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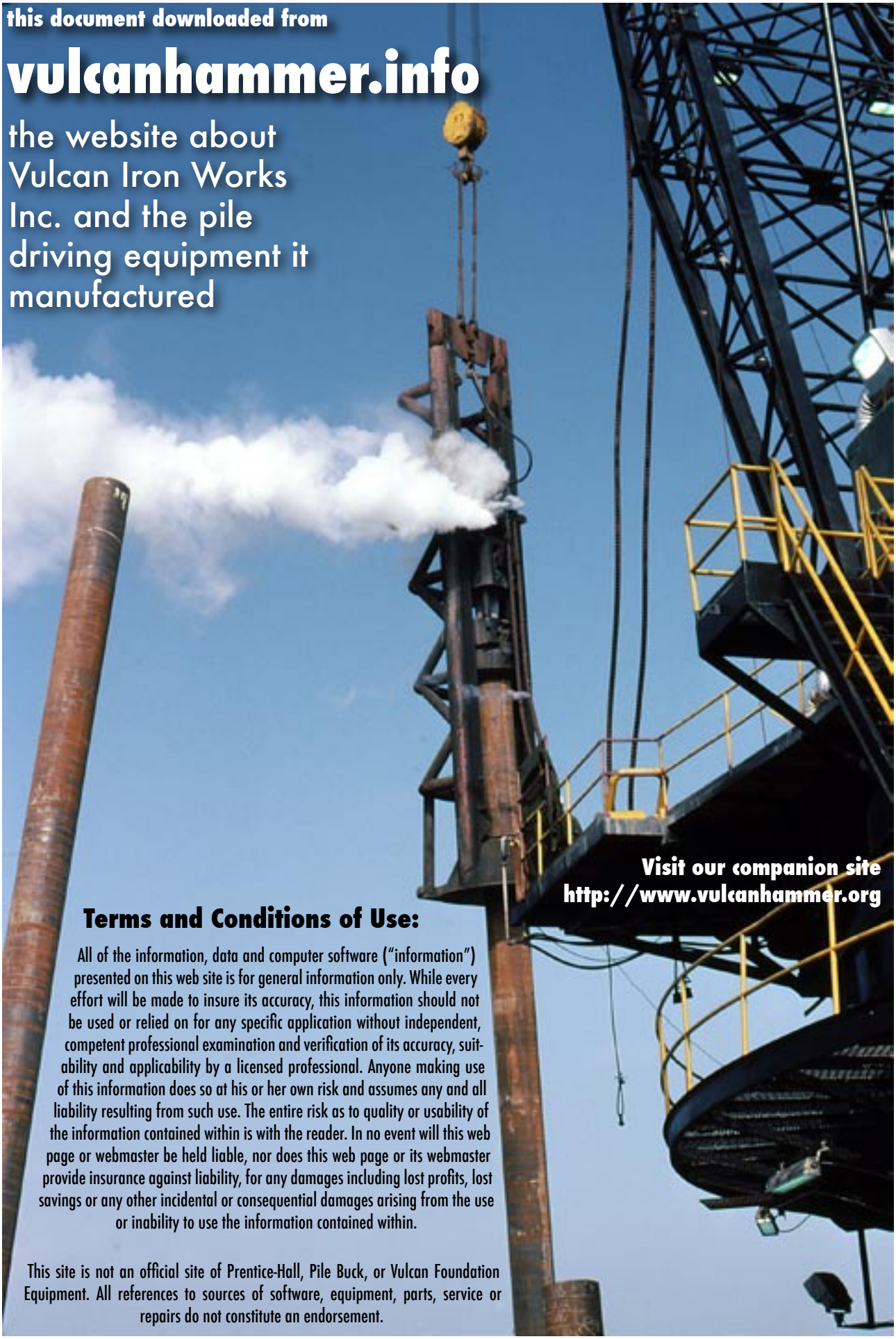

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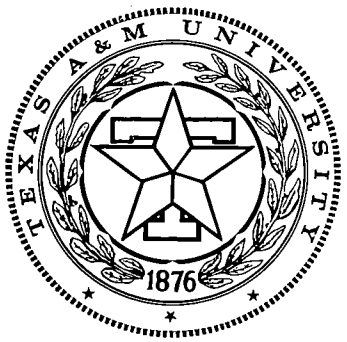

TEXAS
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TEXAS
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DEPARTMENT

COOPERATIVE
RESEARCH

DRIVING PRACTICES FOR PRESTRESSED CONCRETE PILES

In cooperation with the
Department of Commerce
Bureau of Public Roads

RESEARCH REPORT 33-3
PROJECT 2-5-62-33
PILING BEHAVIOR

Reference to Chapt. X

DRIVING PRACTICES FOR PRESTRESSED CONCRETE PILES

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Research Report Number 33-3
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TEXAS TRANSPORTATION INSTITUTE
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Driving Practices For Prestressed Concrete Piles

INTRODUCTION

The purpose of this paper is to briefly describe the phenomena which can cause cracking and spalling of prestressed concrete piles during driving and to outline procedures which will prevent these problems. In some cases of driving of prestressed concrete piles, cracking and spalling have been encountered and in most instances these problems can be avoided by following certain rules of good driving practices. The recommendations presented here are based on sound physical principles and have been proved effective in practice.

The following discussion of problems which are occasionally encountered in driving prestressed concrete piles should not be interpreted to indicate that problems or failures are a natural consequence of the use of prestressed concrete piles. Many thousands of linear feet of prestressed piling have been successfully driven with no problems of cracking or spalling. Even on those projects where problems have been encountered, the piles giving trouble have represented a very small percentage of the total piling on the project.

TYPES OF PROBLEMS

In general, the problems of cracking or spalling of concrete piles which may occur during driving can be classified into four 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.

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 be caused by the following:

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. Table 1 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 2 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 may result in the concrete adjacent to the reinforcing. 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 (see Figure 2B and 3B). Stress magnitudes at the head of the pile due to hammer impact frequently reach 2,000 psi to 3,000 psi. Consequently if the pile tip encounters hard rock the stresses there can theoretically develop up to 4,000 psi 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 (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

TABLE 1. VARIATION OF DRIVING STRESS WITH RAM WEIGHT AND VELOCITY

Wave equation results for 65 ft long pile, 200 sq in. area, and 3 in. wood cushion. Stresses shown are maximum compression at pile head.

Ram Weight lb	Ram Velocity, ft/sec—Stroke, ft			
	11.4 - 2	13.9 - 3	16.1 - 4	18.0 - 5
2,000	1,550 psi	1,850 psi	2,100 psi	2,350 psi
5,000	2,000 psi	2,500 psi	2,980 psi	3,320 psi
10,000	2,400 psi	3,000 psi	3,420 psi	3,820 psi
20,000	2,750 psi	3,380 psi		

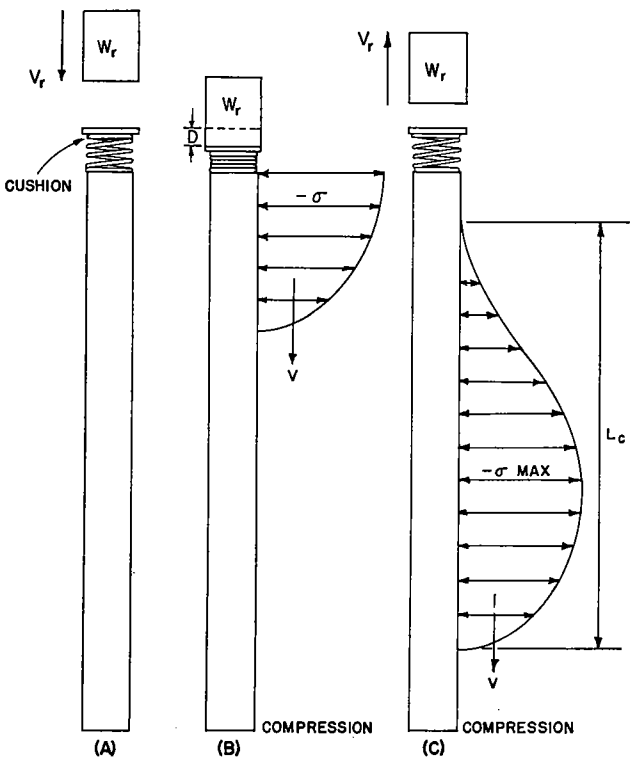

Figure 1. Idealized stress wave produced when ram strikes cushion at head of concrete pile.

the head of the pile. This compressive stress travels down the pile at a velocity

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

where

V = velocity of the stress wave,

E = modulus of elasticity of the pile material, and

ρ = mass density of the pile material.

The intensity of the stress wave (σ max.) depends on the weight of the ram, velocity of the ram, stiffness of the cushion, stiffness of the pile, and soil resistance. 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_c) will depend on the length of time the ram is in contact with the cushion or pile head. A heavy ram will stay in contact with the cushion or pile head for a longer time than a light ram, 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.

TABLE 2. VARIATION OF DRIVING STRESS WITH RAM WEIGHT AND RAM ENERGY

Wave equation results for 65 ft long pile, 200 sq in. area, and 3 in. wood cushion. Stresses shown are maximum compression at pile head.

Ram Weight lb	Driving Energy ft - lb	
	20,000	40,000
2,000	3450 psi	4900 psi
5,000	2980 psi	4200 psi
10,000	2420 psi	3400 psi
20,000	1950 psi	2750 psi

Figure 1B 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 by Figure 1C. 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 2A. 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 2A 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 relative to the length of the stress wave (L_c), and on material damping. If the pile is long compared to the length of the 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.

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

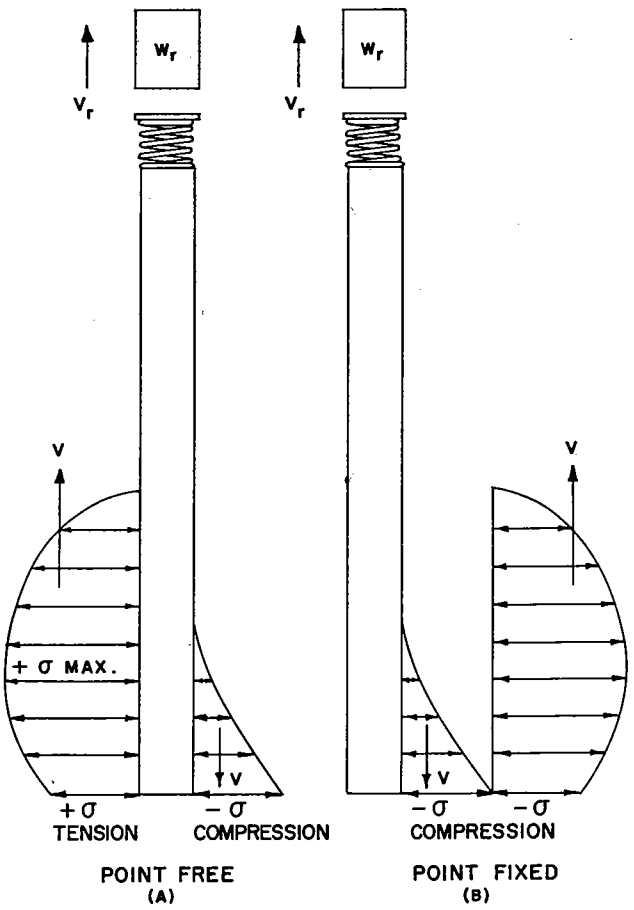

Figure 2. Reflection of stress wave at point of a long pile.

stress wave, as shown in Figure 2B. 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 2B, these two 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 2A). 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. Cracks have occurred by this behavior, however.

Figure 3 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_c) critical tensile stresses are not likely to occur. In Figure 3A 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 two, 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 reflected from the free pile head as a tensile (+) stress wave. If the pile is very short (30 ft or less), the reflected 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 3B 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 3 are highly idealized and simplified, but they should indicate some of the basic factors which can cause tensile stress failures in prestressed concrete piles. In summary, tensile cracks of prestressed 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 magnitudes of prestress and tensile strength of the concrete are too low to resist a reflected tensile stress, cracking will occur.

4. When little or no soil resistance at the point of long piles (50 ft or more in length) is present during driving, critical tensile stresses may occur in the lower half or near mid-length of the pile.

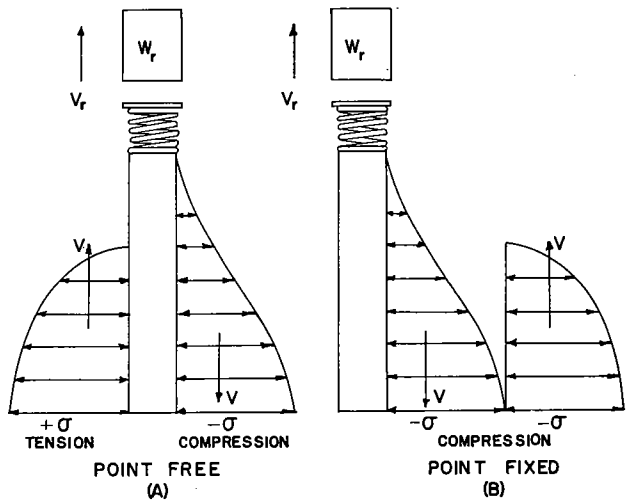

Figure 3. Reflection of stress wave at point of a short pile.

5. When hard driving resistance is encountered at the point of long piles (50 ft or more in length) 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.

GOOD DRIVING PRACTICES

From the preceding discussion of types and causes of concrete pile problems which have occurred, some very basic corrective measures have been revealed.

These rules of thumb for good 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 in. or 4 in. of wood cushioning material (green oak, gum, pine or fir plywood, etc.) may be adequate for short (50 ft or less) piles with reasonably good point soil resistances. Six in., 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 parallel to the end of the pile 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.

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.

4. If pre-drilling or jetting is permitted in placing the piles, ensure that the pile point 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. Ensure that the pile driving helmet or cap fits loosely around pile top so that the pile may rotate slightly without binding within the driving head.

6. Ensure that the pile is straight and not cambered because of uneven prestress or poor concrete placement during casting. Improper storage, handling, or hauling of piling can also cause excessive camber and even cracking. Care should be taken to support or pick up piling at the prescribed points. High flexural stresses may result during driving of a crooked pile.

7. Ensure 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 a reasonable amount of spiral reinforcing at the pile head and tip.

10. Use adequate amount of residual prestress in prestressed piles to resist reflected tensile stresses. The amount of prestress required depends on the driving equipment, length of pile, and soil conditions as previously discussed.

11. Chamfer top and bottom edges and corners of pile.

The rules of thumb summarized here are presented only as guide lines for producers and users of prestressed concrete piling. For quantitative values of dimensional tolerances, amount of prestress, and amount of spiral reinforcement that should be used, one should refer to the applicable governing standards such as ACI, PCI, AASHO, etc. These standards represent the present state of the art concerning prestressed concrete piling. Further research and development in this area is being conducted, and more specific information and improvements are anticipated in the future.

ACKNOWLEDGEMENTS

The literature search, theoretical work, and field tests which led to this summary of rules of good driving practice for prestressed concrete piles were sponsored cooperatively by the Texas Highway Department and the United States Department of Commerce, Bureau of Public Roads. Mr. E. A. L. Smith, Chief Mechanical Engineer of Raymond International (now retired) served as a special consultant to the Texas Transportation Institute during the initial phase of this work. The guidance and support of Mr. Wayne Henneberger and Mr. Farland Bundy of the Bridge Division of the Texas Highway Department is also acknowledged.

SELECTED REFERENCES

Donnell, L. H., "Longitudinal Wave Transmission and Impact," TRANSACTIONS, ASME, Vol. 52, 1930, p. 153.

Gardner, S. V., and New, D. H., "Some Experiences with Prestressed Concrete Piles," Proceedings of the Institution of Civil Engineers, Vol. 18, January, 1961, pp. 43-66, and Vol. 21, April 1962, pp. 867-891, London, England.

Gerwick, B. C., "Torsions in Concrete Piles During Driving," JOURNAL, Prestressed Concrete Institute, Vol. 4, 1959, pp. 58-63.

Glanville, W. H., Grime, G., Fox, E. N., and Davies, W. W., "An Investigation of the Stresses in Reinforced Concrete Piles During Driving," British Building Research Board Technical Paper No. 20, Dept. of Scientific and Industrial Research, His Majesty's Stationery Office, London, 1938.

Hirsch, T. J., "Stresses in Long Prestressed Concrete Piles During Driving," Report of the Texas Transportation Institute, Texas A&M University, September, 1962.

Hirsch, T. J., "Computer Study of Variables Which Affect the Behavior of Concrete Piles During Driving," Report of the Texas Transportation Institute, Texas A&M University, August, 1963.

Hirsch, T. J., "Field Tests of Prestressed Concrete Piles During Driving," Report of the Texas Transportation Institute, Texas A&M University, August, 1963.

Hirsch, T. J., Samson, C. H., and Lowery, L. L., "Driving Stresses in Prestressed Concrete Piles," presented at the annual meeting of the Structural Division of ASCE, San Francisco, California, September, 1963.

Lin, T. Y. and Associates, "Investigation of Cracking of Prestressed Concrete Piles West Atachafalaya Floodway Crossing Bridge No. 3, Louisiana," unpublished report to R. H. Wright, Inc., Fort Lauderdale, Florida, September, 1959.

Portland Cement Association, "Driving Problems With Prestressed Concrete Piles," a discussion published by the Structural Bureau, October, 1962.

Samson, Charles H., Jr., "Pile-Driving Analysis by the Wave Equation (Computer Procedure)," Report of the Texas Transportation Institute, Texas A&M University, May, 1962.

Samson, C. H., Hirsch, T. J., and Lowery, L. L., "Computer Study of Dynamic Behavior of Piling," JOURNAL OF THE STRUCTURAL DIVISION, ASCE, Vol. 89, No. ST4, Proc. Paper 3608, August, 1963, pp. 413-449.

Smith, E. A. L., "Pile Driving Impact," Proceedings, Industrial Computation Seminar, September, 1950, In-

ternational Business Machines Corp., New York, N.Y., 1951, p. 44.

Smith, E. A. L., "Impact and Longitudinal Wave Transmission," TRANSACTIONS, ASME, August, 1955, p. 963.

Smith, E. A. L., "What Happens When Hammer Hits Pile," ENGINEERING NEWS RECORD, McGraw-Hill Publishing Co., Inc., New York, N.Y., September 5, 1957, p. 46.

Smith, E. A. L., "Tension in Concrete Piles During Driving," JOURNAL, Prestressed Concrete Institute, Vol. 5, 1960, pp. 35-40.

Smith, E. A. L., "Pile-Driving Analysis by the Wave Equation," TRANSACTIONS, ASCE, Vol. 127, 1962, Part I, p. 1145.

Siess, C. P., "Dynamic Tests of Prestressed Cylinder Piles," unpublished report to Raymond Concrete Pile Company, January 15, 1958.

Strobel, G. C. and Heald, John, "Theoretical and Practical Discussion of the Design, Testing and Use of Pretensioned Prestressed Concrete Piling," JOURNAL, Prestressed Concrete Institute, Vol. 6, No. 3, September, 1961, p. 22.

Timoshenko, S., and Goodier, J. N., "Theory of Elasticity," McGraw-Hill Book Co., Inc., New York, N.Y., 2nd Ed., 1951, p. 438.

Zollman, C. C., "Investigation of Failure of Three Prestressed Concrete Piles," Concrete Briefs, JOURNAL, American Concrete Institute, Proceedings, Vol. 58, No. 1, July, 1961.