Fundamental Design and Driving Considerations for Concrete Piles

T. J. HIRSCH, Associate Professor and Head of Structural Research Department, Texas Transportation Institute, Texas A&M University

•THE PURPOSE of this paper is to describe and discuss briefly the phenomena which can cause cracking and spalling of concrete piles during driving and to outline procedures which will prevent these problems. In some cases of driving of concrete piles, cracking and spalling have been encountered and in most instances these problems can be avoided by apply certain fundamentals of good design and driving practices.

TYPES OF PROBLEMS

In general, the problems of cracking and spalling of concrete piles which may occur during driving can be classified into 4 types:

1. Spalling of concrete at the head of the pile due to high compressive stress;
2. Spalling of concrete at the point of the pile due to hard driving resistance at the point;
3. Transverse cracking or breaking of the pile due to tensile stress wave reflected from the tip or head of the pile; and
4. Spiral or transverse cracking due to a combination of torsion and reflected tensile stress wave. This type cracking is sometimes accompanied by spalling at the crack.

CAUSES OF PROBLEMS

Compression

Spalling of concrete at the head of the pile is caused by very high or irregular compressive stress concentrations. This type problem can occur from a variety of conditions:

1. Insufficient cushioning material between the pile driver's steel helmet or cap and the concrete pile will result in a very high compressive stress on impact of the pile driver ram.
2. When a pile is struck by a ram at a very high velocity, or from a very high drop, a stress wave of high magnitude is produced. This stress is directly proportional to the ram velocity.

If the pile is idealized as a long elastic rod, with an elastic cushion on top as shown in Figure 1(A), equations for the compressive stress can be developed (10, 22), using the following notation:

σ_c max = maximum compressive stress at pile head, psi;
W = ram weight, lb;
$V = \sqrt{2gh}$ = ram impact velocity, ips;
h = ram free fall, in.;
g = acceleration due to gravity, 386 in./sec^2;
$K = \frac{A_c E_c}{t_c}$ = cushion stiffness, lb/in.;

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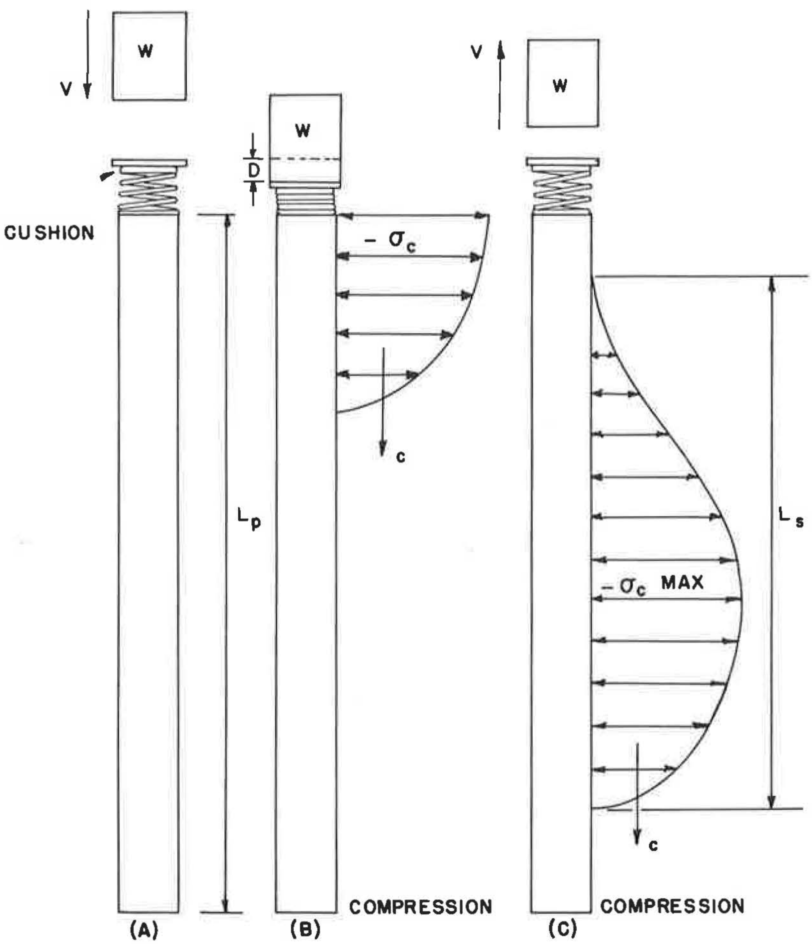

Figure 1. Idealized stress wave produced when ram strikes cushion at head of concrete pile.

A_c = cross-sectional area of cushion, in.^{2};
E_c = modulus of elasticity of cushion, psi;
t_c = initial uncompressed thickness of cushion, in.;
t = time, sec;
A = cross-sectional area of pile, in.^{2};
E = modulus of elasticity of pile, psi;
γ = unit weight of pile, lb/in.^{3};
$n = \frac{K}{2A}\sqrt{\frac{g}{E\gamma}}$; and
$p = \sqrt{\frac{Kg}{W}}$.

Omitting the mathematics, the approximate equations for the maximum compressive stress at the pile head are as follows:

Case I—$n < p$:

$$\sigma_c \max = \frac{-KV e^{-nt}}{A\sqrt{p^2 - n^2}} \sin\left(t\sqrt{p^2 - n^2}\right) \tag{1}$$

where t is found from the expression

$$\tan\left(t\sqrt{p^2-n^2}\right)=\frac{\sqrt{p^2-n^2}}{n}$$

Case II—n = p:

$$\sigma_c \max = -\left(\frac{KV}{nA} - \frac{W}{A}\right) e^{-1} \tag{2}$$

Case III—n >p:

$$\sigma_c \max = -\frac{KV\ e^{-nt}}{A\sqrt{n^2-p^2}} \sinh\left(t\sqrt{n^2-p^2}\right) \tag{3}$$

where t is found from the expression

$$\tanh\left(t\sqrt{n^2-p^2}\right)=\frac{\sqrt{n^2-p^2}}{n}$$

Equations 1, 2, or 3 can be used to determine the maximum compressive stress at the pile head. For most practical pile problems n will be less than p and Eq. 1 will be used. However, this is not always the case. For a given pile these equations can be used to determine a desirable combination of ram weight W, ram velocity V, and cushion stiffness K so as not to exceed a given allowable compressive stress at the pile head. To illustrate the use of the equations consider the following situation. Given:

Concrete Pile
- 65 ft long
- $A = 200\ \text{in.}^2$
- $\gamma = 0.0868\ \text{lb/in.}^3$ (150 pcf)
- $E = 5.00 \times 10^6$ psi

Green oak cushion, grain horizontal
- $A_c = 200\ \text{in.}^2$
- $E_c = 45,000$ psi (for properties of wood see Table 1)
- $t_c = 3.0$ in.
- $K = \frac{A_c E_c}{t_c} = 3.0 \times 10^6$ lb/in.

Steel ram
- $W = 5000$ lb
- $h = 36$ in.
- $V = \sqrt{2gh} = 167$ ips
- $g = 386\ \text{in./sec}^2$

Calculations:

$$n = \frac{K}{2A}\sqrt{\frac{g}{E\gamma}} = 224\ \text{sec}^{-1}$$

$$p = \sqrt{\frac{Kg}{W}} = 481\ \text{sec}^{-1}$$

Since $n<p$, Eq. 1 of Case I applies.

$$\tan\left(t\sqrt{p^2-n^2}\right) = \frac{\sqrt{p^2-n^2}}{n} = \frac{425}{224} = 1.896$$

TABLE 1

MODULUS OF ELASTICITY OF WOOD CUSHIONS LOADED PERPENDICULAR TO GRAIN[a]

Wood	E_c
Pine plywood	23,000 psi
Gum	27,000 psi
Fir plywood	35,000 psi
Oak	45,000 psi

[a]Typical values from Ref. 9.

so

$$t\sqrt{p^2-n^2} = 62.2^\circ \text{ or } 1.085 \text{ radians}$$

$$t = 0.00255 \text{ sec}$$

TABLE 2

VARIATION OF DRIVING STRESS WITH RAM WEIGHT AND VELOCITY

Results from Eq. 1 for 65-ft long pile, 200-in.^{2} area, and 3-in. wood cushion. Stresses shown are maximum compression at pile head. E_c = 45,000 psi.

Ram Weight (lb)	Ram Velocity (ft/sec), Stroke (ft)			
	11.4, 2	13.9, 3	16.1, 4	18.0, 5
2,000	1,790 psi	2,200 psi	2,540 psi	2,840 psi
5,000	2,380 psi	2,920 psi	3,380 psi	3,780 psi
10,000	2,830 psi	3,470 psi	4,000 psi	4,480 psi
20,000	3,250 psi	3,980 psi	4,600 psi	5,150 psi

TABLE 3

VARIATION OF DRIVING STRESS WITH RAM WEIGHT AND RAM ENERGY

Results from Eq. 1 for 65-ft long pile, 200-in.^{2} area, and 3-in. wood cushion. Stresses shown are maximum compression at pile head. E_c = 45,000 psi.

Ram Weight (lb)	Driving Energy (ft-lb)	
	20,000	40,000
2,000	4,010 psi	5,680 psi
5,000	3,380 psi	4,780 psi
10,000	2,830 psi	4,000 psi
20,000	2,290 psi	3,250 psi

From Eq. 1

$$\sigma_c \max = \frac{-KVe^{-nt}}{A\sqrt{p^2-n^2}} \sin\left(t\sqrt{p^2-n^2}\right)$$

$$= \frac{3 \times 10^6 \times 167\, e^{-224 \times 0.00255}}{200 \times 425} \sin 62.2°$$

$$\sigma_c \max = 2920 \text{ psi}$$

Using these equations, Tables 2 and 3 were developed to illustrate the effect of ram weight and velocity on driving stresses. Table 2 shows the variation of the driving stress (compressive) with the ram weight and ram velocity. It can be seen that the stress magnitude also increases slightly with ram weight; however, this is usually not of serious consequence. Table 3 shows the variation of driving stress (compression) with ram weight and ram driving energy. At a constant driving energy the driving stress decreases as the ram weight increases. Therefore, it is better to obtain driving energy with a heavy ram and short stroke than use a light ram and large stroke.

3. When the top of the pile is not square or perpendicular to the longitudinal axis of the pile, the ram impacting force will be eccentric and cause very high stress concentrations.

4. If the reinforcing steel is not cut flush with the end of the pile, high stress concentrations in the concrete adjacent to the reinforcing may result. The ram impact force may be transmitted to the concrete through the projecting reinforcing steel.

5. Lack of adequate spiral reinforcing at the pile head and also pile point may lead to spalling or splitting. In prestressed concrete piles, anchorage of the strands is being developed in these areas, and transverse tensile stresses are present. If no spiral reinforcing is used the pile head may spall or split on impact of the ram.

6. Fatigue of the concrete can be caused by a large number of blows at a very high stress level.

7. If the top edges and corners of the concrete pile are not chamfered the edges or corners are likely to spall on impact of the ram.

Spalling of concrete at the point of the pile can be caused by extremely hard driving resistance at the point. This type resistance may be encountered when founding the pile point on bed rock. Compressive stress under such driving conditions can be twice the magnitude of that produced at the head of the pile by the hammer impact, as shown in Figures 2(B) and 4(B). Field measurements and the results from Eqs. 1, 2, and 3 indicate that stress magnitudes at the head of the pile due to hammer impact frequently reach 2,000 to 3,000 psi. Consequently, if the pile tip encounters hard rock the stresses there can develop 4,000 to 6,000 psi, which will probably produce spalling.

Tension

Transverse cracking of a pile due to a reflected tensile stress wave is a complex phenomenon. It may occur in the upper end, midlength, or lower end of the pile. It usually occurs in long piles (approx. 50 ft or over). It can occur when driving in a very soft soil or when the driving resistance is extremely hard or rigid at the point, such as in bearing on solid rock.

When a pile driver ram strikes the head of a pile or the cushion on top, compressive stress is produced at the head of the pile. This compressive stress travels down the pile at a velocity

$$c = \sqrt{E/\rho}$$

where

c = velocity of the stress wave, in./sec;
E = modulus of elasticity of the pile material, psi; and
ρ = mass density of the pile material, lb-sec^2/in.^{4}.

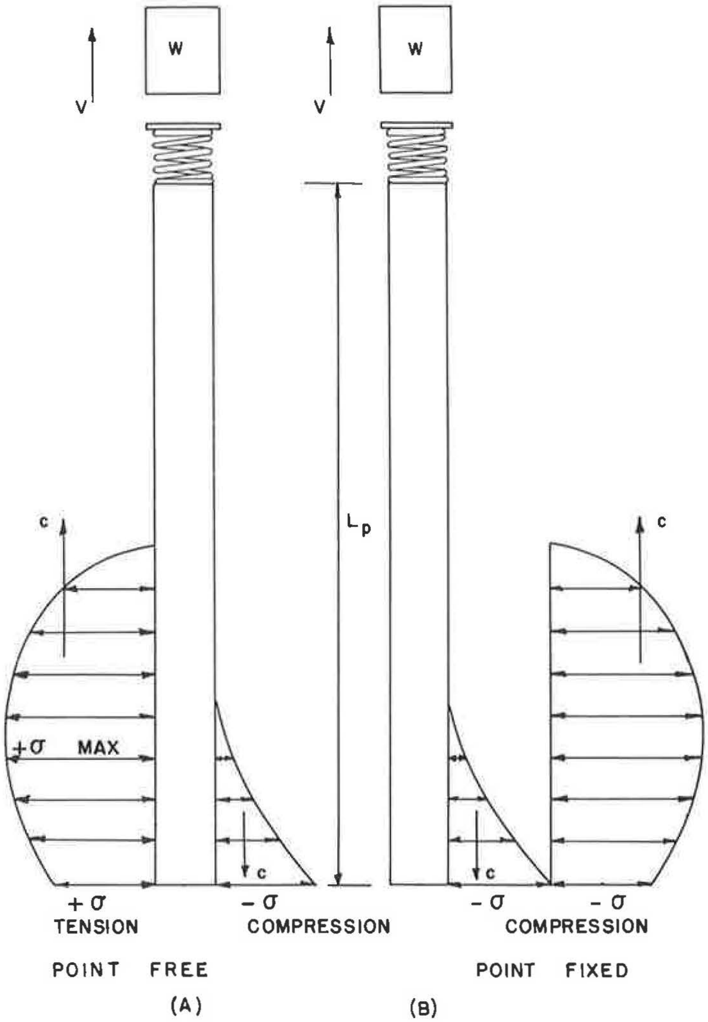

Figure 2. Reflection of stress wave at point of a long pile.

The intensity of the stress wave (σ_c max) can be determined by Eqs. 1, 2, or 3 and depends on the weight of the ram, velocity of the ram, stiffness of the cushion, and stiffness of the pile. Since in a given pile the stress wave travels at a constant velocity (about 13,000 to 15,000 ft/sec), the length of the stress wave (L_s) will depend on the length of time (t_s) the ram is in contact with the cushion or pile head. A heavy ram will stay in contact with the cushion or pile head for a longer time than a light ram, thus producing a longer stress wave. If a ram strikes a thick soft cushion, it will also stay in contact for a longer period of time than when it strikes a thin hard cushion. For Case I (when $n<p$, which is typical for most practical pile conditions), the length of the stress wave can be calculated by

$$L_s = ct_s$$

or

$$L_s = \frac{c\pi}{\sqrt{p^2-n^2}} \tag{4}$$

where L_s is the length of stress wave in inches.

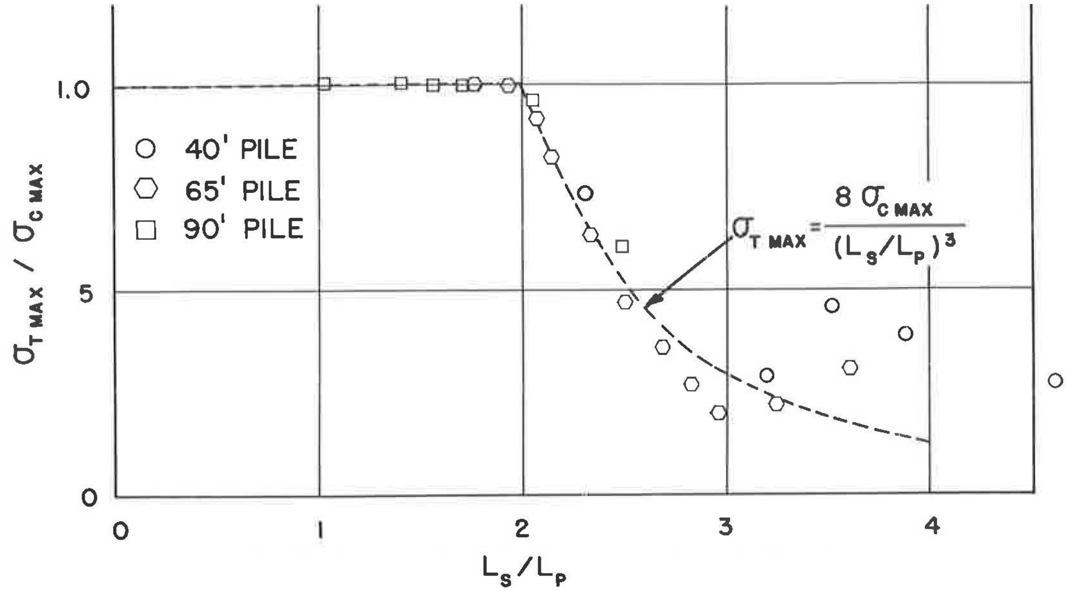

Figure 3. Effect of ratio of stress wave length to pile length on maximum tensile stress for pile with point free.

Figure 1(B) shows the compressive stress wave building up while the ram is in contact with the cushion. After the ram rebounds clear of the cushion, the compressive stress wave is completely formed and travels down the length of the pile as shown in Figure 1(C). When the compressive stress wave reaches the point of the pile, it will be reflected back up the pile in some manner depending on the soil resistance. If the point of the pile is experiencing little or no resistance from the soil, it will be reflected back up the pile as a tensile stress wave as shown in Figure 2(A). If the point of the pile is completely free, the reflected tensile wave will be of the same magnitude and length as the initial compressive wave. As shown in Figure 2(A), these two waves may overlap each other. The net stress at a particular point on the pile at a particular time will be the algebraic sum of the initial compressive (-) stress wave and reflected tensile (+) stress wave. Whether or not the pile will ever experience critical tensile stresses will depend on the pile length (L_p) relative to the length of the stress wave (L_s), and on material damping. If the pile is long compared to the length of the stress wave, critical tensile stresses may occur at certain points. When a heavy ram strikes a thick soft cushion, the stress wave may be around 150 ft in length. When a light ram strikes a thin hard cushion it may be only 50 or 60 ft in length.

The results of a theoretical study (10) on ideal piles with the point free of soil resistance has shown that the maximum reflected tensile stress (σ_t max) can be computed approximately by

$$\sigma_t \max = \sigma_c \max \tag{5}$$

when $L_s/L_p \leq 2$, and

$$\sigma_t \max = \frac{8\,\sigma_c \max}{\left(L_s/L_p\right)^3} \tag{6}$$

when $L_s/L_p \geq 2$.

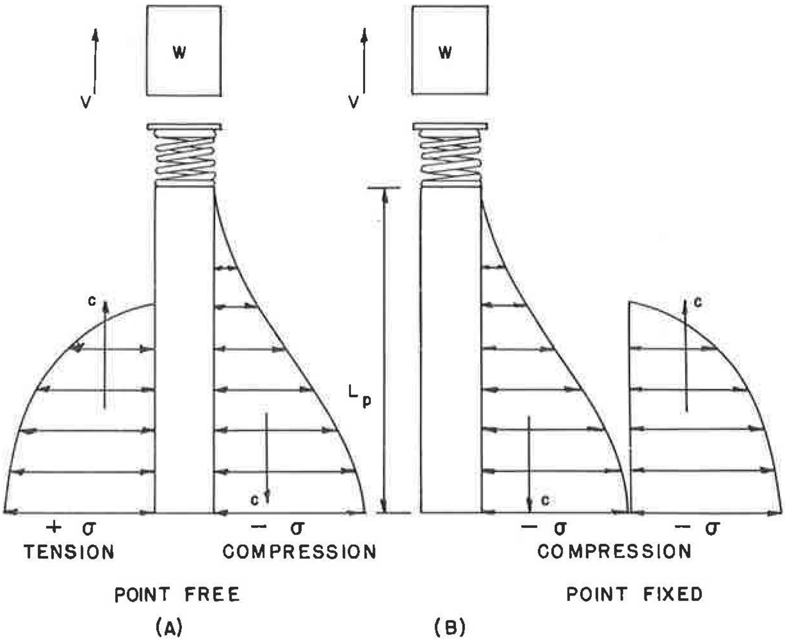

Figure 4. Reflection of stress wave at point of a short pile.

Figure 3 shows in dimensionless parameters how σ_t max is affected by σ_c max, the length of the stress wave L_s, and the length of the pile L_p. The data points shown were computed using stress wave theory (10) and piles with a free point. These values are conservative since material damping of the pile and soil will tend to reduce them.

If the point soil resistance is hard or very firm, the initial compressive stress wave traveling down the pile will be reflected back up the pile also as a compressive stress wave, as shown in Figure 2(B). If the point of the pile is fixed from movement, the reflected compressive stress wave will be of the same magnitude and length as the initial compressive stress wave. As shown in Figure 2(B), these 2 stress waves may overlap each other at certain points. The net compressive stress at a particular point at a particular time will be the algebraic sum of the initial compressive (-) stress wave and the reflected compressive (-) stress wave. (Note that under these conditions the maximum compressive stress at the pile point can be twice that produced at the pile head by ram impact.) Tensile stress will not occur here until the compressive stress wave is reflected from the free head of the pile back down the pile as a tensile stress wave similar to the reflection shown at the free point in Figure 2(A). It is possible for critical tensile stress to occur near the pile head in this case; however, internal damping characteristics of the concrete pile and surrounding soil may reduce the magnitude of this reflected tensile stress wave by this time. Such failures have occurred, however.

Figure 4 shows the reflection of the initial compressive (-) stress wave from the point of a relatively short pile. If the pile is short compared to the length of the stress wave (L_s) critical tensile stresses are not likely to occur. In Figure 4(A) the reflected tensile (+) stress wave overlaps the initial compressive (-) stress wave coming down the pile. Since the net stress at any point is the algebraic sum of the 2, they tend to cancel each other and critical tension is not likely to occur. A similar phenomenon will occur when the reflected compressive (-) stress wave from the point is likely to find the ram still in contact with the pile head when it arrives there. In such a case, little or no reflected tensile stress wave will occur. In Figure 4(B) the initial compressive (-) stress wave is being reflected from the fixed point also as a compressive (-) stress wave. In this case also, little or no reflected tensile stress will occur.

The cases illustrated by Figures 2 and 4 are highly idealized and simplified, but they should indicate some of the basic factors which can cause tensile stress failures in concrete piles. To summarize, tensile cracking of concrete piles can be caused by the following:

1. When insufficient cushioning material is used between the pile driver's steel helmet or cap and the concrete pile, a stress wave of high magnitude and of short length is produced, both characteristics being undesirable.
2. When a pile is struck by a ram at a very high velocity, or from a very high drop, a stress wave of high magnitude is produced; the stress is proportional to the ram velocity.
3. When the tensile strength of the concrete pile is too low to resist a reflected tensile stress, severe cracking will occur.
4. When little or no soil resistance at the point of long piles is present during driving, critical tensile stresses may occur in the lower half or near midlength of the pile.
5. When hard driving resistance is encountered at the point of long piles, critical tensile stresses may occur in the upper half of the pile when the tensile stress is reflected from the pile head.

Torsion

Spiral or transverse cracking of concrete piles is usually caused by a combination of torsion and reflected tensile stress. Diagonal tensile stress resulting from a twisting moment applied to the pile can by itself cause pile failure. However, if reflected tensile stresses occur during driving and they combine with diagonal tensile stress due to torsion, the situation can become even more critical. Torsion on the pile may be caused by the following:

1. The helmet or pile cap fitting too tightly on the pile, preventing it from rotating slightly due to soil action on the embedded portion of pile.
2. Excessive restraint of the pile in the leads and rotation of the leads.

SUMMARY

From the preceding discussion of types and causes of concrete pile problems which have occurred, some basic fundamental considerations have been revealed. These fundamentals for good design and driving practices for concrete piles can be summarized as follows:

1. Use adequate cushioning material between the pile driver's steel helmet or cap and the concrete pile head. Three or 4 in. of wood cushioning material (green oak, gum, pine or fir plywood, etc.) may be adequate for short (approx. 50 ft or less) piles with reasonably good point soil resistances. Six or 8 in. or more of wood cushioning material may be required when driving longer piles in very soft soil. The wood cushioning material should be placed on top of the pile with the grain horizontal and inspected to see that it is in good condition. When it begins to become highly compressed, charred or burned, it should be replaced. Some specifications require a new cushion on every pile. If driving is extremely hard, the cushion may have to be replaced several times during driving of a single pile. Use of an adequate cushion is usually a very economical means of controlling driving stresses.
2. Driving stresses can be reduced by using a heavy ram with a low impact velocity (short stroke) to obtain the desired driving energy rather than a light ram with a high impact velocity (large stroke). Driving stresses are proportional to the ram impact velocity. The maximum compressive stress can be determined approximately by Eqs. 1, 2, or 3.
3. Reduce the ram velocity or stroke during early driving when light soil resistance is encountered. Anticipate soft driving or at the first sign of easy driving reduce the ram velocity or stroke to avoid critical tensile stresses. This is very effective when driving long piles through very soft soil. When the point of the pile is free of resistance, the maximum tensile stress can be determined approximately by using Eqs. 5 or 6.

4. If pre-drilling or jetting is permitted in placing the piles, insure that the pile is well seated with reasonable soil resistance at the point before full driving energy is used. Driving and jetting should not be done simultaneously.

5. Insure that the pile driving helmet or cap fits loosely around the pile top so that the pile may rotate slightly without binding within the driving head to prevent torsional stress.

6. Insure that the pile is straight and not cambered because of uneven prestress or poor concrete placement during casting. High flexural stresses may result during driving of a crooked pile.

7. Insure that the top of the pile is square or perpendicular to the longitudinal axis of the pile.

8. Cut ends of prestressing or reinforcing steel flush with the end of the pile head to prevent their direct loading by the ram stroke.

9. Use adequate spiral reinforcing at the pile head and tip to reduce tendency of pile to split or spall.

10. Use adequate amount of prestress in prestressed piles or reinforcement in ordinary precast piles to resist reflected tensile stresses.

11. Chamfer top and bottom edges and corners of pile to reduce tendency of concrete to spall.

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