OPPORTUNITIES FOR THE USE OF PRESTRESSED CONCRETE PILES

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ABSTRACT

The use of the various pile types in the United States by location in the country is presented to show the opportunities for prestressed concrete. The application of higher strength prestressed concrete piles is discussed using designs of 12 inch square piles. The pile designs are based on both allowable stress design and LRFD. Pile concrete strengths up to 12 ksi are considered and limiting nominal strengths for both allowable stress design and LRFD are compared with the maximum installed stress that can be achieved by driving. The stress induced by driving is limited by specification. A comparative cost evaluation is made to show the advantages of high strength concrete piles.

Keywords: Piles, Prestressed Concrete, High Strength Concrete, Pile Driving, Allowable Stress Design, LRFD.

INTRODUCTION

Prestressed concrete piles are widely used in some parts of the country today; in others they share the market with steel and timber piles and in a large part of the country they are never used. Fig. 1 shows the author's opinion of prestressed concrete pile use based a general evaluation of his experience. But, concrete piles could be used everyplace except in those areas where earthquake design is important or where there is a karst topography of hard rock. Those areas are shown in Fig. 2. They also cannot be used for bridges at sites with severe scour requirements where the soils prohibit sufficient penetration by driving.

The use of higher strength concrete piles will be discussed in view of design code requirements and driving limitations. Both the LRFD and Allowable Stress design methods will be used. The LRFD limitations are those given in ACI 318-02 and the Allowable Stress limitations follow approximately the AASHTO Standard Specification, 1998 Edition. So, what are the advantages of higher strength concrete?

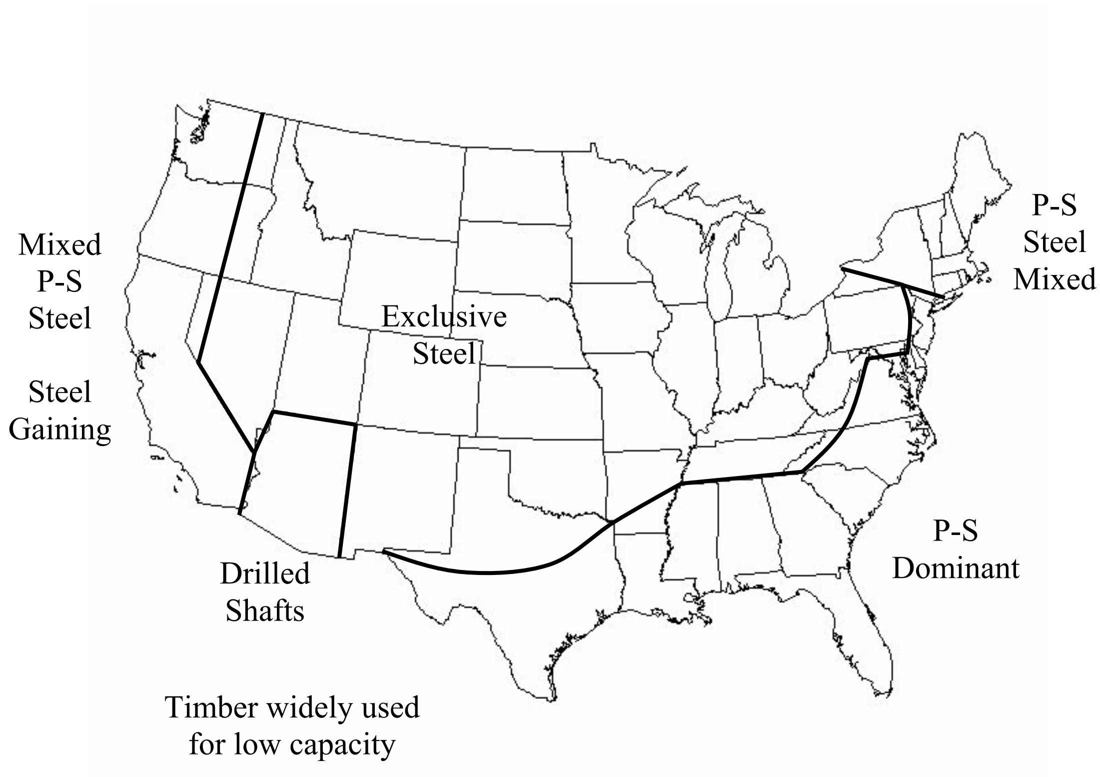

Fig. 1 Pile Use by Location

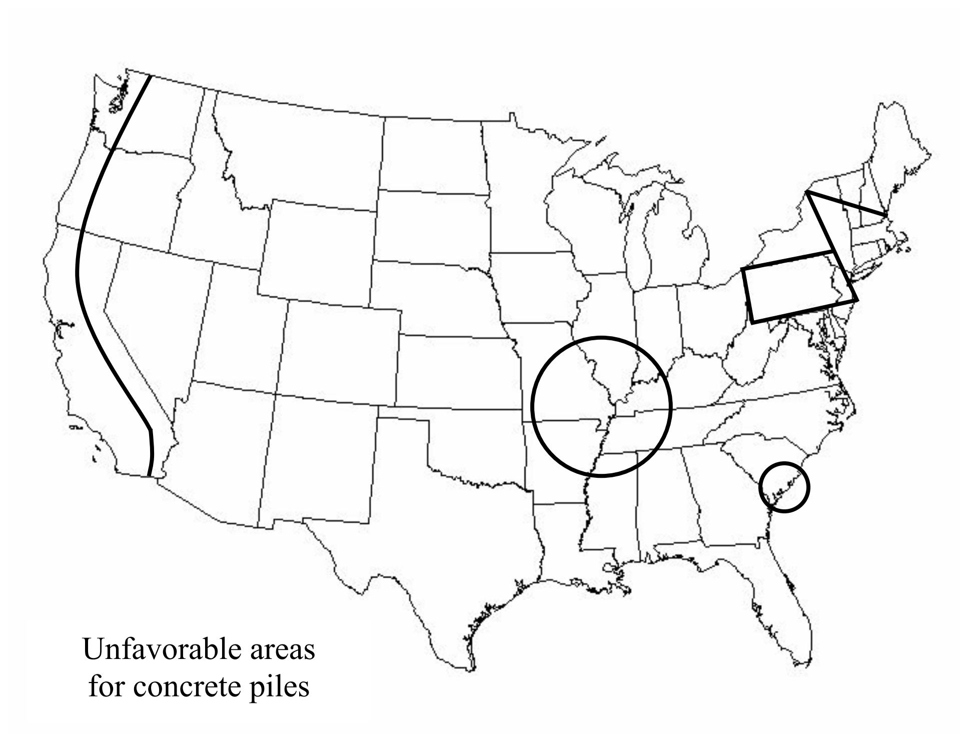

Fig. 2 Areas Not Desirable for Concrete Piles

DESIGN LIMITS

ACI 318-02, Section 10.3.6.3 specifies that the nominal axial load strength is P_o. The Commentary states that for prestressed members, strength is to be computed "including the effect of the prestressing force." However, it was impossible to find the method for accomplishing that for axially loaded members. The stress in the strand was estimated as 170 ksi, a value that is probably too high. So the nominal axial strength for a tied pile was calculated as

$$P_o = 0.80(0.85f'_c A_g - 170A_{ps}) \tag{1}$$

where the units are ksi and the notation is that used in the ACI Code. It seems that little consideration was given to determining the strength of driven piles when the ACI Code was written. A commonly used expression for the allowable design compression stress is

$$F_{all} = 0.33f'_c - 0.27f_{pe} \tag{2}$$

where the units and notation are the same as for Equation (1). The strength for the limiting compression stress for a pile due to driving is usually

$$f_{dr} = 0.85f'_c - 0.f_{pe} \tag{3}$$

Concrete in tension given in the ACI Code, Section 9.5.2.3 is

$$f_r = 7.5\sqrt{f'_c} \tag{4}$$

where f'_c has the units of psi. However, this value comes from limitations on beams. There is no general standard in the pile driving industry for allowable tension stress induced during driving. A commonly used value is

$$F_t = f_{pe} + 3\sqrt{f'_c} \tag{5}$$

But the multiplier on $\sqrt{f'_c}$ can vary from 6.0 to 0. It will usually depend on the exposure.

DESIGN EXAMPLES

Today, it seems that 5.0 ksi concrete is the most common material used for piles. However, much higher strength concrete is widely used in other applications. In some areas, it may be difficult to produce a concrete strength greater than about 8.0 ksi, but, strengths as high as 12 ksi are possible with good aggregate. Spun cast cylinder piles of 12 ksi are now being imported from Asia. These piles are widely used today in China and Southeast Asia.

The design performance for several concrete strengths up to 12 ksi is examined here. The nominal axial compression strength for LRFD design applied to a 12 inch square concrete pile is obtained from Equation (1), and tabulated in the second column of Table 1. The allowable design stress is determined from Equation 2 and used to determine the allowable design load on a 12 inch square pile. They are given in Columns 3 and 4 of Table 1. The tension and compression stress allowed during driving are determined from Equations (3), and (5). An effective prestress of 800 psi has been assumed. Because the prestress is constant for all of the concrete strengths, higher strengths are seen to be more efficient than lower strengths because a constant prestress is subtracted. The ratio is given in the parentheses in column 3.

Table 1, 12 inch Concrete Pile Capacities for Several Concrete Strengths, 800 psi Effective Prestress

Concrete Strength ksi	LRFD Strength P_o kips	Allowable Compression Stress ksi	Allowable 12 in. Pile Capacity kips	Allowable Compression Driving Stress ksi	Allowable Tension Driving Stress ksi
5.0	397	1.43 (1.00)*	205	3.45	1.01**
7.0	593	2.09 (1.46)	301	5.15	1.05
8.0	691	2.42 (1.69)	348	7.70	1.10
10.0	887	3.08 (2.15)	444	7.83	1.11
12.0	1083	3.74 (2.62)	539	9.40	1.13

*The value in parentheses is the allowable compression stress divided by the 5000 ksi value.
**The allowable tension stress is calculated by multiplying the square root by 3.0.

DRIVABILITY STUDY

Now the question that must be answered is, "Can the pile be driven to the capacities obtained from Equation (1) or Equation (2)?" To evaluate drivability, the commonly used tool is wave equation analysis. This analysis models the pile, soil and the driving system for computer analysis. The pile is represented by a one dimensional discrete spring-mass system and the soil as an elastic-plastic spring and a linear dashpot. This concept was developed by Smith[1] in the late 1940's. It came into practice very slowly. Today the most commonly used wave equation computer program is GRLWEAP[2]. It is used routinely in evaluating pile drivability.

GRLWEAP was used to determine the capacities that could be driven for an example where the concrete strength varies from 5.0 ksi to 12.0 ksi. In each case, a diesel hammer was selected that would drive to a limiting blow count of 10 blows per inch, a commonly used value, and to the maximum capacity that could be reached without exceeding the limiting driving stresses. The compression stresses due to driving were limited to the values defined by Equation (3) and tabulated in Table 1, Column 5. A 70 foot long pile was selected for analysis and typical soil parameters were used. The soil resistance was assumed to be 30 percent on the shaft and 70 percent on the toe. Diesel hammers were used because the stroke increases with increased resistance and it can be quite large at the end of driving. The results including the hammer type and stroke are tabulated in Table 2.

The ultimate capacity that can be driven to 10 blows per inch within the allowable driving stresses is shown in the second column of Table 2. A factor of safety of 2.0 is assumed to obtain the "Driving Design Capacity" for the allowable stress capacities. The Driving Design Capacity can be compared directly with P_0. or with the Ultimate ASD Capacity. This strength is obtained by multiplying the Allowable Design Capacity from Equation (1), by 2.0. In every case the capacity that can be driven is less than the allowable capacity.

The allowable driving stress is compared with the actual driving stress in Columns 4 and 5. All of the driving stresses are close the limiting values as a result of the hammer selection. In the last two columns the hammer type, and the stroke at the limiting condition are given.

Table 2, Driving Stresses and Capacities by Wave Equation Analysis for a 12 inch square 70 Foot Long Pile

Concrete Strength ksi	Ult. ASD Capacity kips	P_o Capacity kips	Driving Stress ksi	Allowable Driving Stress Ksi	Driving Capacity kips	Hammer Type	Stroke ft.
5.0	412 (70)*	397	3.32	3.45	275	D-12	7.8
7.0	602 (177)	593	5.20	5.15	425	D-16-32	8.4
8.0	696 (196)	691	5.99	6.00	500	D-22-23	8.1
10.0	887 (149)	887	7.68	7.70	680	D-30-32	9.2
12.0	1077 (277)	1083	9.10	9.40	800	D-44	7.61

*The difference between the allowable design capacity times 2.0, to obtain ultimate design capacity, and the driving capacity.

The capabilities of high strength concrete piles are quite remarkable. If the concrete strength is doubled from 5.0 ksi to 10.0 ksi the driving capacity given in Table 2 is increased by a factor of 2.5. The ASD capacity is increased by about 2.2. It should be understood that the driving capacity is affected by the match of the hammer and the pile. The prestress does not need to be increased with the high strength concrete so the design capacity increases by a larger factor than the concrete strength. By increasing the concrete strength from 5.0 ksi to 12.0 ksi the drivable pile capacity is increased by a factor of 2.85. Of course, the drivable capacity will depend on the hammer selected.

To provide another evaluation of the issues for the examples in Table 2, the same conditions were used with some parameters varied. The obvious items to change are the pile length and the hammer type. The results are shown in Table 3.

First, a 100 foot long pile of 8.0 ksi concrete was analyzed with the D-22-23, the same hammer that was used on the 70 foot pile included in Table 2. The capacity was slightly smaller than the 70 foot pile but the driving stress was the same. It would be expected that the driving stress would be the same if the stroke was unchanged because the driving stress is directly related to the ram impact velocity.

Table 3, Examples of Different Pile Lengths and Hammer Types for 12 inch, ASD Ultimate Capacity, 8.0 ksi Concrete

Pile Length ft.	Ultimate Capacity kips	Design Capacity kips	Allowable Driving Stress ksi	Driving Stress ksi	Hammer Type D-22-23	Stroke ft.
100	450	348	5.99	6.00	Vul No. 1	7.8
100	350	175	5.99	3.33	Vul No. 1	3.0
70	350	175	6.00	3.33	Vul No. 1	3.0
30	350	175	6.00	3.33	Vul No. 1	3.0
70	330	165	3.45	3.01	Vul No. 1	3.0

Next a Vulcan No. 1 air hammer was investigated for pile lengths of 70 and 100 feet. The capacities were the same in both cases but they were about 100 kips less than was developed by the diesel hammer. The driving stress was considerably smaller than was generated by the diesel hammer. This would be expected due to the much smaller stroke of the air hammer. Then a 30 foot long pile was analyzed to see if the short pile length would be more advantageous for the air hammer with the heavy ram. If the ram is heavy enough the reflected compression stress can add on to the downward traveling stress at that time and so produce a larger force at the pile toe. The performance was the same as the previous cases. Finally, the air hammer was used on a pile with 5.0 ksi concrete. In this case, the hammer performed better than the same case driven with the diesel. Probably, the longer stress wave generated by the heavy ram combined with the lower allowable driving stress produced the improved results.

COST STUDY

Now compare the 5.0 ksi pile size that would be required to carry the same load as is carried by the higher strength piles. The results are shown in Table 4. The weight per foot for the equivalent 5 ksi pile is given in the last column. The 20 inch pile weighs almost three times the weight of a 12 inch pile. This weight must be hauled to the jobsite, picked up and handled by the crane.

It is interesting to consider the ratio of the drivable design load to the allowable design load. For the cases considered, the average ratio is 1.4 and the ratio ranges between 1.3 and 1.6. This ratio could be useful in making a quick estimate of the maximum possible driving stress. Of course, the drivable capacity will vary depending on the soil and the particular hammer used. Before a design is finalized a wave equation study must be made.

Table 4, Alternative to 5000 psi pile

Concrete Strength ksi	Allowable Design Load kips	Drivable Design Load, F.S. = 2.0 kips	Equivalent 5 ksi Pile inch	Equivalent Pile wt/ft kips/ft
5.0	207	135	12	0.15
7.0	300	185	14	0.20
8.0	350	250	18	0.34
10.0	444	340	20	0.42
12.0	539	385	20	0.42

SUMMARY

The study of the efficacy of using higher strength concrete for piles indicates that considerable advantage accrues to such a change. Strengths as high as 12.0 ksi were analyzed and they showed a large increase in capacity over the current practice of using 5.0 ksi concrete. An increase in capacity of a factor about 2.5 is possible. However, to use such high capacities requires the use of very large hammers compared with current practice. If changes are to be made they should be introduced gradually. Perhaps 8 ksi concrete could be used and driven to driving stresses that are near the limiting values. Then the pile concrete strength could gradually be increased.

It was shown that it is difficult, if not impossible, to drive concrete piles to the allowable design stresses. Instead, driving stresses will exceed the allowable limit before the design stress is reached. Usually, the blow count is not critical as soon as the driving stress.

If high strength concrete is to be used it will be necessary that the hammer be selected carefully. It must operate at a high impact velocity. It is of interest that the use of an air hammer was effective with 5 ksi concrete. Since the allowable stress is lower it is possible to achieve driving stresses that are near the allowable driving stress. But, the typical 3.0 foot stroke of an air hammer will not produce the necessary impact velocity to take advantage of the higher allowable stress of high strength concrete. The properly selected diesel hammer can do that and probably a properly selected hydraulic hammer.

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