POTENTIAL FOR HPC IN DRIVEN PILE FOUNDATIONS

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ABSTRACT

Prestressed concrete piles are widely used as deep foundation elements. In the United States design loads and concrete strengths have changed little over the past thirty years. The perception exists that there is little advantage to increasing concrete strength since the existing design loads are usually much less than code allowable loads. Two examples are given here to show possible advantages of the use of high performance concrete (HPC), particularly high strength concrete. It is shown that design loads are usually limited by driving stresses. Therefore, if higher strength concrete is used, increased driving stresses could produce higher design loads with associated reduced installed cost.

INTRODUCTION

Deep foundations of prestressed concrete, driven piles are commonly used in many parts of the world. However, over the past two decades they have been changed by cast-in-place concrete foundation solutions. During this period little has changed in most of prestressed concrete pile design and installation practice in the United States. It is the thesis of this paper that there are opportunities for increasing design loads on precast concrete piles by using high performance concrete and particularly high strength concrete. An increase in design loads will improve the cost effectiveness of driven piles.

Precasters have shown little interest in increasing concrete strength in piles. Design stresses are usually quite low when compared with allowable stresses so it has appeared that there is little reason to increase concrete strength.

In the design of piles there are three strength failure modes that must be satisfied. The structural strength of the pile must be adequate to carry the load, the soil strength must be adequate to carry the load, and the pile must be installable (driveable). The structural strength of the pile under service loads is the least likely of the three limitations to be critical. When tested statically to failure most piles fail by penetration into the soil, thus soil failure (a geotechnical consideration). The third requirement, pile driveability, is

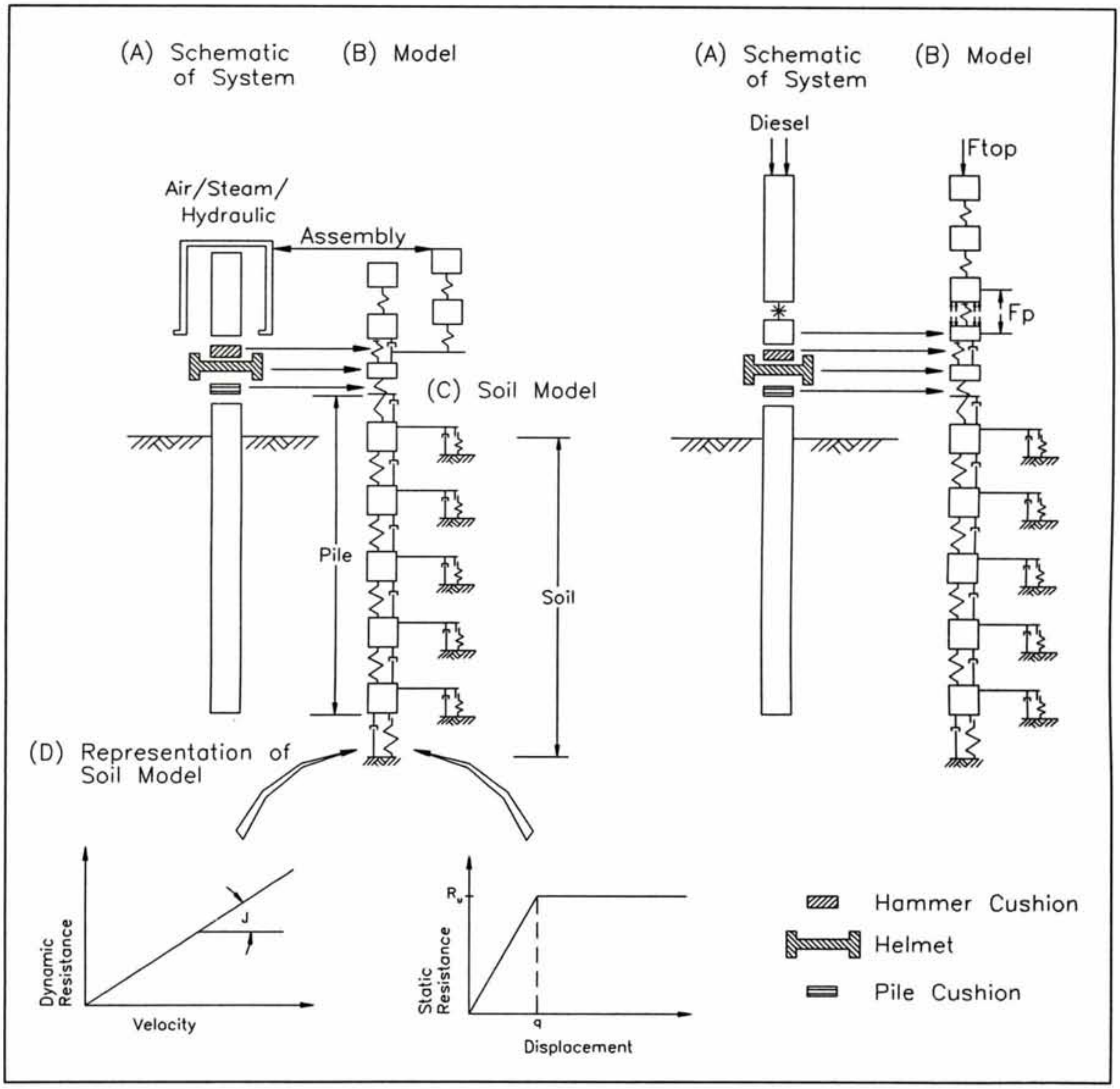


Figure 1: Numerical Model of Pile Driving

also often critical. This condition is satisfied when the compression stresses induced during driving are not excessive, the tension stresses due to driving are also satisfactory and the required blow count can be reasonably achieved.

In order to increase geotechnical capacity, the usual solution is to drive the pile harder and thus increase the possibility of damage during installation. Clearly these two limiting conditions are closely interconnected. In general, the compression stress induced at impact is related to the ram impact velocity while the length of the stress wave induced by impact is determined by the ratio of the weight of the ram to the weight of the pile. As this ratio increases the length of the stress wave increases. If a large peak compression stress is induced by a high ram impact velocity in easy driving conditions, that peak compression will reflect back as a tension wave and may produce excessive tension stresses. Experience has shown that a small number of excessive tension stresses may not cause tension failure while a large number is likely to cause damage.

A number of other limitations on pile design may be critical that will not be discussed here. These design limitations relate to serviceability conditions and, while they are certainly important they are more likely to be critical with increasing design loads. In this paper only strength and driveability conditions will be discussed.

MODELING OF PILE DRIVING

A method for the numerical evaluation of pile driving was created about 50 years ago by E. A. L. Smith, Chief Engineer of the Raymond Company[1]. This development was continued to create a useful capability that was proprietary to the Raymond Company[2]. Further research was done at Texas A & M University[3] and Goble Rausche Likins and Associates, Inc. (GRL)[4] and this produced public domain dynamic pile analysis software. A large literature has been generated particularly over the last 25 years. It is beyond the scope of this paper to do a detailed review that work. Currently, the dominant software for pile driving dynamic analysis is GRLWEAP, a commercial program that is a derivative of the original work of GRL[5]. This program was used in the study presented here.

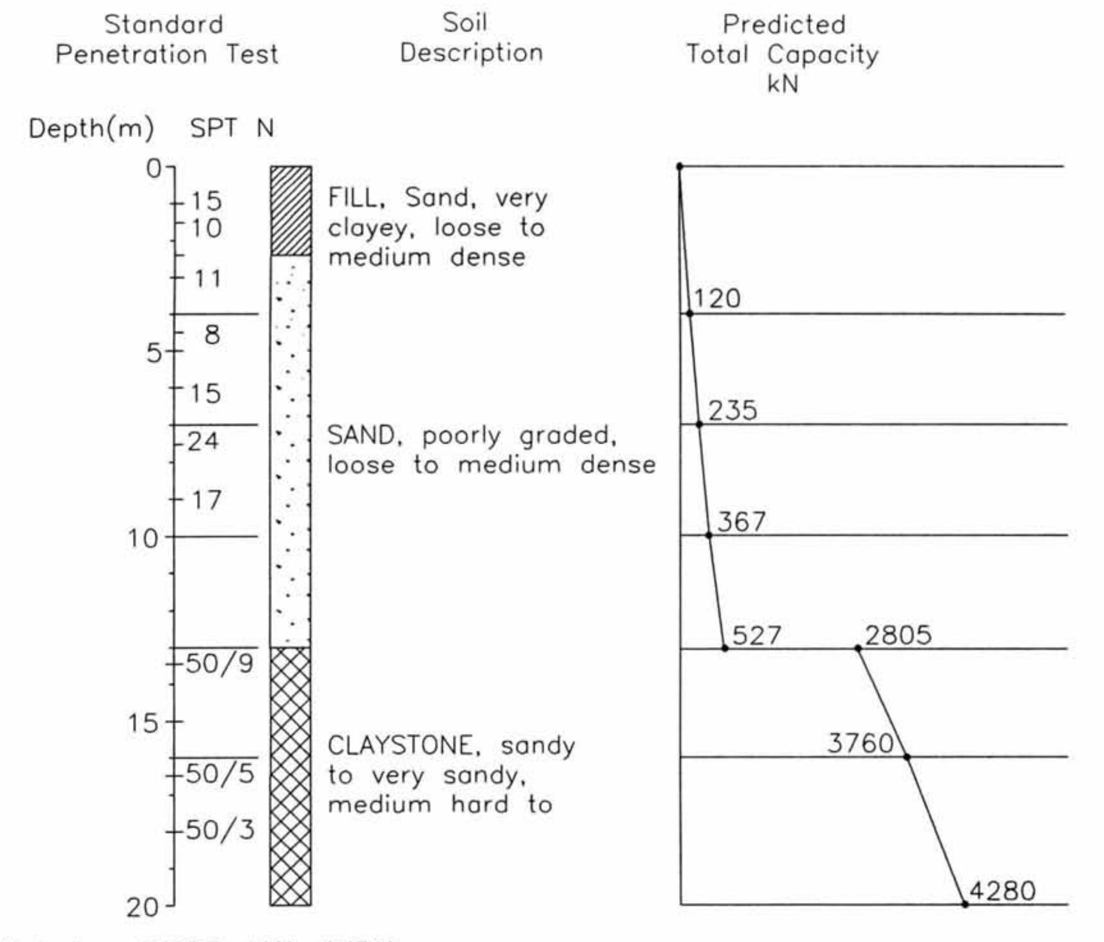
The general model of pile driving developed by Smith is used in GRLWEAP and is shown in Figure 1. The hammer, driving system and pile are represented as a one dimensional, damped, lumped mass, dynamic system. The pile driving ram is put in contact with the driving system with an appropriate impact velocity. The impact velocity generates motion in the driving system and pile. The hammer operation can be quite complex, including the thermo-dynamics of diesel hammer combustion, but can be modeled in the program. Extensive studies have been carried out to verify and improve hammer models[4]. In some cases such as diesel hammers extensive development was required to achieve agreement between the model and hammer performance. These hammer models have been developed and stored in GRLWEAP so that the user does not have to have extensive experience with pile driving hammer modeling.

In addition to the one dimensional system model of the hammer and pile, the soil is represented as a series of elastic-plastic springs with linear dashpots (Figure 1). The static capacity of the pile is the sum of the ultimate strengths of the individual elastic-plastic springs. These values are determined from the soil behavior combined with the selected pile ultimate capacity during pile installation based on geotechnical considerations. Pile driveability can be evaluated by determining the static soil resistance as a function of depth using a geotechnical analysis and then calculating the pile penetration for the required total pile capacity. During the analysis the force in each of the springs connecting the discrete masses is determined at each time increment. Critical values of compression and tension stresses are selected from the analysis.

The pile design evaluation process will be illustrated with two examples.

ANALYTICAL HPC EXAMPLES

Consider first the example of a 300 mm (12 inch) square pile driven at a site illustrated by the boring log shown in Figure 2. This boring was obtained at a location near Denver, Colorado, and it is typical of some of the soils just east of the Rocky Mountains. The rock can be penetrated by pile driving. The total shaft and toe resistances calculated by static soil analysis of the subsurface conditions is given as a function of depth in Figure 2.

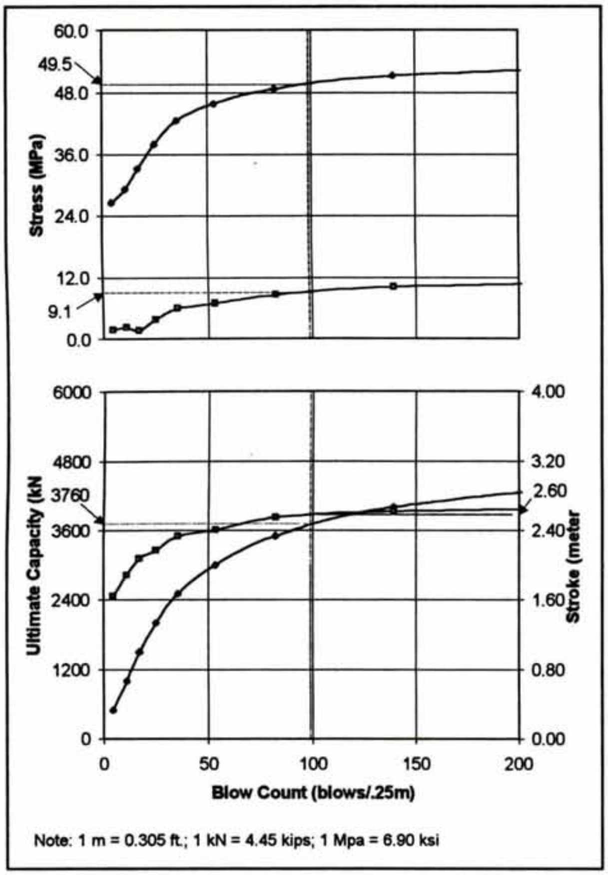


Note: 1 m = 0.305 ft.; 1 kN = 4.45 kips

Figure 2: Soil Boring for Example of Pile Driven into Soft Rock

This analysis was made using the program DRIVEN, made available in the public domain by the Federal Highway Administration. The driving response of a high strength concrete pile, driven into this material, will be examined by wave equation analysis. In performing the wave equation analysis, the GRLWEAP program, Windows Version, 1998-1 was used. The pile concrete material was assumed to have a cylinder strength of 80 MPa (12,000 psi) and an elastic modulus of 37.3 MPa (5400 ksi) with a stress wave speed of 4,000 m/sec (13,200 ft/sec). The driving characteristics were studied with several likely driving systems. The most interesting of those studied was a D-36-32 diesel hammer because of the high impact velocity delivered by this hammer. It is a single acting diesel hammer with a calibrated throttle making it possible to control the operation of the hammer. It has a ram weight of 35.3 kN (7.9 kips) and a rated energy of 120 kJ (88 ft-kips).

With a soil resistance distribution as shown in Figure 2, the depth of penetration will not vary greatly for different, realistic driving systems and driving will be easy over most of the depth. Therefore, the most useful method of analysis is to determine a Bearing Graph. In this approach to driveability evaluation a resistance distribution is assumed using that obtained in the geotechnical soils analysis. Then a range of pile capacities is analyzed using the assumed resistance distribution. The results of this Bearing Graph analysis are shown in Figure 3. In the Bearing Graph analysis, the resistance distribution obtained from the static analysis is used a an input together with traditional values for damping and quake and the relationship between driving resistance (blow count) and the important parameters are given. As shown in Figure 3 with a blow count of 100 blows/0.25 m (10 blows/inch) an ultimate capacity of 3760 kN (845 kips) is predicted. Associated with these values is a maximum compression stress of 49.5 MPa (7.2 ksi) and a maximum tension stress of 9.1 MPa (1.3 ksi). It is interesting that the maximum tension stress is associated with the highest driving resistance. This case occurs when a large compression stress reflection arrives at the top of the pile after separation of the pile top from the ram resulting in a tension stress during the second downward traveling wave.



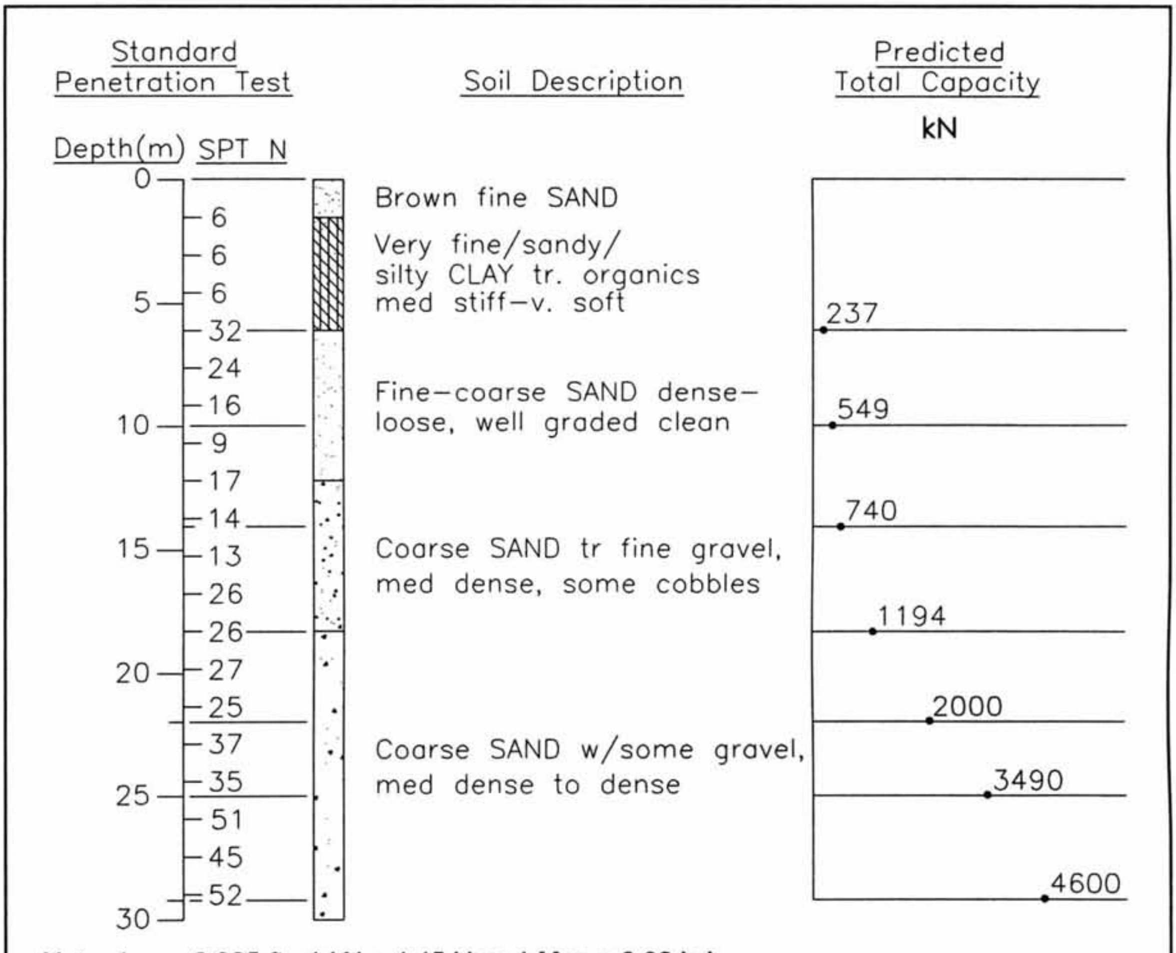
Note: 1 m = 0.305 ft.; 1 kN = 4.45 kips; 1 Mpa = 6.90 ksi

Figure 3: Bearing Graph – 300 mm square Concrete Pile, D36-32 Hammer

If a factor of safety of 2.0 is used this implies a design load of 1880 kN (422 kips) and a nominal design stress of 20.9 MPa (3.0 ksi). This magnitude of design load is twice as large as is typically used in United States practice and that should have a very favorable effect on driven pile cost.

Of course, there are questions if driving stresses of this magnitude can be used. In the authors' experience, driving stresses of this magnitude have been observed in spun cylinder piles, driven with a large diesel hammer in Hong Kong. Current United States practice recommends that driving stresses not exceed 85 percent the cylinder strength minus the effective prestress. This condition is satisfied. However, carefully controlled, instrumented, driving tests should be run to verify driveability and to establish driving limitations.

A second example illustrates another condition for prestressed concrete piles. In this case the pile is primarily a friction pile with only a rather small amount of end bearing. The subsurface conditions for the site are shown in Figure 4. The boring log shows sands that generally increase in density with depth. The DRIVEN program was used to determine total pile capacity with depth for a 300 mm (12 in.) square concrete pile that is the same as was used in the previous example. The capacity also shown in Figure 4. In evaluating the conditions shown a different analysis than the bearing graph used above is

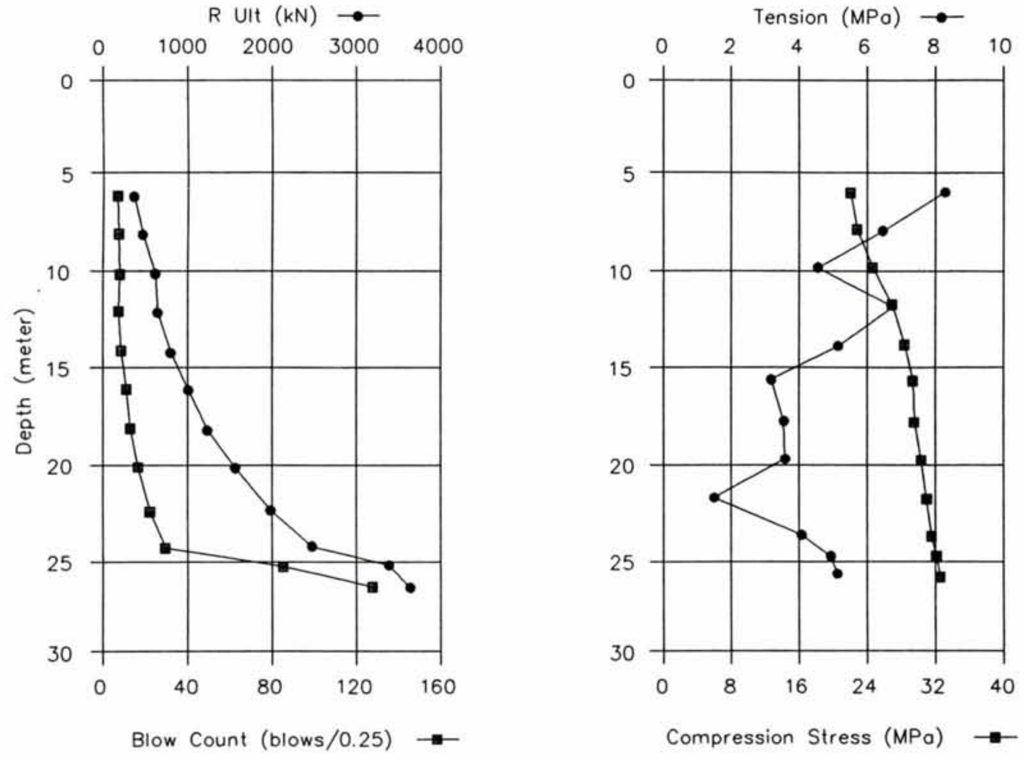


Note: 1 m = 0.305 ft.; 1 kN = 4.45 kips; 1 Mpa = 6.90 ksi

Figure 4: Subsurface Information for Second Example

appropriate. A driveability analysis is used to predict the driving record that would be expected.

In the driveability analysis, single wave equation analyses are made at several increasing depths and at each depths, the blow count is determined as well as driving stresses and other useful information. The results of the analyses are shown in Figure 5. A driving resistance of 350 blows/meter (105 blows/foot) can be considered acceptable at a depth of 25 meters (83 feet). This condition is associated with a capacity of 3500 kN (786 kips), a maximum compression stress of 33 MPa (4.8 ksi) and a maximum tension stress of 8.1 MPa (1.17 ksi). It would appear that these stresses are acceptable since they are well below the accepted limiting values. This would again make possible the use of a design load of 1800 kN (200 tons). Perhaps the consideration that is most critical is the driving time. In the previous example it could be expected that the pile would drive quite easily into the rock and then come fairly quickly to the required blow count. In this case, the driving time is estimated in the wave equation analysis to be about 20 minutes. It is often observed that damage is more likely in cases of long periods of high driving stresses and it may be critical here.



Note: 1 m = 0.305 ft.; 1 kN = 4.45 kips; 1 Mpa = 6.90 ksi

Figure 5: Driveability Analysis for Example Two

These two examples show the possibilities available in the use of HPC (high strength) for driven piles. The commonly used allowable design stress would be 24 kPa (3.8 ksi) while the actual stress is 19 kPa (2.8 ksi). The allowable service load stresses are easily within acceptable limits the driving stresses are high enough to cause concern. If it is true that HPC to a strength of 80 MPa (12 ksi) would be only slightly more expensive than the usual concrete then the cost effectiveness of the material is attractive for driven piles.

In order to take advantage of this material two steps should be taken. First, more modest strength increases with associated small increases in design loads should be used on a trial basis. This will make it possible to test the concept gradually in practice with a small risk. A carefully controlled study should be made on hard driving applications. Hammers should be used that can generate large impact stresses. Tests should be run with high impact stresses over large numbers of hammers blows. It should be possible to organize a cooperative study between precasters, pile driving contractors, and owners that could offer great advantage in installed cost. Well-defined limits on driving stresses and number of hammers blows could be established.

CONCLUSIONS

Wave equation analysis has shown that the limits that govern driven prestressed concrete pile installation are geotechnical considerations and driveability. Structural strength of the pile under service load will not be a limitation. There appears to be an application for HPC (high strength) in concrete driven piles that would offer substantial cost savings due to load carrying efficiency. This study has been only analytical. Driving tests should be run to assure that the required high dynamic compression and tension driving stresses can be tolerated by the pile without damage. Such tests could define the limits on dynamic stress and length of driving time.

If the loads studied can be used it will have a major effect on pile installation cost. A well controlled pile installation can substantially reduce deep foundation cost.

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