PRESTRESSED CONCRETE PILES

A state of the art presentation on prestressed piling as used throughout
the world is discussed in this General Report to the FIP Symposium
on Mass-Produced Prestressed Precast Elements in Madrid, Spain, May 1968.
Historical information, design data and notes along with manufacturing
techniques, installation practices, discussion of problems and failures
and a complete bibliography are all covered in this comprehensive report.

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Prestressed concrete piles are extensively employed throughout the world in marine structures and foundations. The advantages they offer are their strength in bearing and bending, their durability and their economy. Piling initially appeared to be one of the simplest applications of prestressing. As experience has accumulated over the years, however, applications of prestressed concrete piling have grown increasingly sophisticated, with piles acting under combined stresses and often serving as major structural elements.

The total annual world consumption of prestressed concrete piling is extremely large, approximately 57,-000,000 m (187,000,000 ft.) per year; it thus becomes extremely important to examine anew all aspects of manufacture, installation, economics and technology.

The development of prestressed concrete piling has coincided with the expansion of the science of soil mechanics, and piles are now being required to withstand high dynamic stresses during installation in order to meet the requirements of soil engineers. The huge number of prestressed concrete piles being installed each year gives, by itself, an adequate testing sample from which statistically valid results can be drawn, even with the many variables present.

In recent years, prestressed concrete piles have broken through into new fields of utilization. This is partly a result of their demonstrated economy in mass production, and partly because of their technical properties and performance. For these reasons, it is important to investigate the entire field of prestressed concrete piles, under the headings of: utilization; design; manufacture; installation; economy; sheet piling; fender piles; splices; problems and failures; durability; research and development.

National Reports have been received from Japan (Prestressed Concrete Engineering Association), Germany (DDR), Australia (Prestressed Concrete Development Group), USA (Prestressed Concrete Institute) and the USSR (Research Institute for Concrete and Reinforced Concrete). In addition, eminent engineers and specialists in prestressed concrete piling from a number of different countries have contributed valuable assistance by furnishing data and details on specific installations and aspects of prestressed concrete piles.

Prestressed concrete piles have been extensively employed in at least 21 countries, including both highly developed and less developed countries, and in a variety of environments including sub-arctic, tropical and desert.

In Japan alone, there are 45 factories producing 1,000,000 tons of foundation piles annually, while in the USA more than 2,000,000 m (6,-560,000 ft.) annual production is divided between marine and foundation construction. Prestressed concrete piles support major bridges and wharves in Australia, New Zealand, Peru, Ecuador, Venezuela, Netherlands, Kuwait, Norway, Spain, Italy, Singapore, Malaya, Sweden, USSR, Canada, England and USA, to name but a few countries in order to illustrate the wide range of application in different economies and climates.

Prestressed concrete piles have been constructed in the form of cylindrical piles up to 4 m (13.1 ft.) in diameter, as used on the Oosterschelde Bridge in the Netherlands, and up to 70 m (230 ft.) long, as employed in off-shore platforms in the Gulf of Maracaibo, Venezuela. Prestressed piles have been driven in increments, spliced together during driving to form foundation piling up to 60 m (197 ft.) long to support multi-story buildings in Honolulu and New Orleans. They have been spliced to lower sections of steel and driven as composite piles to support major bridges in California and New South Wales, Australia. Frequently, prestressed foundation piles are being extended up as structural columns to support a bridge deck or even to support the second floor of a parking structure.
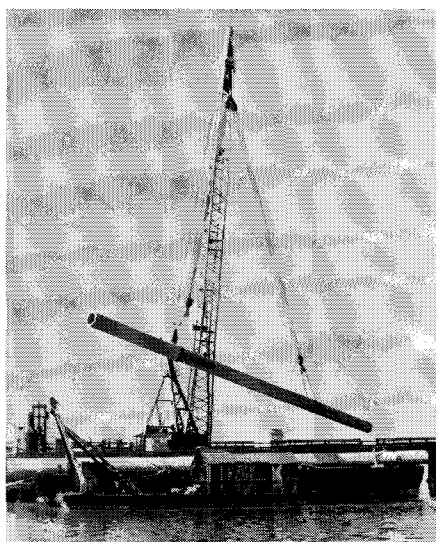

Fig. 1. Hollow cylinder pile being maneuvered into position by crane

Prestressed concrete cylinder piles (Fig. 1) may be used effectively as structural columns and pier shafts. They may be set in pre-drilled holes and then seated by driving or by means of a concrete plug. Prestressed concrete piles are being increasingly used to resist uplift (tension), bending and dynamic loads. They are acting as fender piling to resist ship impact on harbor structures in Kuwait, Singapore and California and as protective fenders for major bridge

piers. Prestressed sheet piles are widely employed as retaining structures for quay walls and bulkheads.

The Japanese National Report asserts the following advantages for prestressed piling:
- Crack-free under handling and driving
- Can be economically designed for given loads and moment
- Uniform high quality, high-strength concrete
- Readily spliced and connected

The USA report adds:
- High load-carrying capacity
- Durability
- Ease of handling, transportation and pitching
- Ability to take hard driving and penetrate hard material
- High column strength and ability to resist moment or combined moment and bearing
- Ability to take uplift
- Economy.

Fig. 2. Long foundation pile (without splices) being used for construction in an American city

In some parts of the United States, there has been a trend towards manufacturing and driving prestressed foundation piling in single long lengths without splices, even for buildings in crowded cities (Fig. 2). Thus piles 40 m (131 ft.) long have been installed for major buildings in San Francisco and Boston. In other areas of the USA (New Orleans and Honolulu), and rather more generally in Japan, Scandinavia, etc., the main trend is towards the manufacture of standardized segments, spliced during driving.

When necessary, prestressed concrete piles can be readily followed down below the existing ground surface, permitting a more economical sequence of pile driving, excavation and concreting instead of having to perform the driving in a deep hole with maximum excavation exposed.

High-capacity prestressed concrete piles are particularly advantageous for deep foundations with heavy loads in weak soils. They can be driven successfully through riprap and debris, or through hard strata such as coral, and can penetrate soft or partially decomposed rock.

DESIGN

The design of prestressed concrete piles requires consideration of handling, transportation, pitching, driving, permanent loads (both axial and bending), and transient bending loads. Each of these requires an appropriate consideration of allowable stresses and, in certain cases, of allowable deflections.

As a general rule, prestressed piles should be basically designed for the permanently installed condition and then checked for transient bending loads, e.g. seismic or wind. A cer-

tain minimum prestress and a certain minimum amount of spiral binding are required for successful installation. These minimum values can then be checked against the conditions of handling, transporting, pitching and driving, and modified as necessary. The design for resisting axial and bending loads may be made as follows:

1. Concentrically loaded short column

a. Design load based on ultimate load

$$N = N_u/S$$
$$= (Kf'_c - 0.60f_e)\,A_c/S$$

where N = allowable bearing load for design

N_u = ultimate bearing load

S = factor of safety, usually 2.5, 3 or 4

K = coefficient of uniformity, assumed by some to be 0.85, especially for piles cast vertically and up to 1.0 for piles cast horizontally

f_e = effective prestress after losses

A_c = cross-sectional area of concrete

f'_c = 28-day strength (6 x 12-in. cylinders)

The Japanese on the other hand, use the following formula for the ultimate strength of piles prestressed with bars:

$$N_u = (f_c - f_e)\,(A_c + nA_s)$$

where n = secant modular ratio, about 6.5 at ultimate conditions.

b. Design load based on allowable stress in pile. Most codes specify stress values ranging from $0.20f'_c$ to $0.33f'_c$. Based on recent studies and evaluation, the author recommends

$$N = (0.30f'_c - 0.25f_e)\,A_c$$

For the usual case, this reduces to $N = 0.275f'_c\,A_c$.

2. Concentrically loaded long column

a. Ultimate load. For long columns where buckling may occur, Euler's formula may be used. For pin-ended conditions, the effective length, L, shall be the full length of the pile. For piles fully fixed at one end and hinged at the other, L can be taken as 0.7 of the length between hinge and point of fixity. For piles fully fixed at both ends, assume L to be 0.5 of the length.

b. Design load. A safety factor of 2 is generally considered sufficient for buckling load. Design loads should be based on the short column value up to $L/r = 60$ and a straight-line function used between $L/r = 60$ and $L/r = 120$. For L/r greater than 120, the pile should be investigated for elastic stability, taking into account the effect of creep and deflection.

3. Moment-resisting capacity

a. Ultimate. This is approximately given by these formulae (for the typical prestressed pile design and materials):

$M_u = 0.37\ dA_sf'_s$ for solid square piles

$M_u = 0.32\ dA_sf'_s$ for solid circular and octagonal piles

$M_u = 0.38\ dA_sf'_s$ for hollow square piles

$M_u = 0.32\ dA_sf'_s$ for hollow circular and octagonal piles

where A_s = total steel area of all tendons

f'_s = ultimate strength of tendons

d = diameter of pile

M_u = ultimate moment capacity

A safety factor of 2 should be applied for normal loading; for seismic or wind loading, the factor is 1.5.

b. Elastic theory. Determine allowable tension, f_t, in the concrete. This may be taken as 0, as 0.5 modulus of rupture, or as 0.8 modulus of rupture, depending on frequency of load, exposure, corrosive conditions, etc.

$$M = (f_e + f_t) Z$$

where M = allowable moment
Z = section modulus of pile

4. Combined moment and direct load

The existence of direct load generally increases the moment capacity within the elastic range, by adding to the available compressive stress (prestress plus stress due to direct load) to resist tensile fiber stress. The ultimate moment capacity of the pile is reduced by direct load.

Typical load-moment interaction diagrams are shown in Fig. 3. It can be roughly estimated that, for a typical foundation pile carrying 60 per cent of the allowable axial load, the ultimate moment capacity is given by $M_u = 0.29dA_sf'_s$ for solid square piles and by $M_u = 0.25dA_sf'_s$ for round piles. For hollow piles, the lever arms are $0.30d$ and $0.26d$, respectively.

At the pile head, where combined moment and direct load may be critical, the favorable effect of transfer length (i.e. prestress varying from zero to full over the transfer length) may be taken into account.

Permanent bending loads may be imposed by:
- Dead weight of a raking pile
- Lateral load of soil
- Eccentricity of axial load
- Rigid frame action (i.e. structural bending moments imposed).

Transient bending moments may be imposed by:
- Waves and currents
- Ice
- Lateral forces from ships or barges
- Wind on structure
- Seismic forces.

For many of these transient loads, allowable stresses may be increased by one-third.

For the handling of prestressed piles from manufacture, the value of f'_c should be the ultimate compressive strength at the age in question. Impact must be considered in handling and transporting, with values of 50 and 100 per cent being applied, depending on the techniques employed. The 50 percent value is most common. In the USSR, a factor of 1.5 is applied to calculations for strength in handling, and a factor of 1.25 is applied to calculations for crack resistance during handling. During handling and transporting, values of allowable tension ranging from 0 to 0.4 modulus of rupture are used.
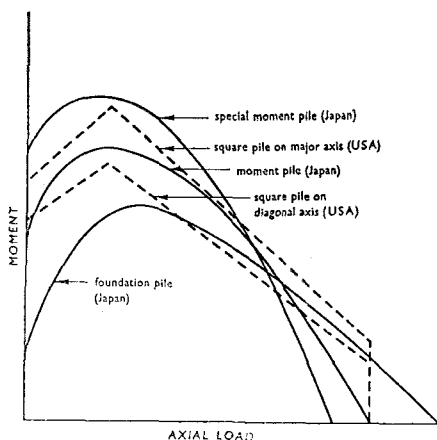

Fig. 3. Typical load-moment interaction curves for prestressed concrete piles

During pitching of the pile, the stresses rapidly diminish as the pile is raised to the vertical. However, the stress conditions in the pile are generally quite complex, depending on the rigging and the angle made by the lines with the pile. The usual practice, which assumes vertical lines leading from the horizontal pile can be grossly erroneous.

A raking pile goes through a complex series of stress reversals. Frequently, the critical design condition is the overhang of the pile below water until it touches bottom. There will be a high negative moment at the main support until the pile head has been driven to this level. There is a tendency for the toe to "kick out" during driving. In its final position, the pile will be in simple positive bending due to dead weight.

In general, prestressed piles do not necessarily require full prestress at head and toe. Therefore, a longer transfer length may often be tolerated and release strengths need not be quite as rigorous as, for example, for short beams.

For prestressed piles which have to resist axial tension (uplift), a design tension load of $N_t = f_e A_c$ may be employed. This gives a factor of safety against cracking, since the load at cracking,

$$N'_t = (f_e + f'_t)\, A_c$$

For ultimate strength,

$$N_{tu} = f'_s A_s.$$

where f'_t = ultimate tensile strength of concrete

Under seismic and wind loads, axial tension and bending moment may occur at the head of piles serving as a foundation for chimneys, stacks, etc., and can generally best be provided for by means of auxiliary mild steel bars in the pile head.

The Japanese National Report tells of three standard classes of pile, classified according to the effective prestress:

Foundation piles have $f_e = 40$ kg/cm² (565 psi)

Moment piles have $f_e = 80$ kg/cm² (1130 psi)

Special moment piles have $f_e = 100$ kg/cm² (1420 psi)

In the USA, foundation piles over 12m (40 ft.) long generally have an effective prestress f_e of 50 to 60 kg/cm² (710 to 850 psi). With greater design moment requirements, values of f_e up to 85 kg/cm² (1200 psi) are used. For fender piles subject to pure bending, values up to 100 kg/cm² (1420 psi) are employed. These moment-resisting piles suggest new approaches to many structural and foundation problems.

DESIGN FOR RESISTANCE TO DRIVING STRESSES

Earlier in this paper, reference was made to empirical minimum values of longitudinal prestress and spiral binding. These are, of course, of great importance because, empirical as they may be, the regularity of statistical performance indicates that fundamental behavior is involved. The empirical minimum values of longitudinal prestress adopted in a large number of countries all range from 45 to 65 kg/cm² (640 to 925 psi). This is the effective prestress after losses. When less prestress has been used, excessive difficulty has been encountered with horizontal cracking during driving.

I would like to suggest the following hypothesis. The dynamic modulus of rupture is about 0.8 of the static modulus of rupture. For a typical prestressed pile, this may be 34 kg/cm² (480 psi). The effective longitudinal prestress will normally be about 50 kg/cm² (710 psi). Thus a total of 84 kg/cm² (1190 psi) is avail-

able to resist a dynamic tension wave before horizontal cracking. However, tensile stresses of this order of magnitude are frequently measured during driving. The tendons to produce a unit prestress of 50 kg/cm² (710 psi) have a steel area of 0.5 percent and, at yield, can resist a force of approximately 70 kg/cm² (995 psi) before stretching. However, the existence of the crack has probably dampened the tensile wave to something less than this value, so progressive failure does not normally result. If less than this amount of effective prestress is used, the steel at the crack will stretch, the concrete will be destroyed in compressive fatigue, and brittle fracture of the tendons will soon result.

Therefore, I recommend a minimum steel area of 0.5 percent for prestressing steel with a yield strength of 15,000 kg/cm² (213,000 psi). By way of corroboration, many recommendations for conventionally reinforced (mild steel) concrete piles call for 3 percent steel area, with a steel of only 2600 kg/cm² (37,000 psi) yield strength. Thus 0.5/3 = 1/6 is inversely proportional to the ratio of yield strengths, 15,000/2,600 = 6/1. Exceptions to this rule exist for short piles (less than 12 m (40 ft.) long) and for piles which are installed by means other than driving. Empirical minimum values of 30 kg/cm² (425 psi) (about 0.3 percent steel area) have been set in some countries for such short piles.

No general theory has been developed for the design of spiral binding for piles. Considerably less spiral is used than is required for similar structural columns. Steel areas of 0.06 to 0.2 percent are widely employed and many thousands of piles have been successfully driven with these small amounts.

In the USSR, for piles up to 9 m (30 ft.) long, transverse reinforcement is used only at head and tip. However, since their behavior at sub-zero temperatures has not yet been thoroughly evaluated, their use is confined to residential construction where they will be completely buried in soil.

However, longitudinal cracking is occurring with disturbing frequency in hollow-core and cylinder piles. The British Prestressed Concrete Development Group (now incorporated into The Concrete Society) recommends a greater area of spiral for hollow-core piles than for solid piles. My tentative recommendation would be to use 0.3 to 0.4 percent steel area for cylinder piles.

During driving, the bursting effect at the head and tip of the pile is much greater. There are tensile bursting forces due to the prestress and radial bursting pressures from the hammer blow. The lateral binding requirement for most existing prestressed pile designs gives a steel area of 0.5 percent for 120 cm (47 in.) from the head. The British Prestressed Concrete Development Group recommends 0.6 percent volume in a top section of length equal to three times the least dimension. The USSR increases the steel area by placing 5 layers of mesh at the head, spaced at 5 cm (2 in.).

The requirements for lateral binding for prestressed beams generally set values at A_s/A_c of 0.4 percent solely to resist tensile stresses from prestressing in the transfer zone. In piles subjected to hard driving, there are bursting tensile stresses of the same order of magnitude as the tensile strength of the concrete. This would seem to require a steel area of 0.8 to 1 percent in the top cm (10 in.) for proper resistance to spalling.

This will properly balance yield of steel with initial cracking of the concrete. Empirically, it has been found that the provision of about 1 percent steel area in the top 30 cm (12 in.) of cylinder piles prevents the head splitting. Sometimes this is provided in the form of a band around the top. It is interesting to note that this band occasionally breaks in hard driving, indicating that the bursting stresses are real. I prefer to use hoops of mild steel placed as close as possible to the outside of the wall. Cover for durability is normally of no importance at this location.

Chamfering of the circumferential edges and top corners of the pile head reduces the tendency to bursting and spalling.

DESIGN NOTES
(see also Fig. 4)

1. Toggle and lifting holes are undesirable because of stress concentration. Their use has resulted in pile failures during driving in New Zealand and elsewhere.

2. Pile-to-cap connections may take one of the following forms:

   a. Mild-steel dowels are grouted into holes in the pile head. These holes may be preformed or drilled after driving.

   b. The prestressing tendons may be extended into the pile cap. For design, embedments of 45 to 72 cm (18 to 28 in.) are usually employed for strands, and they are treated as the equivalent of mild-steel reinforcement. For tension piles, embedments are generally 72 to 100 cm (28 to 39 in.).

   c. The pile head may be extended up into the cap a distance of 45 to 72 cm (18 to 28 in.). The surface of the pile head should be roughened and cleaned before concreting.
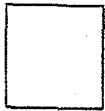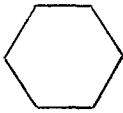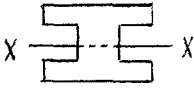
   d. For hollow-core piles, rein-

forcing steel cages may be concreted into a plug in the pile head. To ensure bond, the inside surface of the pile head should be cleaned and roughened (e.g. by sand-blasting), epoxy bonding compound applied, and low-shrinkage concrete placed in the plug. Precast plugs containing the reinforcement have been employed, with the annular space between cylinder piles and precast plug filled with grout.

   e. Also for hollow-core piles, structural steel members may be concreted in a plug instead of reinforcing bars.

   f. Post-tensioning of the pile head to the cap has been frequently proposed but infrequently used owing to site labor requirements. It remains a technically attractive approach, using either the extensions of the tendons from the pile or separate prestressing bars grouted or concreted in the pile head.

3. The matter of distribution of tendons has been given considerable study, particularly in Japan for hollow-core piles. The Japanese have found that the ultimate bending moment is not appreciably affected as long as there are at least four tendons around the periphery of the cylinder. Recently, in the USSR, the tension reinforcement for short foundation piling up to 9 m (30 ft.) long has been grouped in the center of the cross-section.

4. Pile shoes are unnecessary for the great majority of piles; the tips may be square or blunt. For driving in sands, silts and clays, a square tip is satisfactory; a blunt tip is generally best for driving in gravels, boulders, etc. Pile tips are generally given additional spiral reinforcement and this is especially important when piles are driven onto rock, as com-

Shape	Advantages	Disadvantages
(triangle)	Highest ratio of skin-friction perimeter to cross-sectional area. Low manufacturing cost.	Low bending strength.
(square)	Good ratio of skin-friction perimeter to volume. Low manufacturing cost. Good bending strength on major axes.	
(hexagon)	Approximately equal bending strength on all axes. Good penetrating ability. Good column stability (l/r ratio).	Surface defects on top sloping surfaces as cast are hard to avoid.
(circle)	Equal bending strength on all axes. No sharp corners aid appearance and durability. Minimum wave and current loads. Good column stability (l/r ratio).	Manufacturing cost generally higher. Surface defects on upper surfaces as cast are hard to avoid.
(rectangle) or (rounded-end shape)	May be used where greater bending strength is required around one axis, especially if minimum surface to lateral wave and current forces is desired.	Difficulty in maintaining orientation during driving.
(cross/plus shape)	High bending moment about axes in relation to cross-sectional area.	High cost of manufacture. Difficulty of orientation.
X (I-beam shape) X	High bending moment about axis X–X in relation to cross-sectional area.	High cost of manufacture. Difficulty of orientation.

NOTE: *Hollow cores may be employed with most shapes. Varying cross-sections may be employed along the length of the pile, such as enlarged tips for bearing, enlarged upper sections for moment, or a change to a circular upper section in order to eliminate corners, etc. These changed sections may either be cast monolithically or spliced on at any stage.*

Fig. 4. Cross-sectional shapes for prestressed concrete piles

pressive stresses at the tip may then become very high (theoretically up to twice the head compressive stress if there is no overburden above the rock, reducing to about equal with normal overburden). Pile shoes are of advantage in helping piles to penetrate buried timbers, coral and rock. They may take the form of plates, points or stubs. Steel stubs can best be fixed by embedding 1.25 to 1.6 m (4 to 5 ft.) into the concrete and then enclosing this by heavy spiral binding. Means must be provided to ensure thorough consolidation of concrete around the stub and to prevent air being trapped. In Norway, piles are seated in sloping hard rock by means of the "Oslo point", a steel pipe dowel which is drilled through the pile after driving and grouted into the rock. In Singapore, prestressed tension piles were anchored to granite by drilling through the hollow core, grouting a tendon in, and prestressing the pile to the rock.

5. Attention is called to the need for adequate vents in cylinder piles to prevent the build-up of hydrostatic head inside when driving in soft material.

6. Adequate cover must be provided to ensure durability and to prevent corrosion of the spiral and tendons. European practice appears to be from 2.5 cm (1 in.) in fresh water and soil to 4 cm (1.5 in.) in salt water. American practice calls for 4 cm (1.5 in.) in fresh water and up to 7.5 cm (3 in.) in salt water.

7. Many countries and authorities employ square piles with either a round or a "square" spiral reinforcement pattern. Other countries prefer octagonal and round piles with a round pattern. Observation of many thousands of piles of both patterns and sections has failed to produce any evidence for the assertion that the corners of square piles with round patterns are more liable to crack or break off.

8. Structural lightweight aggregate concrete has been successfully employed for prestressed concrete bearing piles, sheet piles and fender piles. It offers lighter unit weight in air (for handling, transporting, and pitching); lighter mass (for driving); and greatly reduced net dead weight when submerged in water or water-bearing soils. Experience indicates greater flexibility and a slightly greater tendency for the pile head to spall; the latter should be countered by increased spiral wrapping at the head and perhaps several layers of cross-bars or mesh.

9. For hollow-core piles, with solid head and/or tip, the transitional change in cross-section should be made gradually. Additional mild steel, both longitudinal and circumferential, may be necessary at this transition. Similarly, at splices or head zones where mild steel reinforcing bars are embedded, the locations of the ends of the bars should be staggered longitudinally.

MANUFACTURE

The manufacture of prestressed concrete piling has developed along several different lines:

1. Long line pretensioning method, producing single pile lengths up to 65 m (213 ft.) and also sections for splicing; diameters up to 130 cm (51 in.) for both solid and hollow core; all shapes and cross-sections.

   a. Fixed forms

   b. Sliding forms and extrusion

2. Segmental construction, with segments joined together and post-tensioned. Joints are dry, concreted or epoxy-glued.

a. Spun segments

b. Segments cast vertically

3. Centrifugally spun pile sections for lengths about 12 m (40 ft.). Pile sections may be joined by welding.

a. Pretensioned against moulds or internal core

b. Post-tensioned

Materials for prestressed piles are selected on much the same basis as other prestressed concrete elements. There is one additional requirement, namely, durability and protection of the steel from corrosion in adverse environments such as sea-water and alkali soils, which usually dictates a higher cement content than that required for strength alone. For sea-water exposure, aggregates must be sound against sulphate attack and non-reactive. The alkali content of the cement is usually closely restricted. When piles will be exposed to freezing and thawing, both with and without sea-water present, the concrete should be air-entrained.

Method 1: Long-line pretensioning. The long-line pretensioned manufacturing process has been widely developed for the mass-production of piles of all shapes and sizes. The most economical mass-production is achieved with multiple fixed forms, producing square pile sections. The sides of the forms are given a slight draft, permitting the piles to be stripped directly from the forms. A typical production sequence is as follows:

a. Set out pre-cut bundles of spiral coil.

b. Pull strands down bed, through the coils; take up slack and stress.

c. Spread out coils to proper spacing and tie to strands.

d. Insert segmental end gates and clamp.

e. Cast and vibrate concrete.

f. Cover and keep damp for 3 to 4 hr., then raise temperature ½ deg. C/min. (1 deg. F/min.) to 65°C (150°F) and hold for 10 hours.

g. Release prestress.

h. Allow temperature to fall at ½ deg. C/min to within 20°C (36°F) of ambient temperature.

i. Lift from forms to storage.

j. Cure with water (optional).

The supplemental water curing should be employed for piles which will be exposed in service, for large, thin-walled hollow-core or cylinder piles, and in a drying atmosphere. When the pile is first removed from the forms, it is still hot and moist from the steaming, and the moisture evaporates very quickly. It is during this first two or three hours that supplemental water curing is most needed. Some factories spray on a membrane curing compound to hold in the moisture.

Step (h) is important primarily for large, solid piles. If they were to be exposed to cold atmospheric conditions while the inside cores were still hot, thermal stresses might cause cracking or crazing. Thermal strains and shrinkage strains are additive. Steam covers should be tight enough to provide protection against cold winds, and to insure relatively uniform temperatures inside. If, because of wind, for example, there is a substantial difference in curing temperature, then when the prestress is released into the member, the modulus of elasticity will vary, plastic flow will occur and the resulting pile will have a decided "sweep".

For piles with circular and octagonal cross-sections, the side forms may be hinged or the top sections made removable. The top sections

may be removed shortly after concreting (i.e. before steam curing) in order to permit finishing of the top surface. Where the side forms are left on during curing, there will be inevitable minor surface defects on the upper surfaces due to the bleeding of water and air. Proper vibration and mix design will help to minimize these but cannot prevent them. The problem is more acute with the drier mixes of lower water/cement ratio. These minor surface defects will consist of numerous "blisters" about 5 mm (0.2 in.) deep and 1 cm (0.4 in.) in diameter and, of somewhat more serious consequence, air voids 3 to 4 mm (0.12 to 0.16 in.) in diameter and up to 1 (0.4 in.) and even 2 cm (0.8 in.) deep. The latter should be filled throughout the tidal or freeze-thaw exposure zones.

Because there appears to be no technique for completely eliminating these surface defects with fixed side forms, the use of removable top forms appears to be the preferable technique.

Forms for long-line pretensioning must be designed so as to prevent transverse fins or obstructions, such as at the end gates. Any such fins will lock to the freshly set concrete while the form is expanding under steam curing and cause transverse tensile cracks, which may later be aggravated during driving.

Another method of forming these upper surfaces of octagonal and circular piles is to use sliding forms. A section of form surmounted by a hopper and fitted with several form vibrators, is pulled along rails at the spring line (top of fixed bottom forms) at from 0.3 to 1 m/min. (1.0 to 3.3 ft./min.). The sliding section is about 7 m (23 ft.) long. The concrete consistency, the vibration, and the speed of travel must be carefully

controlled in order to prevent sloughing. Sometimes the hopper is equipped with a screw-type feeder. Occasionally, a second small hopper trails the first, feeding mortar to the surface. Such slip-forms have a tendency to drag the surface and produce minor crazing and tensile micro-cracks. It is therefore customary to specify that, if slip-forms are used, they shall be so designed and operated that they do not produce any visible cracks or significant residual tensile stresses.

Hollow-core and cylinder piles produced on a long-line pretensioning bed have their inside "cores" formed by fixed, collapsing mandrels. These are collapsed either mechanically or hydraulically. For smaller cores, up to 30 cm (12 in.) diameter, these cores or voids may be formed by expendable tubes of paper (cardboard) or by pneumatically inflated rubber tubes which should be well-reinforced so as to maintain their circular shape and provide longitudinal rigidity between points of support. A British innovation is to stretch temporary prestressing tendons, wrap paper or close-spaced wire mesh around them, and use this to form the core. After curing, the temporary tendons are released and re-used.

All such mandrels or core forms must be held accurately in place to prevent sag and, particularly, to prevent flotation as the concrete is vibrated. Hold-down devices must be frequent enough to hold the core within the specified tolerance, usually about 1 cm (0.4 in.). The use of the stressed tendons to hold down the core is generally most unsatisfactory because, as the core floats during casting, the tendons are similarly displaced.

Sliding internal core forms have

been used to form cores up to 110 cm (43 in.) in diameter. These must be guided and supported, ahead of the concrete being cast, by beams, rollers or the prestressing strands. The system must be designed so that the spiral coils are not displaced as the mandrels move. The tail support may be the freshly cast concrete. These sliding mandrels are fitted with numerous form vibrators. Sometimes heating units are mounted in the mandrel in order to give early strength to the fresh concrete.

The internal surfaces of a slip-formed core must be kept moist, especially in the period before regular steam curing. Hot moist air and low-pressure steam have been employed. Extrusion machines have been developed to form both inside and outside surfaces of hollow-core piles. With one proprietary machine, U-shaped staples are automatically inserted behind the concreting instead of spirals.

In Malaya and Fiji, large-diameter cylinder piles have been manufactured using precast rings as spacers and formwork supports. These rings are placed every 3 m (10 ft.), and the tendons run through preformed holes. The forms are then placed and the concrete cast. Particular care must be taken to get full bond between the cast concrete and precast segments, so as to insure full concrete tensile strength for driving.

Method 2: Segmental construction. Segmental construction involves the manufacture of short segments which are joined and then prestressed. The best-known application is to cylinder piles. By one technique, segments are produced by centrifugal spinning. The core-formers are stressed so as to prevent their outward displacement. Special means are employed to ensure perfect ends, with no honeycombing, water pockets, etc. The segments are cured and then placed on an assembly bed. After the joints have been coated with an epoxy glue, the tendons are inserted, stressed and grouted. Finally, the anchorages are released.

Segments may also be cast vertically, as was most dramatically demonstrated on the 4 m (13.1 ft.) diameter piles for the Oosterschelde Bridge. These segments were assembled, the joints were concreted and then the entire pile was post-tensioned.

Method 3: Centrifugally spun sections. In Japan, a number of large modern mechanized factories manufacture pile sections by a third method, that of centrifugal spinning. The plants there use bar, wire or strand for prestressing tendons. In some plants the tendons are tensioned against the mould, and the concrete placed while the mould is spun at low speed. The speed is then increased for consolidation and the mould finally reaches a peripheral speed of 350 m/min (1150 ft./min.). This whole process takes only 8 minutes. Some plants cure in steam at 65°C (150°F) for 12 to 24 hours followed by water curing for 3 days.

During spinning, there is a tendency for the bars to move outward, leaving a small void inside. This can be overcome by proper mix design, by prestressing bars before concreting, and by controlling the rate of spinning at the various stages.

INSTALLATION

Prestressed piles may be installed by a variety of techniques, alone or in combination. These include driving, jetting, drilling and weighting. Vibration, which has been extensively applied to steel piling in recent

years has, as far as I know, been applied to prestressed foundation piles on an experimental basis only. It has been applied to prestressed sheet piles in Eastern Europe. Large conventionally reinforced concrete piles have been installed by vibration in the USSR and there is no reason to believe that this method would not be fully satisfactory and give even better performance with prestressed piles. The absence of shrinkage cracks should minimize the damping of vibration.

Most prestressed piles are installed by driving, either alone or in combination with jetting. The hundreds of thousands of prestressed piles successfully installed by driving under the widest possible variations in sub-surface conditions attest to the general efficacy of this method. Some general rules have been developed to ensure successful installation. These rules have emerged in remarkably similar form in the many countries which developed them (Japan, Britain, Australia, USA).

1. The pile and hammer should be in alignment.

2. The pile head should be square and free from protruberances or projecting wire or strand. Binding should be avoided in the pile helmet.

3. Avoid excessive hammer (ram) velocity. Reduce ram velocity in soft soils.

4. Provide adequate cushioning at pile head. 15 to 35 cm (6 to 14 in.) of softwood has consistently proved most effective in reducing internal stresses in the pile and in providing maximum penetration of the pile. Provide a new cushion for each pile. The Japanese use corrugated paper board packing. Other materials used are rubber

(including crude rubber sheets), felt, sacking, asbestos fibre, coiled hemp rope and plywood.

5. Protect pile splice rings, or other fittings, with a ring cap.

6. Avoid excessive restraint to pile, either in torsion or bending. The pile position and orientation, once the pile is well embedded in the soil, cannot be corrected from a position at or near the head without causing distress.

7. For cutting off, clamp on a steel or wood band and cut with chisel and hammer or small pneumatic drill. Prior cutting of a circumferential slot with a concrete saw cut or rotary drill, will facilitate a neat, unspalled head.

8. When pre-drilling or jetting, the tip must be well seated before full driving energy is applied.

The greatest driving efficiency is obtained by using a heavy ram, a soft head cushion, and low-velocity impact.

With very long slender piles, guides or supports should be employed to prevent "whip", vibration and buckling during driving. With raking piles, supports must be provided for the overhanging lengths— both those above ground and, when driving in water, those below.

The lifting and handling points for pitching must be properly marked and used. With long piles and multiple (two to six) pick-up points, the angle which the slings make with the pile affects the stress, and pick-up points may therefore be different from those used for handling at the plant and in transport.

In construction over water, pile heads are sometimes pulled into correct alignment. With long unsupported lengths, it is easy to overstress the pile. Thus, specifications should limit the amount or force of

pulling to ensure against over-stress. A common limitation for a 10 m (33 ft.) water depth is to limit the force to 200 kg (440 lb.) by using a winch preset to this maximum force.

After piles have been driven in rivers or harbors, they may require temporary lateral support against tidal current, wave forces, etc., and, in the case of raking piles, against dead-weight deflection.

Diesel hammers are widely used to install prestressed piles. Because of generally light ram and high velocity of impact, particular care must be taken to provide a proper head cushion.

Jetting is often employed to aid driving. This may be pre-jetting (pilot jetting) to break up hard layers, or may be jetting during driving. In the latter case, it is hazardous to jet at or below the tip during driving as this may create a cavity, and produce a "free end" condition, leading to excessive tensile stresses and cracking in the pile.

Pre-drilling—dry, with water, or with bentonite slurry—may be effectively used to aid penetration through hard and dense upper layers. This is increasingly employed as soil engineers are requiring deeper penetration for settlement control.

The pulling and removal of prestressed concrete piles is very likely to produce tensile cracks. If pulling is essential, extensive jetting should precede the pull and special care should be taken to insure a truly axial pull.

Repairs to damaged or cracked prestressed piles in marine installations sometimes become necessary. The following methods have been successful:

- Underwater-setting cement (which must not contain $CaCl_2$)
- Underwater-setting epoxy

- Steel or concrete jacket, connected to pile with tremie grout.

Any repairs should be preceded by thorough cleaning and the patch must be protected until it has adequate strength and resistance to the water.

On the Oosterschelde Bridge in the Netherlands, the piles were sunk by internal dredging and weighting. The derrick barge was so rigged that a part of its weight could be imposed on the pile. After the proper elevation had been reached, a bottom plug of underwater concrete was placed.

On the San Diego-Coronado Bridge in California, the piles were installed through dense clay and sand strata to a suitable bearing zone in three stages. In stage 1, they were pre-jetted, and driven to a point about 2 m (6.5 ft.) above design tip. In stage 2, side jetting well above the pile tip plus driving with the hammer brought the pile to a point 1 m (3.3 ft.) above design tip. Stage 3 employed the hammer alone, with a specified number of blows, to ensure thorough consolidation of the sand around the pile.

STRESS-WAVE THEORY

The stress-wave theory explains many of the observed phenomena connected with the driving of prestressed piles. When a prestressed pile is struck by a hammer blow, the impact lasts from 4×10^{-3} to 8×10^{-3} seconds. The compression wave travels at the speed of sound in concrete—about 4000 m/sec. (13,100 ft./sec.) for a typical prestressed concrete. The wave-length is normally 16 to 50 m (52 to 164 ft.) depending on the duration of impact. The maximum compressive stress in the pile

head will be from 70 to 240 kg/cm² (1000 to 3400 psi), but can reach 300 kg/cm² (4300 psi). When this compressive stress wave reaches the pile tip, if the tip is on a hard bottom, the reflected wave is compressive; if on a soft bottom, it is a tensile wave.

The toe stress may thus reach a compressive stress of twice the head stress when driving through water onto rock. Conversely, when driving into very soft material, a tensile stress of up to 50 per cent of the compressive head stress may be reflected. Actual tensile stresses, as measured by strain gauges, run up to 150 kg/cm² (2000 psi).

In practice, the condition of soft driving and reflected tensile waves has often proved to be serious. Horizontal cracks appear suddenly, almost mysteriously, about one-third of the length down from the head and are spaced about 0.5 m (1.6 ft.) apart. Puffs of concrete dust are produced, followed by spalling and widening of the crack. Repeated driving produces fatigue in the concrete adjacent to the crack including a definite rise in temperature, and eventually brittle fracture of the tendons. The actual point or points of cracking tend to occur initially at a point of discontinuity, such as a lifting point, insert, form mark or honeycomb; this tends to confuse the diagnosis but is generally irrelevant.

There are some 21 variables involved in computing driving stresses. A number of computer programs have been set up. Among the variables are weight of pile, length, modulus of elasticity, damping properties, weight of ram, velocity of impact, stiffness of cushion, soil resistance, and end condition.

In my opinion, the stress-wave theory is basically valid but has two limitations. First, it over-estimates

the tensile stress because it fails to take fully into account the effect of side friction and dissipation of energy into the surrounding soil. Second, it often predicts maximum tensile stresses over the entire middle third of the pile length, whereas cracking has been observed only near the top third point.

This theory does emphasize the importance of head cushioning, which reduces the maximum stresses up to 50 per cent. It explains why, for the same energy, a heavy ram with low velocity produces much lower stresses than a light ram with high velocity.

The amplitude of the stress wave can be reduced by reducing the velocity of impact (shorter stroke or fall), and by increasing the head cushion thickness. This is particularly important in soft driving and, most of all, when a pile breaks through a hard stratum of fill or sand and thus has its sides held by friction with its tip free.

Lightweight concrete has a lower modulus of elasticity. This reduces the velocity of the stress wave to about 3000 m/sec. (9800 ft./sec.) and the maximum compressive and tensile stresses are reduced by 18 and 22 percent respectively. There is apparently greater internal damping within the lightweight concrete, which is partly offset by the lower tensile strength of the concrete.

Theoretically, with a pile driven through water onto rock, a high compressive stress can reflect from the toe, travel to the head and, if the ram has left the the pile head, be reflected as a tensile wave from the head. This appears to be a rather rare condition in practice, owing to damping, skin friction, etc.

ECONOMY

The true economy of prestressed

concrete piles is found in an evaluation of their ability to perform the assigned structural function, with adequate safety, over a long period, at minimum cost. Thus, the structural behavior of the pile, its ability to be transported, handled, driven and connected, as well as its durability, are just as important as the costs of manufacture.

Prestressed piles have proved to be the most economic solution for a wide range of piling installations whenever their inherent structural properties can be well utilized, whenever a large volume is required, and whenever durability becomes a major consideration.

For marine structures, the criteria are a life of 25 to 50 years, good column strength, high load-bearing capacity, bending strength, ability to be handled and driven in long lengths, and low first cost. Prestressed piles are generally superior to other types of piling and have therefore been widely adopted for marine installations.

For foundations, the criteria are low first cost, structural strength as a short column, and ability to be handled and driven to required penetration. In comparing various competitive types and sizes of piling for foundations, an analysis should be made which considers the structural capacity of the pile, the soil capacity for the size and penetration considered, the costs of furnishing, transporting, and driving, and the size, depth and cost of the footings. The time of construction should also be evaluated.

Prestressed piles prove quite competitive in most such analyses, and often turn out to be the most economical solution. They must, of course, be directly compared with other forms of concrete pile. As compared with precast conventionally reinforced piles, the major savings lie in column strength, durability and steel cost. Prestressed piles require about one-sixth as much steel weight as conventionally reinforced piles. Since the unit cost of prestressing steel installed is about double, the net cost is only $\frac{1}{6} \times 2 = \frac{1}{3}$.

One major economic factor in favor of prestressed piles for foundations (as compared to steel or timber piles) is that, for many soil conditions, they develop the required bearing at substantially less penetration. This is often true for both skin-friction and end-bearing conditions.

Labor requirements for manufacture vary substantially, depending on method and volume of manufacture. Where a high sustained volume is maintained, the manpower can be properly allocated to ensure full utilization. A number of countries reported on man-hour requirements, but it would appear unfair to compare them as all factors are not known. However, the lowest reported man-hour requirements were on long-line pretensioning beds using multiple fixed forms.

PRESTRESSED CONCRETE SHEET PILING

Prestressed concrete sheet piles present the advantages of durability and excellent appearance. They are not always directly economical in first cost as compared with steel because sheet piles must usually work in both positive and negative bending. To meet this structural problem, a reasonable amount of eccentricity of prestressing force may be selected and mild steel may be added at points of high moment, especially high negative moment. The amount of allowable tension in sheet pile design is a question of exposure (dur-
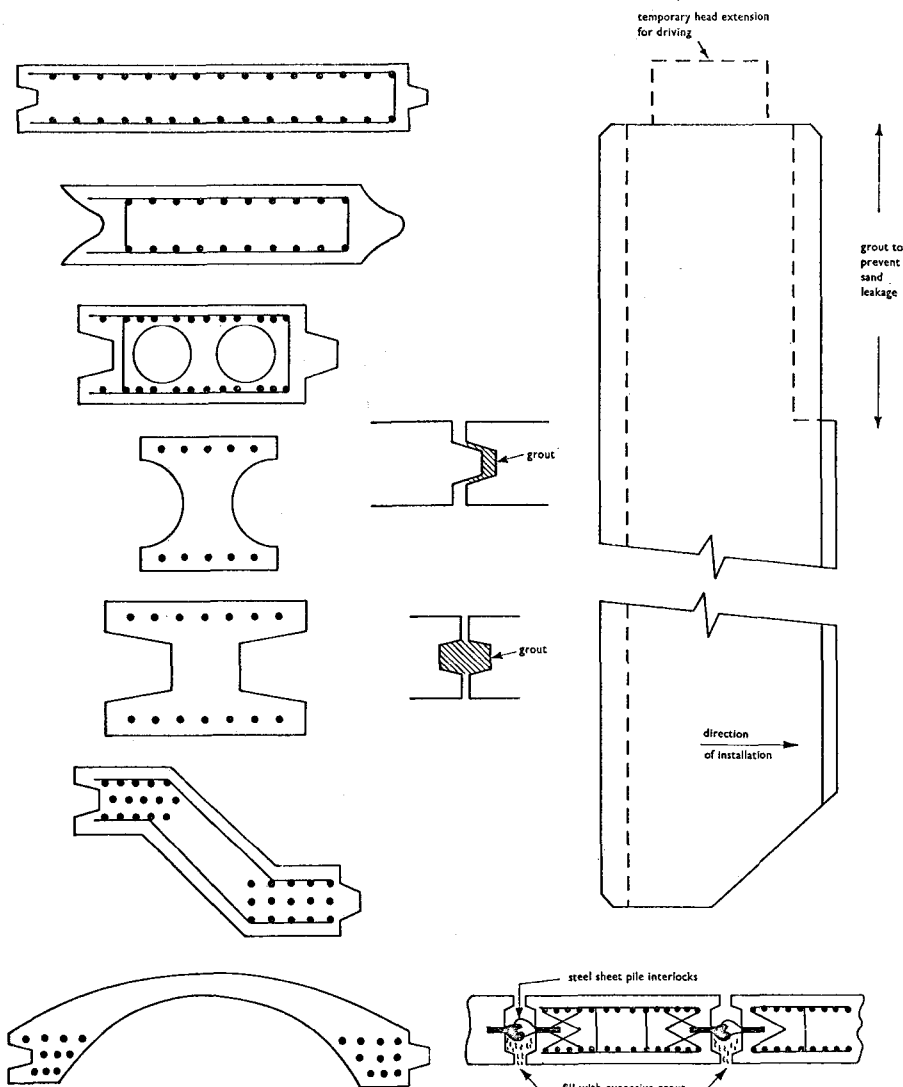
Fig. 5. Typical cross-sections and details of prestressed concrete sheet piles

ability) and type and duration of load. Values of zero and one-half modulus of rupture are commonly used. Typical sections in general use are shown in Fig. 5.

Some difficulties have occurred in the breaking off of the wings of the groove when driving sheet piles. This may sometimes necessitate detailing the mild-steel bars so that they extend into the wings. Prestressed sheet piles may be installed with gang jets or with pile hammers; generally, both are used together. In East Germany, vibratory hammers are used. A special helmet must be used to enable one pile to be driven to the same grade as the adjoining pile. Several countries report casting on the head, at time of manufacture,

a short narrow extension which serves as a driving block for the hammer. After driving, this extension may be cut off and the tendons tied into a capping beam, or the space between extensions used for tiebacks.

In driving, the majority opinion is that the male end (tongue) should lead, to prevent the plugging that would occur if the female end (groove) was leading. When a double-groove joint is used, a steel pipe splice is usually driven with the pile and later withdrawn.

In some building foundations, prestressed concrete sheet piling has been driven as a perimeter wall. This then serves as a bulkhead during excavation, and is incorporated in the final construction as the building wall.

Joints have to be grouted to make them tight against sand leakage. When accessible, they may be packed by hand; expansive cement has been used. In grouting through water, a canvas or polyethelene bag (tube) may be pushed down on a grout pipe, then the grout injected as the pipe is withdrawn.

One recent study gives the following relative figures for cost per unit area per unit of moment-resisting capacity:

- Steel sheet piles, yield point 2500 kg/cm^2 (35,600 psi), unpainted 92
- Steel sheet piles, yield point 3500 kg/cm^2 (50,000 psi), unpainted 90
- Prestressed sheet piles, with $f'_c = 550$ kg/cm^2 (7800 psi) cylinder strength 100
- Steel sheet piles, painted for corrosion protection 105

PRESTRESSED CONCRETE FENDER PILES

Prestressed piles have many ad-vantages to offer as fender piles, dolphin piles, and other piles resisting primarily lateral forces. They are durable and economical. They can be designed to maximize deflection and energy-absorption by keeping the moment of inertia low in relation to strength (by choice of section), by use of concrete with a low modulus of elasticity (such as structural lightweight aggregate concrete) and by proper choice of prestress levels.

One use of fender piles is for wharves and piers, where ships must constantly berth without damage to ship or fender system. Prestressed fender piles were employed on wharves at Kuwait, Singapore and Los Angeles, and on a test installation in San Francisco (see Fig 6).

Structural lightweight aggregate concrete appears ideal for fender and dolphin piles because of its greater deflection and energy absorption. The greatest problem with prestressed dolphin piles is their lack of ultimate strength when design loadings are greatly exceeded. They tend to snap off under excessive impact. Therefore it is suggested that greater reserve ultimate strength be provided in the form of additional unstressed strands.

Prestressed fender piles are usually designed for a maximum tension of up to one-half the modulus of rupture. It is important to prevent cracking that will reduce durability; on the other hand, it would be wrong to make them too stiff. The design should emphasize energy absorption. As regards durability, they can be economically replaced at intervals during the life of the structure itself, so they do not require as great a factor of safety as do foundation piles.

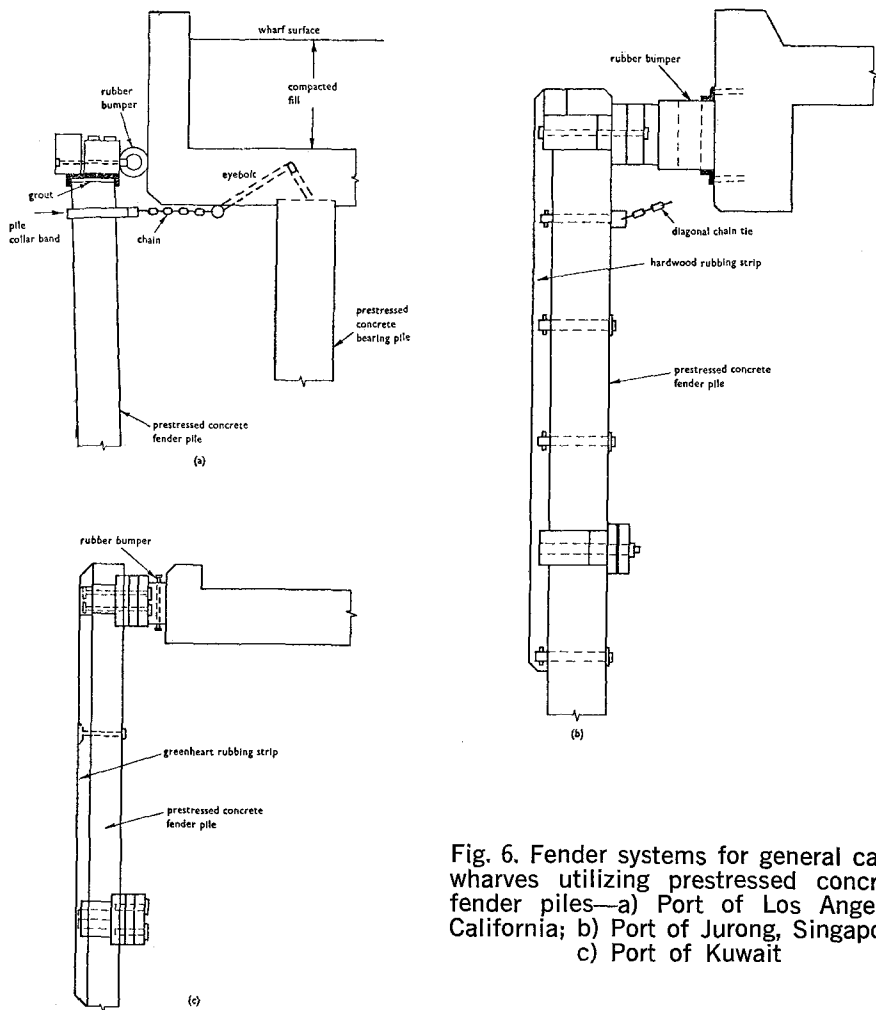Another type of fender is the protective fender for bridge piers (Fig.

Fig. 6. Fender systems for general cargo wharves utilizing prestressed concrete fender piles—a) Port of Los Angeles, California; b) Port of Jurong, Singapore; c) Port of Kuwait

7). This is designed to protect the pier, and the prevention of damage to ships and the cost of repairs are not of primary concern. Here, ultimate strength plus durability are paramount. Prestressed concrete fender piles have been used for protection of piers on all major bridges recently constructed in California.

SPLICES

Many of the recent developments in prestressed concrete piling have centered on techniques of splicing (see Fig. 8). The ideal splice would be capable of being effected without significant interruption to driving, be as strong and as durable as the pile itself, and be cheap. The splice must develop adequate strength in compression, tension, shear, torsion and moment, as required, both during installation and in service.

The epoxy-dowelled splice has come closest to meeting all requirements when high moment capacity is

required. In Norway, small insulated wires are wrapped around the tubes and electric heating is used to accelerate the hardening. In the USA, external steam heat has been used for the same purpose.

Mechanical splices are most economical when only direct compression must be transferred. A number of proprietary mechanical splices are marketed and no attempt is made to illustrate all of them here.

PROBLEMS AND FAILURES

Proper design, manufacturing techniques and installation practice can only be achieved by a careful analysis of problems and failures. These represent an extremely small proportion—considerably less than 1 percent—of the total number of prestressed piles which have been successfully installed. These known problems are presented as specific cases, with assigned cause and corrective action taken.

1. Horizontal cracking under driving. This is the most common problem. Puffs of "dust" are seen about one-third of the length from the top
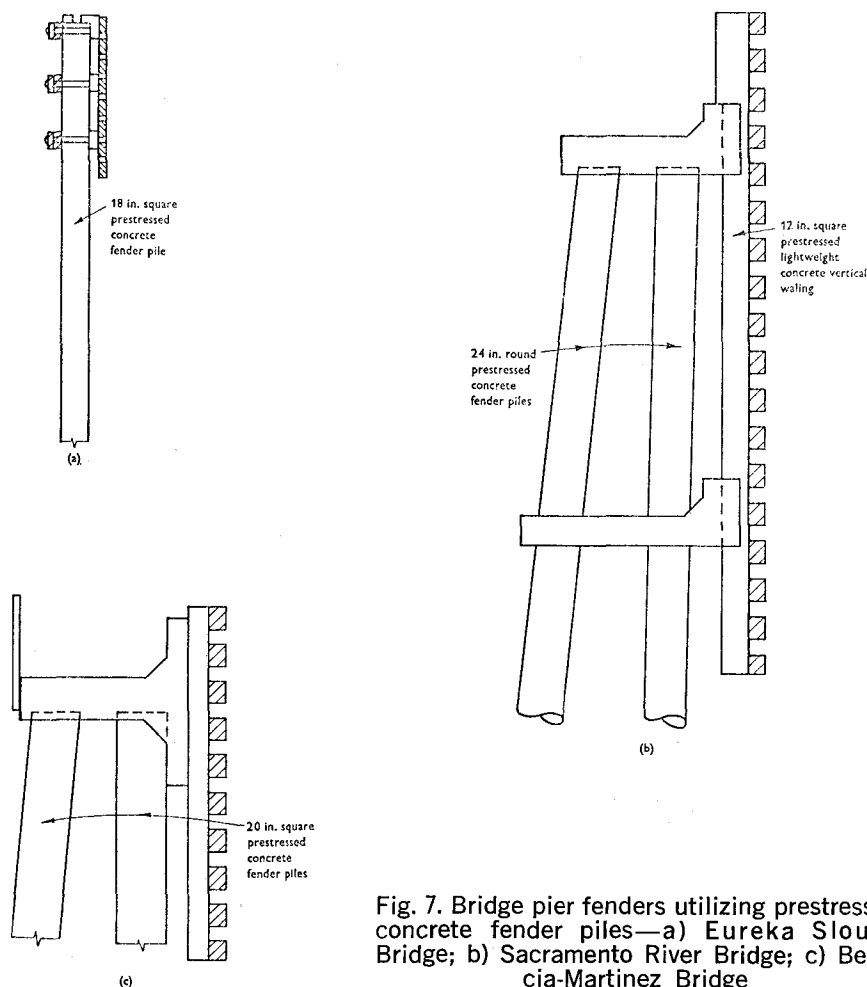

Fig. 7. Bridge pier fenders utilizing prestressed concrete fender piles—a) Eureka Slough Bridge; b) Sacramento River Bridge; c) Benecia-Martinez Bridge
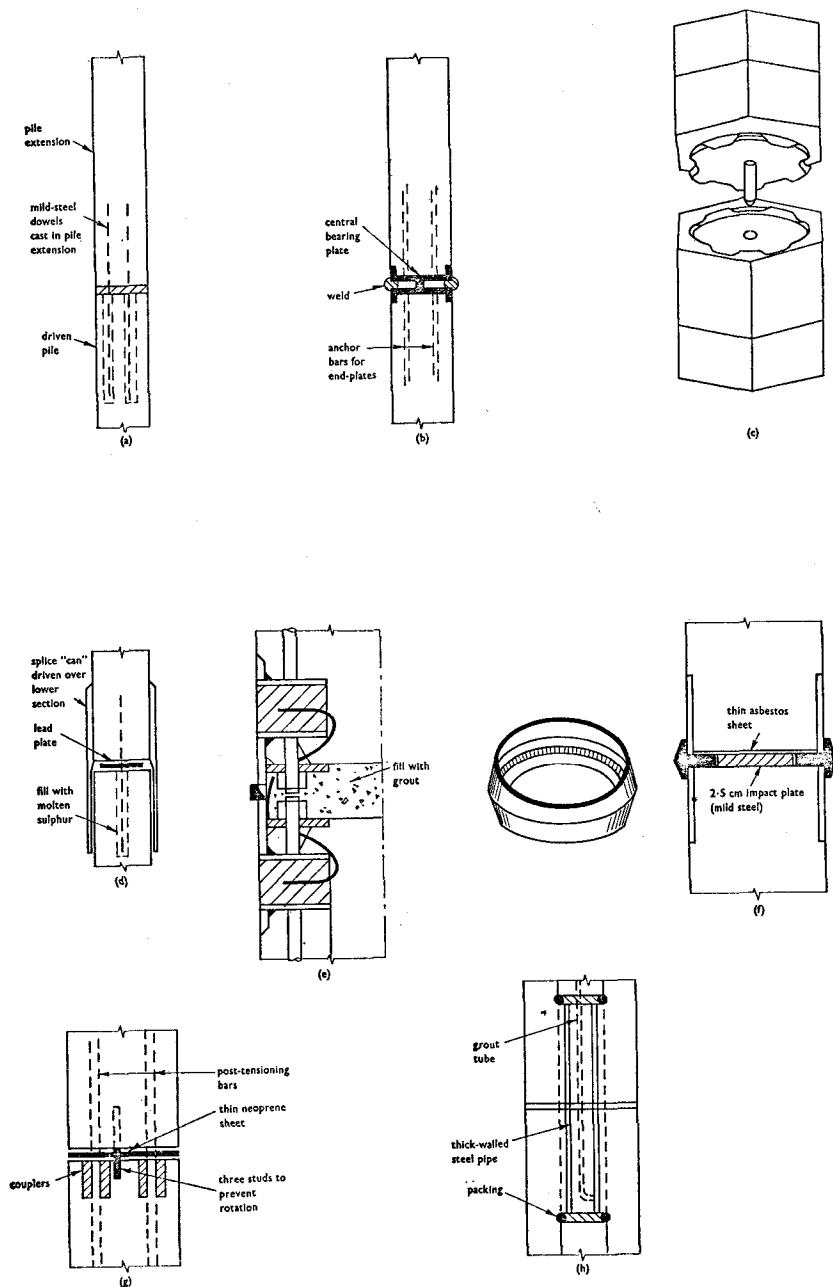
Fig. 8. Typical splice details for prestressed concrete piles—a) epoxy-dowelled splice, USA, Norway; b) welded splice; c) Hercules splice, Sweden; d) can and dowel splice; e) welded splice, Japanese patent; f) "Brunsplice" joint, USA patent; g) post-tensioned splice, Great Britain; h) steel pipe splice for hollow piles, Norway

and horizontal cracks appear at half-meter (1.6 ft.) intervals, with considerable spalling at the surface. If driving continues, the concrete will disintegrate in fatigue failure, and grow sensibly hot just above the crack. Eventually, the tendons will break in brittle fracture.

Cause: Tensile rebound stresses from free-end condition at toe.
Cure: a. Increase amount of softwood cushion.
b. Reduce height of stroke (fall) of ram.
c. Do not jet or drill below tip of pile during driving.
d. Increase weight of ram.

2. Inclined cracking with extensive surface spalling.

Cause: Torsion plus rebound tensile stress.
Cure: Steps a, b and c in (1) and, in addition,
d. Make sure driving head cannot restrain pile from twisting.
e. Do not restrain pile in leads or template.

3. Vertical splitting of cylinder piles or hollow-core piles during installation.

Cause: a. Soft mud and water forced up inside to a level above outside levels, creating an internal hydrostatic head.
Cure: Provide adequate vents in pile.
Cause: b. Hydraulic ram effect of hammer hitting water column.
Cure: Do not drive pile head below water level *or* provide a special driving head with very large openings (greater than 60 per cent of void area).

Cause: c. Shrinkage cracking in manufacture.
Cure: a. Adequate water cure.
b. Re-design mix to minimize shrinkage.
c. Increase area of spiral.

Cause: d. Piles split while being filled with concrete, because of hydrostatic head of liquid concrete.
Cure: a. Reduce rate of pour to ensure it will obtain initial set without exceeding tensile strength of pile concrete and also within acceptable strains of spiral, whichever may be lower.
b. Increase area of helix.

Cause: e. Vertical splitting at top during driving due to bursting stresses.
Cure: a. Increase spiral at head.
b. Increase cushioning at head.

Cause: f. Vertical splitting at or above toe due to plug of soil wedging in void.
Cure: a. Prejet or predrill to break up plugs.
b. Jet or drill inside to break up plugs during driving.
c. Increase spiral.
d. Use solid tip.

Cause: g. Jetting inside produces internal hydrostatic head.
Cure: Provide vents in pile walls.

4. Vertical cracking of cylinder piles after installation.

Cause: a. Freezing of water or mud inside.
Cure: a. Provide sub-surface vents to allow circulation of water.

b. Place wood or styrofoam log inside.

c. Fill pile with frost-proof material.

Cause: b. High river level suddenly fell, leaving water inside higher than out, combined with drying shrinkage on outside and colder temperature outside.

Cure: a. Ensure adequate vents.

b. Fill piles with concrete core.

c. Increase spiral.

Cause: c. Piles cracked from logs, debris, etc. carried by river.

Cure: Fill with sand or concrete.

5. **Breakage of prestressed vertical and raking piles in wharf by ice masses during a spring thaw.**

Cause: Ice masses slid down raking piles, wedged against adjoining vertical piles, broke both.

Cure: In such an environment, design pile layout so ice masses cannot wedge between piles.

6. **Excessive spalling at head under driving.**

Cause: Hammer impact on unrestrained concrete.

Cure: a. Chamfer head.

b. More cushioning.

c. More spiral at head.

d. Make sure head is square and plane.

7. **Disintegration in service of corners of prestressed piles below water line.**

Cause: Reactive and unsound aggregates.

Cure: a. If caught very early, seal entire pile surface with underwater-setting epoxy, or chip to undamaged concrete and patch with epoxy-mortar or underwater-setting cement mortar.

b. Jacketing, with a structural jacket.

c. Replacement.

8. **Vertical hair-line cracks along center of faces of solid piles.**

Cause: Differential shrinkage of outside of pile plus differential cooling, especially in cold, dry, windy weather.

Cure: a. Provide graduated cooling period during last phase of steam curing.

b. Cure by water immediately after removal from steam cure.

9. **Horizontal hair-line cracks on top surface at lifting points.**

Cause: Negative moment exceeds concrete strength plus prestress.

Cure: a. Provide mild steel at lifting points.

b. Use more lifting points.

DURABILITY

Prestressed concrete piles are generally chosen because of their inherent durability. It is important then that this durability be ensured and protection provided wherever prestressed piles are used in an adverse environment.

The primary protection to the tendons and spiral against sea water, chloride and sulphate attacks is provided by the concrete cover. This must be impermeable and non-porous; otherwise, salt-cells will be set up causing electrolytic corrosion. An adequate cement content is needed to insure sufficient alkalinity at the surface of the steel. The USSR re-

ports that the porosity is reduced by prestressing, which maintains a permanent compressive stress in the concrete.

The factors are, therefore: thick enough cover; non-porous concrete; adequate cement content; sound, non-reactive aggregates; maintenance of a high level of compressive stress (prestress).

Freeze-thaw, combined with salt water, is perhaps the severest exposure for concrete piles. In Norway, such piles used to be lagged with 4 to 5 cm (1.6 to 2.0 in.) of treated timber, but now unprotected prestressed piles with 8 to 10 percent entrained air are used, and special attention is paid to achieving an impermeable concrete cover. Freeze-thaw sea water tests by the U.S. Army Corps of Engineers in Maine showed that air-entrained pretensioned concrete was more durable than any other concrete. The USSR specifies three types of frost-resistant concrete, the choice depending on the exposure in service.

There is a general belief that cracks, even hair-line cracks that have closed again under prestress, are a major path for corrosion. Research by Dr. P. W. Abeles has indicated that very small cracks do not necessarily impair the durability of the pile. My examinations confirm that hair-line cracks are not nearly as serious a matter as permeability of the concrete cover. Under continual prestress, and in the presence of water, autogenous healing of hair-line cracks may take place.

RESEARCH AND DEVELOPMENT

The following areas appear fruitful for further research and development.

1. The amount of spiral reinforcement needed at all points in the pile.

The relation between this and the tensile strength of concrete, the longitudinal driving stresses, the bearing capacity and the combined stresses at the pile head.

2. Further correlation of the stress-wave theory with actual strain gauge measurement and with the properties of soils.

3. An investigation of long-term durability. Whenever piles which have been exposed to adverse environments, such as sea water, are removed (as for repair of ship damage), then a detailed investigation should be made of chloride concentrations and of whether or not any electrolytic corrosion has begun.

4. The behavior of prestressed piles under combined loadings at ultimate load, e.g., under seismic loading.

5. The post-cracking behaviour of prestressed piles under driving: amount of steel required, energy absorption, damping, low cycle fatigue of steel and concrete, coordination with research on seismic behaviour of prestressed concrete.

6. The effect of prolonged driving on the properties of a prestressed pile. It has been assumed that, if installed without cracking, its properties remain unchanged despite perhaps a thousand cycles of compression and tension. Is there a reduction in compressive or tensile strength or change in modulus of elasticity due to fatigue or does a "work hardening" take place? The latter may well occur at the head of the pile, as some field observations indicate a possible gain in strength.

7. The use of very high strength concrete for foundation piles; the limitations, if any, on unit loads; the long-term behaviour under sustained load plus prestress; economics.

8. Further development of fender

piles: lightweight concrete, rubber strips, use of epoxy surfacing to resist abrasion, additional steel for ultimate behaviour.

9. Development of a fully-prestressed splice that is economical and quick to make.

10. Grout injection through piles to increase skin friction; correlation with soil mechanics research and application to tension piles.

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