed by driving that damaged all six HP 310 x 79 (12 x 53) driven as reaction piles.



Through Muck To Rock On Ohio DOT Tests

The State of Ohio, with Federal Highway Administration funding, experimentally drove H-piles through 7 to 8 m (23 to 25 ft) of soft silt then directly on to a hard limestone to obtain guidance for foundation design. Three piles were driven with each of five hammers to develop comparisons of driving capabilities and characteristics. (Ref. 4)

Figure 6. Piles were driven with five different hammers. The vertical and adjacent batter pile were driven with a Link Belt 520 (3,640 kg m or 26,300 ft lb). Next pile was driven with a Vulcan 08 (3,600 kg m or 26,000 ft lb). Hammer seen is a Kobe 25 (7,000 kg m or 50,700 ft lb). Case-Goble device for instantaneous determination of pile capacity is seen in the van.

Table 1. Pile hammers used in Ohio DOT Tests. (From manufacturer's published data) The Link Belt is a double-acting diesel; the Vulcan is single-acting, air powered; the Kobe are single-acting diesels; the MKT is double-acting, air powered.

	Energy		Ram Weight		Total Weight		Strokes
Hammer	Kg m	Ft lb	Kg	Lb	Kg	Lb	Minute
Link Belt 520	3,640	26,300	2,300	5,070	5,670	12,550	80-84
Vulcan 08	3,600	26,000	3,630	8,000	7,600	16,750	50
Kobe 13	3,400	24,400	1,300	2,860	3,600	8,025	45-60
Kobe 25	7,000	50,700	2,500	5,510	5,950	13,100	39-60
MKT 9B3	1,210	8,750	720	1,600	3,170	7,000	145

A vertical pile and a pile on a 1:4 batter were driven with each of the five hammers listed in Table 1. An additional HP 250 x 62 (10 x 42) with a cast steel tip reinforcement was driven with each of the four more powerful hammers. It was not thought necessary to protect the end of a pile driven with the 1210 kg-m (8,100 ft lb) hammer; but when pulled both the vertical and batter piles driven with the small hammer were found to be damaged beyond end-bearing capability. (The paper at this seminar by Ray Grover of the Ohio Department of Transportation covers this in more detail.)

Figure 7. Pile at left, with point protection, was driven with the Kobe 25, a 7,000 kg m (50,700 ft lb) hammer as was the third pile. Others in Ohio test were driven with smaller hammers.

Photos show the driving and some of the pulled piles on the Ohio DOT tests. It should be emphasized that these piles were driven through a soft silt then suddenly on to a hard limestone. It has long been recognized that tip protection is essential under this condition. The U.S. Steel Corp. booklet on H-piles states: "If impenetrable rock is overlaid with soft material with little horizontal stability, the pile tip must be built up with points."

Pile Capacity By Dynamic Measurement

The driving was monitored by the Case-Goble method of dynamic pile capacity determination. This is based on the now widely accepted wave equation. The Pile Analyzer records strain and acceleration in a unit that has been developed to a size that can be put into a couple of suitcases for air transport or taken to a job by car. With knowledge of pile type, size, and length an instantaneous determination of total capacity can be made.

This system was developed by Prof. George Goble while at Case-Western Reserve University in Cleveland. Dr. Goble is now Chairman of the Department of Civil, Environmental and Architectural Engineering at the University of Colorado, Boulder, CO. These units are finding increasing use for checking pile capacity; they are available for purchase or rental at moderate cost. More than 20 driven piles can be checked for capacity in half a day with a mobile crane, an efficient hammer, and a crew experienced with the device. It can be used for timber, precast concrete, H and pipe piles.

Transducers are placed on top of the pile or attached to a side and connected to a recording device. The force and acceleration during driving are recorded in analog form on magnetic tape. The tape record can be converted to digital form and further processed using FORTRAN software.

Returning to the Ohio tests, the Case-Goble computer recorded good capacity for all piles at the first blows as each pile struck the limestone. But after a very few blows on piles without end protection the indicated capacity dropped off rapidly; the hammer-pile sound became a dull thud. The pile continued to move down, as if it were penetrating the limestone. When pulled, the piles were found to have the tips badly mangled. (See photo.)

Piles with the protection of cast steel points stopped moving when the limestone was struck. The sound continued to be a live "ring"; the computer showed increasing capacity for each of the piles. Under continued driving with powerful hammers the piles with point protection started to buckle in column failure in the 2.5 m (8 ft) length above the ground. There was no evidence of column bending from driving in the length embedded in the soil on any of the piles.

Another job reported in the Ohio DOT test series involved HP 10 x 42 driven into a shale. Here all piles installed and tested performed satisfactorily. H-piles are being driven into boulder-filled stream beds and through dumped rock. With end proteciton, H-piles can be driven straight enough that they can be used as a single line column support exposed up to the superstructure.

Laboratory Tests Develop Reasons For Pile Deformation

After loading H-piles--with and without point protection--to failure in a laboratory compression machine, Dr. Roger Slutter, director, Fritz Engineering Laboratory at Lehigh University had comments as briefed here.

"The flanges of a steel pile at the tip are very susceptible to buckling when the tip of the flange encounters resistance in driving. The AISC and AREA specifications give limits on the ratio b/2t and the AASHO specifications give a limit of b/t as a means of indicating when the flange width of a section is such that the section can be described as a compact section (b is width, t is thickness of flange). For ASTM A 36 steels the limit of b/2t suggested is 8.5. For all pile sections except HP 250 x 85 (10 x 57) the ratio of b/2t exceeds 8.5.

Figure 8A. Loading under corners of H caused early failure in Lehigh tests.

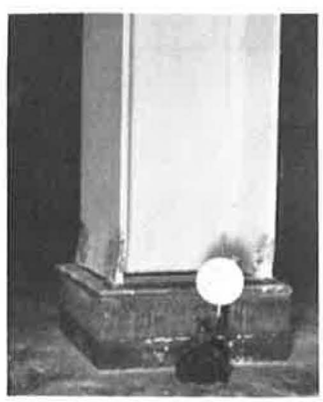


Figure 8B. Loading under web through cast steel point distributed load.

"All rolled sections have residual stresses formed when the section cools after rolling. The flange tips, which cool first, have a compressive residual stress and webs have a tensile residual stress. The compressive residual stress in the flange tip for light steel sections of similar shape is about 914 k-cm^2 (13 ksi). To this must be added the stress from driving. For a pile cross section the flange could be expected to buckle at a compressive strength of 1406 k-cm^2 (20 ksi) would produce buckling.

"For a load under the web of a pile that has a tensile residual stress of the order of 492 k-cm^2 (7 ksi), it would require an applied stress of 1900 k-cm^2 (27 ksi) to buckle the web. Since pile sections have the same web and flange thickness, the pile tip performs far better when the web is the first to meet resistance in driving. The highest tensile residual stress is found at the junction of the web and flange. When the tensile stress generated by buckling is added to the tensile residual stress the flange will tear from the web at stress levels lower than the yield stress. This explains why driving without end protection is so variable.

"Pile points overcome the unfavorable geometry of the pile cross section in several ways: They have a more favorable b/t ratio than the pile cross section; They do not have the unfavorable residual stress distribution that exists in the pile section; They tend to distribute the load more uniformly over the cross section of the pile regardless of what point first encounters resistance. Finally, they provide bracing for the delicate flange corner." (End of comments by Slutter; Ref. 5)

Additional H-pile Sections

New in the H-pile field are additional sections in the 310 mm (12 in.) depth and a series of 330 mm (13 in.) H. These are, or are to be, rolled by Armco at Houston and Inland in the Chicago area. Neither Armco nor Inland can roll the conventional 360 mm (14 in.) with up to 378 mm (15 in.) wide flanges of the H sections. The fabricators expect to have a sales advantage with the 13 in. H. Some suppliers are equipment makers are unenthused about required additional sizes and inventories. But American Iron and Steel Institute has accepted the new sizes and worked out dimensions for them. Table 2 gives metric and conventional details.

H-piles are available in a wide range of sizes and areas to meet any load-bearing requirement. They are easily handled; they can be extended to any length. If an end or section is damaged, the rest of the length can be salvaged at little cost. Splices can be made by conventional full penetration welding. More popular is a manufactured unit with flared ends, which slips on one end of a pile then safely and quickly aligns the added length and assures that the ends stay in line. The splice is two shop fabricated U sections with an accurately positioned spacer. The outside of the flanges of the top length of H is beveled. The splicer is slipped on the pile; a short fillet weld is made to the flange near each corner of the U-shaped splicer. The new length is positioned on the driven length. A penetration weld is made along the full width of each flange to complete the joint.

Pipe Piles - Driven Open or Closed End

Use of pipe piles in the U.S. varies considerably from year to year. Currently only occasional projects are designed with pipe piles--despite the fact that engineers like the opportunity to look down the tube to assure themselves all is well. Pipe driven open-end, cleaned out to rock and again driven for firm contact, then filled with high quality concrete is allowed high loading under most jurisdictional codes.

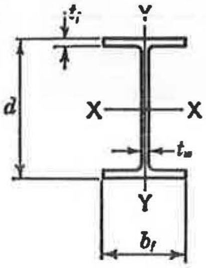
Pipe to be driven open-end as a pile should have a minimum outside diameter of 254 mm (10 in.) and wall thickness of 6.3 mm (0.25 in.). Wall thickness for 356 mm (14 in.) and larger pipe should be 7.9 mm (0.310 in.). Pipe more than 450 mm (18 in.) should be at least 9.5 mm (0.375 in.) wall. Stress usually allowed is 0.35 f_y on ASTM A 272, pipe; stress on concrete fill may be 0.33 f_c; in the past a top limit of 6.9 MPa (1,000 psi) has been common, but this has been increased.

Wall thickness must be gaged to driving obstructions and expected end contacts. Driving shoes of cast steel are used to protect the end of the pipe. Such shoes usually are an outside type with perhaps 9.5 mm (3/8 in.) extension beyond the pipe. This may reduce friction while driving; this generally is accepted as being desirable. An inside shoe is available; it is preferred, and needed, in permafrost where the soils do not reform and friction along the pipe is essential. It is difficult to do chopping and cleaning in the pipe when an inside shoe is used.

Both types of cast steel shoes attach with a minimum of welding as they have a square ledge on which driving is done in compression. This contrasts with wrapping a hardened, thick structural plate around the pipe and attaching it by welds in shear. Special techniques and perhaps heat-treating are required.

An extension of the open-end pipe is the Drilled-In-Caisson. The open-end pipe is driven to contact, cleaned out and a hole drilled into the rock at least 30 cm (1 ft) deeper than the diameter of the

Table 2. H-Shapes Table A1.4 From American National Standards Institute/American Society for Testing and Materials publication A6-77b provides details of new H-shapes.



Designation (Nominal Depth in Inches and Weight in Pounds per Linear Foot)	Area A, in.^{2}	Depth d, in.	Flange		Web Thickness t_w, in.	Designation (Nominal Depth in Millimetres and Mass in Kilograms per Metre)	Area A, mm^2	Depth d, mm	Flange		Web Thickness t_w, mm
			Width b_f, in.	Thickness t_f, in.					Width b_f, mm	Thickness, t_f, mm	
HP14X 117	34.4	14.21	14.885	0.805	0.805	HP360X 174	22 200	361	378	20.4	20.4
X 102	30.0	14.01	14.785	0.705	0.705	X 152	19 400	356	376	17.9	17.9
X 89	26.1	13.83	14.695	0.615	0.615	X 132	16 800	351	373	15.6	15.6
X 73	21.4	13.61	14.585	0.505	0.505	X 108	13 800	346	370	12.8	12.8
HP13X 100	29.4	13.15	13.205	0.765	0.765	HP330X 149	19 000	334	335	19.4	19.4
X 87	25.5	12.95	13.105	0.665	0.665	X 129	16 500	329	333	16.9	16.9
X 73	21.6	12.75	13.005	0.565	0.565	X 109	13 900	324	330	14.4	14.4
X 60	17.5	12.54	12.900	0.460	0.460	X 89	11 300	319	328	11.7	11.7
HP12X 84	24.6	12.28	12.295	0.685	0.685	HP310X 125	15 900	312	312	17.4	17.4
X 74	21.8	12.13	12.215	0.610	0.605	X 110	14 100	308	310	15.5	15.4
X 63	18.4	11.94	12.125	0.515	0.515	X 93	11 900	303	308	13.1	13.1
X 53	15.5	11.78	12.045	0.435	0.435	X 79	10 000	299	306	11.0	11.0
HP10X 57	16.8	9.99	10.225	0.565	0.565	HP250X 85	10 800	254	260	14.4	14.4
X 42	12.4	9.70	10.075	0.420	0.415	X 62	8 000	246	256	10.7	10.5
HP8 X 36	10.6	8.02	8.155	0.445	0.445	HP200X 53	6 840	204	207	11.3	11.3

pipe. A heavy H-section may be set into the pipe and socket; it may extend to the surface where a milled contact can be made to directly support major columns of power plants and the like. For lighter loads of H-section or reinforcing bars twice the depth of the rock socket may extend above the rock to transfer load to the pipe. In this arrangement loading has been allowed as high as 0.35 f_y (with f_y taken as not greater than 241 in SI, MPa units or 35,000 psi) on the pipe; 0.45 f_c (up to 13.8 MPa-2,000 psi) on concrete and 0.50 f_y on protected steel in the core.

Conical Points For Closed-End Pipe

Pipe is most often installed with the bottom closed with a conical point or flat plate. Conical points are quite generally preferred. Flat plates may be used because they are cheaper. Pipe thicker than 3.1 mm (1/8 in.) is usually allowed working stress. Pipe with a wall thickness less than 4.7 mm (0.188 in.) generally must be driven with an inside mandrel. Even the 4.7 mm (0.188 in.) wall requires special care; pipe 6.2 mm (0.25 in.) thick will withstand ordinary driving.

Conical points push the soil aside, compressing rather than displacing it so maximum friction is quickly restored. They also distribute the load to the entire periphery of the pipe at obstructions and final bearing. The 60 degree configuration seems best for penetration and for resistance to damage. Flatter points on large diameter piles have been known to have difficulties. Outside-flanged points can be beveled so attachment can be made without welding; swabbing on a little roofing tar will take care of severe water conditions. The inside-flange concial point requires welding as it is not practical to make it to the many inside dimensions of different wall thicknesses. Additionally, the pipe might split from hard driving over an inside flange.

Flat plate closure on pipe piles is said to develop a cone ahead of the driving similar to the conical point. It has been found when testing piles that this compressed cone slowly spreads to the surrounding soil and may permit continuing movement. This delays completion of a test and introduces questions about possible settlement of the structure.

Splice Pipe Piles Without Welding

Like H-piles, pipe can be economically adjusted to different lengths and unexpected conditions. Cut-offs can be salvaged for reuse. Pipe can be extended readily by adding sections. For butt welding the upper sections should have the contact end beveled for good penetration. (The driving end of the pipe should be left square for the hammer.) For welding, a spacer bar with break-off nibs is available for insertion in the pipe for back-up.

A tapered outside splicer, with a square-ledge stop at the center, can be set on the driven length and the added length driven down into it. This swages the two ends tightly into the splicer bar to make a friction joint without welding. The same splicer device is available without taper for welding on the bottom section while in convenient horizontal position. Driving can be done on the splicer. Another length of pipe can be set in and welded down-hand. This is especially useful where headroom for driving is small and several splices must be made adequate to resist uplift. The splicers also are useful for underpinning; here they are usually installed without welding as the jacking is axial on the square end of the pipe.

Corrugated Shells and Uncased Piles

In recent years several mandrels have been developed for installing uniform diameter corrugated shells for silling with concrete. Shells are made by several fabricators and generally are 12 to 18 gage with 12 x 50 mm (½ x 2 in.) corrugations. They are welded or crimped watertight and have a pan or boot for end closure.

Shells are pulled up over the mandrel which is then pneumatically, hydraulically or mechanically expanded to fit into the corrugations, Figure 9. This holds the shell firmly while driving is done and others make mandrels; most of these are available on a rental basis. Step-taper piles generally are driven with a non-expanding core, which drives by contact of shoulders at size changes of the shell--usually 2.4 to 3.6 m (8 to 12 ft). An enlarged precast concrete tip with a corruaged shell cast into its center and extended to lengths needed has proven effective in some soils, Figure 10. An earlier practice of driving a closed-end pipe mandrel, filling it with concrete and withdrawing the pipe to leave an uncased shaft in the ground has been almost entirely replaced by augering a hole for the concrete.

Timber Piles

Timber piles are used for support of many structures and for waterfront needs. Clean-up of pollution in some harbors has made the waters hospitable to marine organisms that destroy piles. Structures in such harbors should be frequently examined to determine that support capacity continues adequate.

The American Wood Preserves Association have been effective in increasing the allowable loads and permissible stress on timber piles. Some engineers feel this may have gone too far. Use of steel to provide end protection for wood piles is increasing. A "boot" that covers the full available area of the pile is substantially more effective than use of a point that requires cutting is not symmetrically done.

Most timber piles installed currently are creosote treated. Piles that will always be below a permanent water table, as for many bridge foundations, can be untreated at a substantial savings. Sometimes untreated

Figure 9. Guild mandrel.

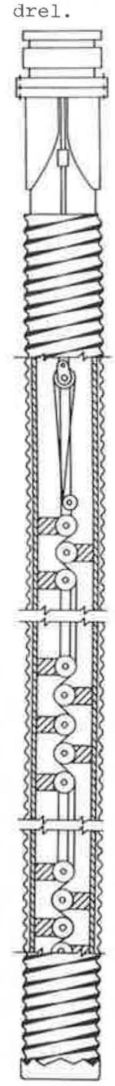
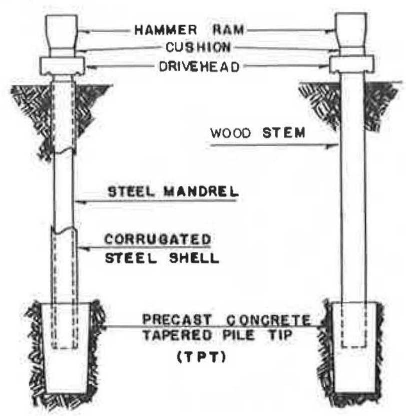


Figure 10. Enlarged precast tapered tip.



timber may be used for a lower section of pile with cast-in-place concrete for the length above permanent ground water. A casting is available for attachment by welding to corrugated shell; barbs for driving into the top of a driven length of timber. A pipe mandrel is placed inside the shell for driving the timber to greater depth and drawing the shell down with it for filling with concrete. Similar connections are available for pipe or fluted steel lower ends with corrugated tops.

Precast-Prestressed Piles Gain In Use

Precast--and usually prestressed--piles are a growing foundation support material. They have their tip problems as well as splicing difficulties. Splices are avoided where possible.

Big equipment makes it practical to cast and drive in up to 30 m (100 ft) lengths; piles may be substantially longer where they can be set in deep water. In New Orleans in the deep silts of the Mississippi River Delta 20 to 30 m (65 to 100 ft) lengths may be spliced to reach very deep bearing strata. Many means of splicing precast piles have been developed; all concerned with long precast piles keep striving for the perfect splice.

Current practice is covered in a Prestressed Concrete Institute committee report "Recommended Practice for Design, Manufacture and Installation of Prestressed Concrete Piling." This appeared in the March-April 1977 Journal of the Prestressed Concrete Institute (150 N. Wacker Drive, Chicago, IL 60606) and is available as a 32 page reprint. Details of splicers and some comprehensive tests are in a reprint form the PCI Journal, No. 5 and 6 in 1974.

H-Stubs For West Coast Prestress

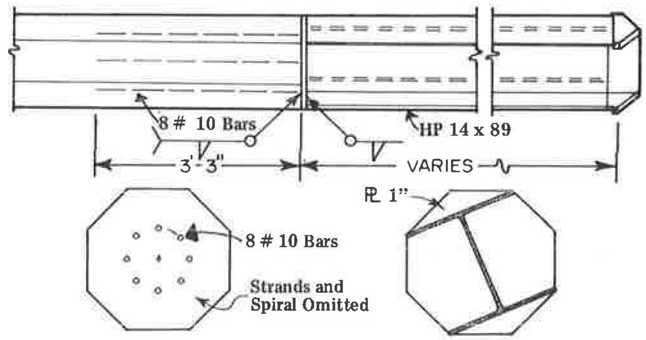
A recent development with precast piling is use of H-pile extensions for penetration in difficult ground. The H provides a toe hold in rock encountered at a sharp angle to the pile axis as well as protection for the concrete end. With a cast steel point on the H-stub it has been practical to penetrate into boulder-filled glacial till at a dock for the new Trident, the world's largest submarine. For this Pacific Northwest installation 610 mm (24 in.) octagonal prestressed concrete piles had a HP 360 x 152 (14 x 102) extension with cast steel point.

Figure 11. For the home port of the Trident Submarine on Puget Sound, H-stubs on 24 in. prestressed piles provided for driving into dense till.

This could penetrate to develop needed uplift resistance for piles more than 30 m (100 ft) long. The H was connected by welding to a plate that had ten No.11 bars 1.2 m (4 ft) long attached to the other side. The bars were slipped into the 370 mm (14½ in.) center void of the 610 mm pile and grouted in.

A nearby project for the Port of Vancouver, WA, on the Columbia River, utilized HP 360 x 132 (14 x 89) attached to 460 mm (18 in.) octagonal prestressed piles, Figure 12. It was found that with a cast steel shoe an H-pile extension could penetrate very dense gravels of the Troutdale formation for 10 m (30 ft) to develop 40 tons resistance to uplift. Unprotected H-ends were damaged and could not be driven deeply into the till. (Ref. 6)

Figure 12. Prestressed 18 in. octagonal pile with HP 360 x 132 (14 x 89) tip.



H Protection For Prestress In New York

In New York harbor prestressed concrete is desirable to minimize corrosion in the exposed length. Rock slopes sharply so H-pile ends are needed to secure bearing and minimize breakage. On test piles for a proposed convention center HP 360 x 174 (14 x 117) were cast 2.4 m (8 ft) up into 610 mm (24 in.) square prestressed piles and extended a few feet beyond the end of the concrete. Needed lengths of H were attached as extensions to reach required depth.

Hard driving on sloping rock damaged the end of unprotected piles. With a cast steel point a pile was driven without damage to 342 blows of a 8,300 kg m (60,000 ft lb) hammer for 10 mm (3/8 in.) penetration in a futile attempt to reach a deeper rock line erroneously indicated on plans. Point, pile and hammer all withstood this terrific overdriving.

The Wave Equation

By use of a differential equation that describes the mechanics of force transmission along an elastic rod (pile) that has been subjected to a mass having a specific initial velocity a Wave Equation has been developed. From this the energy transmission and the stress at any point along a pile being driving can be computed. This was first described by E.A. Smith, then Chief Mechanical Engineer of Raymond Concrete Pile Co.

All Elements Are Considered

In the wave analysis the propagation of the stress wave by a particular hammer operating under specific conditions is analyzed. This is done for each finite element of length. An almost infinite number of computations are required, made practical only by use of a computer.

Elements considered in anaylsis include: the soil into which the pile is to be driven; the piles selected for consideration, their weight, stiffness and length (splices add another element as wave propagation through them changes); the hammers available, the weight of the ram and its impact velocity, plus the characteristics of the driving cap, cushion blocks and the like.

The wave equation is the only method currently in use for determining the stress in a pile while it is being driven. This is a much greater stress than is developed under the static load of a structure.

The wave theory is valuable in planning for installation of large heavy piles, especially in precast concrete. It is helpful in selecting the hammer-cap block-cushion combination that will be most effective in installing big piles.

Wave Equation Has Limits

The wave equation is a theoretical solution rather than the empirical solution of most pile formulas. It describes only the structural dynamics of soil, pile and hammer. It does not solve the associated soils mechanics problems or infallibly predict the length of pile.

Like other foundation aids the wave equation will assist but cannot replace the judgment developed from experience in the field of pile driving by engineers and contractors.

Unsolved Problems

The foundation field probably will always have unsolved problems. Design and construction move out into areas previously thought unusable. Heavier loads are put on longer piles to be driven under tougher conditions. Foundations always area challenge to more economical and dependable solutions. No two sites are alike; even adjacent piles may be substantially different in driving characteristics and resistance to hammer blows. There will always be a need for experienced and competent foundation anaylists.

Negative Friction

Like the weather, everybody talks about downdrag or negative friction on piling, but no one has found a practical solution. It is recognized as a problem in many soils where consolidating clays will grip the bitumen has been placed on precast concrete piles. Handling piles with bitumen soft enough to alleviate friction is difficult and costly. An English contractor, who has installed such piles, has commented that on some work adding piles to carry the downdrag would have cost no more. It would have been less messy and perhaps more dependable. Applying soft bitumen to H-piles is not known to have been done successfully.

At Knoxville, Tennessee, fly-ash was used around HP 250 x 62 (10 x 42) in an attempt to prevent adherence of the weight of 7 m (22 ft) of compacted fill above a compressible strata. The piles were coated with 3 mm (1/8 in.) of rather hard bituminous material. A 25 mm (1 in.) square bar 280 mm (11 in.) long was welded transversely across the outside of each flange of the 3 m (10 ft) above the tip of the 15 m (50 ft) length to open a larger hold as the pile was driven.

Specifications required that fly-ash be mounded up around the H while driving so that it would follow down along the pile. Fly-ash is a hard-burned, microscopic-size waste by-product of coal-fired power plants. It is non-absorptive--essentially small roller bearings. Fly-ash used amounted to 10 mm (3/8 in.) of thickness around the length of the pile to which it was applied. There was no attempt to even-out its distribution. Funds were not available for testing to determine the value or amount of the fly-ash coating. Bentonite was considered for this application but the fly-ash was thought to be easier to handle on the job site.

Pile Corrosion Is Spotty

For piles driven into most ground and capped below the surface corrosion of steel is not a problem. But it should always be a consideration where piles are exposed even in fresh water as alternate wetting and drying and sulphates speed deterioration. Bituminous coatings, preferably shop applied after cleaning to white metal, is effective if it can be kept on during handling and driving.

Exposure in salt water and salt atmospheres frequently causes rapid deterioration of steel. Tie rods holding sheet pile walls are especially vulnerable. Extensive corrosion is often found in the tidal/splash zone. Butt welds deteriorate rapidly under some conditions, due to galvanic action. This has caused complete failure of support for some structures.

Cathodic protection can be used to direct corrosive forces to sacrificial anodes. For some areas it is essential. But it requires monthly inspection and maintenance; this can be expensive. Prestressing concrete piles helps to close cracks and prevents water getting to the steel to cause rusting and progressive spalling of the concrete.

Jacketing Can Be Effective

Concrete jacketing of steel piles can be effective. If practical this should be carried to below the mud line. Galvanic action has been known to occur between steel in contact with concrete and steel at contact with water.

American Seaport, February 1978 issue, reports that the Port of Los Angeles Testing Laboratory has developed a method of heat shrinking a 20 mil polyethylene jacket around the circumference of a wood or other circular pile. There is other information. (Ref 7)

Lessons From Exposed And Pulled Piles

Soldier pile installation is of special interest to pile designers and installers. Where driving and subsequent excavation is to rock the ends of the piles may be exposed *in situ*. The strata and obstructions through which the pile is driven and the conditions of the end can be evaluated. Sheet piling also is often exposed full length inside a cofferdam. Pulled piles, extracted for test observation or for salvage and reuse, give an excellent indication of how all piles fare under similar conditions.

Design for bracing and tie-back systems for cofferdams and excavations are beyond the scope of this paper. Sheet piling booklets of Bethlehem Steel Corp. and United States Steel Corp. have excellent design information. A reprint of a series of articles from CONSTRUCTION METHODS AND EQUIPMENT on "How to Work with Sheet-Piles" is available from

L.B. Foster Co. and some sheet pile manufacturers.

Piling Can Cost Less

Piling can cost the owner less if he can be convinced of a few simple facts from the start:

1. It is his site--with its inherent problems.
2. Adequate subsurface investigation pays off in more economical design, fewer on-site surprises.
3. Test piles should be driven, tested and pulled in advance of final design and results utilized to plan and specify the least costly foundation.
4. All information about the subsurface must be given prospective bidders. Witholding pertinent data that is known--or should have been known--can be a basis for a valid claim.
5. The engineer, with the owner's knowledge--and particiaption, if possible--should discuss field conditions with a reputable local pile contractor in the early stages of design.
6. Specify by name what is wanted. Detail acceptable alternates in preference or addition to "or equal".
7. Do not try to make the contractor responsible for all the unknows of the owner's land or for replacement of piles that meet the specification and are installed as has been specified.
8. If a site can be expected to have installation problems provide for them rather than wealing them to the contractor. A competent contractor will include enough in his proposal to cover unknowns that are not provided for in the bid documents. If there are no troubles, he has an unearned profit. An inexperienced contractor may take a hopeful chance. If there are problems, he goes bankrupt; the bonding company dilly-dallys; the job is delayed; the engineer contributes extra time and energy; and the owner pays.

For jobs where pile driving may be a substantial part of the contract (perhaps not applicable to small bridges) two additional suggestions may be helpful:

9. Provide separate payment for mobilization and moving out pile driving equipment. On a unit pile length contract that overruns the contractor may be entitled to an excessive profit; it lengths substantially underrun, he will be seriously injured and will claim additional payment. The owner pays more. Paying separately for moving on and off keeps the unit price for driving low so inequity from length variation is minimized.
10. Pile installation is one of the early activities. Construction above it may continue for a year or two until the last door is hung and painted. Provide in the contract for payment in full to the foundation contractor within a short time after that part of the work is satisfactorily completed. The general contractor will not have to listen to pleas for payment. The owner will get a better price if prompt, full payment can be planned for.

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