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Response of Full Scale Drilled Shafts in Loose Soils Exposed to Induced Vibrations

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ABSTRACT

A number of studies have been conducted in an effort to understand wave attenuation and ground response during installation of deep foundations. This research stems from the need to better understand the effect of vibration on green concrete. "Green concrete," is defined as freshly placed and maturing concrete within 24 hours after initial placement. Construction activities create vibratory inducing forces, which unaccounted for or unmitigated, have detrimental effects to existing and newly in-place structures. The differences between common construction vibrations and those produced during deep foundation construction are the amplitudes and duration of vibrations. The study focuses on effects during the installation of deep foundations through vibratory methods and age effect of the vibrations on green concrete. The installations follow the Florida Department of Transportation (FDOT) guidelines.

The field investigation monitors peak particle velocities during installation, and their effect on green concrete. The principal findings from the field study were: (1) vibrations with peak particle velocities of up to 2.5 in/sec do not cause damage to green concrete at distances of two times the shaft diameter and beyond, and (2) in general, a spacing of three times the shaft diameter is a safe specification for ensuring that shaft vibration does not damage the concrete.

Keywords: Construction Vibrations, Early-Age, Concrete

1. INTRODUCTION

1.1 STATEMENT OF THE PROBLEM

The infrastructure of the state's roadways requires increased vehicular capabilities of the roads. Consequently, the greatest challenge is posed in the construction or lane widening in existing bridges or overpasses. The bridge work needs deep foundations, i.e. piles or drilled shafts, for the piers and columns.

The construction of drilled shafts, using the casing method inducing ground vibrations with varying intensities is very common in Florida, especially for deep foundations in waterways. The casing method in drilled shaft construction may be used on a temporary or permanent basis. Specifications of the Florida Department of Transportation require that all drilled shaft casing be removed except those intended to be permanently placed in the boreholes (FDOT Specification 455-15.4). If the permanent casing method is specified for certain site conditions, then the final shaft length needs to compensate for the reduced skin friction due to the presence of the casings. In any case, vibrations are induced during the process of driving the casings and extracting them, in addition to other construction-related vibrations.

Current specifications provide regulatory procedures for the protection of existing structures from the drilled shaft construction induced vibrations. Under Article 455-1.1, structures within a distance of ten shaft diameters or the estimated depth of excavation, whichever is greater, should be monitored for settlement and the possible development of structural cracking. Existing footings within a distance of three times the depth of the excavation should also be monitored. Vibration monitoring equipment should be capable of detecting velocities of 2.5 mm/sec (0.1 in/sec) or less. It is mandatory that the source of the vibrations cease immediately when structural settlement reaches 1.5 mm (0.06 in.), vibration levels reach 13 mm/sec (0.5 in/sec), or damage is caused to existing structures.

The FDOT Specification 455-1.4 Vibrations on Freshly Placed Concrete (Drilled Shafts and Piers is as follows: Ensure that freshly placed concrete is not subjected to vibrations greater than 1.5 in/sec from pile driving and/or drilled shaft casing installation sources located within the greater dimension of three shaft diameters (measured from the perimeter of the shaft closest to the vibration source) or 30 feet (from the nearest outside edge of freshly placed concrete to the vibration source) until that concrete, has attained its final set as defined by ASTM C-403 except as required to remove temporary casing before the drilled shaft elapsed time has expired.

A waiting period of about 12 to 24 hours may be required before construction proceeds although FDOT specifications do not necessitate such a time span for every project. Delay periods are usually set by the project engineers at the sites. The rationale behind these restrictions is to allow additional curing time for freshly placed concrete to avoid any possibility of change in its physical or mechanical properties. Despite the fact that uncontrolled vibrations are usually not allowed during concrete placement, such restrictions have been considered by contractors as subjective and unsubstantiated.

1.2 Objectives

This project objective was to study the effects of vibration on green concrete (freshly placed and maturing, within twenty-four hours of initial placement).

To develop recommendations for mitigating age effects of vibrations on green concrete and criteria for distance from source and acceptable levels of vibration based on evaluation and result of testing.

1.3 Background

During the drilled shaft casing installation, vibration is transmitted from the source of installation to the surrounding soil causing ground motion affecting adjacent structures. The intensity of the ground motion and the severity of the induced vibration depend on factors such as soil type, form of the amplitude-time history of the vibration, polarity of certain type of waves, and configuration of the adjacent structures. (Dowding, 1996) has pointed out that frequency is as important as peak particle velocity in determining the response of above ground structures, and frequency in combination with propagation velocity for the response of below ground structures.

Site sub-soil characterization is significant in the design and ultimate performance of the drilled shaft. The interaction between the soil and foundation is dynamic. Ground response to excitation is dependent on subsurface characteristics. The propagated waves in the soil layers are characterized by various modes of vibration including compressive, shear, and surface waves. Even within the shear mode of vibration, there are two specific types of waves, namely vertical and horizontal shearing waves. For the stability of adjacent structures, the horizontal shearing waves should be of concern due to their detrimental effect on the lateral movement of the structure, and the build-up of the pore water pressure reducing the effective stresses in the soil surrounding the foundation. The intensity of the shear waves depend on the source and on the direction of the propagated, reflected, and refracted waves, which in turn depend on the material properties and geometry of the surrounding media.

Typical earth vibrations due to construction, as function of distance, have been presented by (Wiss, 1967). Typical vibration criteria for building damage have been summarized by (Amick and Gendreau, 2000), with particle velocities widely ranging from 100 in/s to 2 in/s depending on building categories. However frequencies are not addressed. Amick and Gendreau (2001) have also summarized the geometric and material attenuation coefficients for different soil types.

Literature does not present any conclusive evidence that construction-induced vibrations would significantly affect concrete properties. Evidence suggests that "there are no detrimental effects due to vibration of concrete during its setting and curing period. There is evidence that beneficial effects may even be derived" (ASCE, 1984). This conclusion was previously reported by (Bastian, 1970). In one case, cored samples from shell piles subjected to pile driving activities eighteen feet away, showed that compressive strength testing, three days after the initial pour, exhibited higher strength than the control samples. Based on this observation, Bastian concluded that vibration of concrete during its initial setting period was not detrimental, and no minimum concreting radius should be established for this reason. However, ASCE later published a recommendation limiting pile driving within 100 feet of concrete which has not attained its designed strength (ASCE, 1993). Limitations have also been suggested by (Tawfiq, 2003), that "for a period equal to the final time of the concrete there should be no vibrations allowed within a distance of 3 shaft diameter". Tawfiq recommended limiting the maximum peak particle velocity, to 2 in/sec at the suggested distance. In slight contrast, the spacing of 3 times the diameter was indicated by (Reddy et al., 2000). Reddy et al. also concluded that "concrete cured up to 24 hours is not damaged due to vibration.

(ACI Committee 609, 1936) reported the benefits of vibrators, but failed to explain the effect of vibration on a fresh concrete. The frequencies of early vibrators were limited to 3000-5000 cycles per minute (50-80 Hz). (L'Hermite and Tournon, 1948) reported their fundamental research into the mechanism of consolidation. They found that friction in aggregates is the most important factor preventing consolidation (densification) of fresh concrete, but that this friction is practically eliminated when concrete is in a state of vibration. (Meissner, 1953) summarized previous research studies, and reviewed the state of the art on available equipment and its characteristics. The (ACI Committee 609, 1960) gave specific recommendations for vibrator characteristics applicable to different types of construction and field practices. (Walz, 1960) described the various types of vibrators: internal, surface form, and table, and their applications. He also showed that the reduction in internal friction is primarily the result of acceleration produced during vibration. (Olsen, 1987) used accelerometers to measure the rage of movement of fresh concrete, and was able to establish the minimum energy level required to achieve a degree of consolidation of 97 percent or more.

In drilled shaft construction, freshly placed concrete can be subjected to either over-vibration or re-vibration. The difference between the two occurrences is the time delay involved in vibrating the concrete. Over-vibration of concrete results from subjecting the concrete mix to a long duration of vibration, or due to use of grossly oversized equipment and vibration of the concrete many times over the recommended amount. Re-vibration occurs by subjecting the concrete to additional vibration cycles at successive time delays.

Accordingly, fresh placed concrete during drilled shaft construction may be subjected to over-vibration, if the surrounding vibrations due to construction activities continue to be generated for a long period during concrete placement, or the fresh concrete is exposed to additional cycles of construction vibrations at different time levels.

Over-vibration may result in segregation, or sand streaks. In the same shaft, concrete segregation can produce different densities with the depth. This variation in the densities may adversely affect the design capacity of the drilled shaft and the durability performance of the concrete. Keeping in mind subsurface condition in Florida, durability represents one of the major parameters in designing any underground concrete structures. The problem of concrete over-vibration has been discussed by (Forssblad and Sallstrom, 1995), (Alemo and Grandas, 1993), and (Stark, 1996). (Forssblad and Sallstrom, 1995) suggested that the duration of vibration in concrete to amount 60 to 70 percent of the total casing time or the vibration effort can be obtained as follows:

$$V_e = 1800/C \quad (1)$$

where:

V_e = vibration effort, s/m^3

C = casting capacity m^3/hr

They also found that the optimum vibration effort ranged between 200 s/m^3 to 325 s/m^3. Using this relationship, a drilled shaft with 4 ft diameter and 20 feet depth can sustain 50 minutes of continuous vibration, without inducing any changes in the concrete density or compressive strength.

On the effect of re-vibration of fresh concrete, literature does not present any conclusive evidence that construction-induced vibration would significantly affect concrete properties. However, (Tuthill, 1977) reported that re-vibration may produce benefits, particularly for the wetter mixtures, in eliminating water gain under reinforcing bars, reducing bugholes, specifically in the upper portion of deep lifts, all of which increase the strength of the concrete. Simulating a field blast condition, (Esteves, 1978) conducted laboratory testing on concrete prisms subjected to transient impact loading. At different intervals of curing time, he observed the development of microcracks versus the amplitude of the particle velocities. Surface cracks were noticed for concrete prisms subjected to impact compression waves at 10 hr of curing time. The particle velocities that produced these cracks reached a level of 9.8 in/sec (250mm/sec).

If the longitudinal-wave propagation velocity of fully cured concrete is assumed to be 3,000 m/s (10,000 ft/sec), the plane-wave strain associated with the minimum velocity for cracking will be:

$$\varepsilon = \frac{\dot{\upsilon}}{c} = \frac{150 mm/\sec}{3000 m/\sec} = 50\mu \quad (2)$$

Other studies have shown that during curing, the modulus, and, therefore, the compressive-wave velocity are much lower than the final value. Thus, the strain calculated with this larger propagation velocity is a lower bound.

(Esteves, 1978) results indicated that there is a period of greater susceptibility to vibration cracking (between 10 and 20 hours); however, the high threshold during this period (150mm/s) explains why other studies have also shown that there is no loss of final strength from transient vibration (Howes, 1979); (Oriard and Coulson, 1980). (Hulshizer, 1996) suggested some vibration acceptance levels for freshly placed and maturing concrete. In general, (Hulshizer, 1996) found that a value of 5.0 in/sec would represent an average value for an acceptable particle velocity during field construction. This limit may increase or decrease, depending on the type of vibration (impact or harmonic) and on the duration of the vibration (short period or continuous).

Two of the pile vibration tests conducted by the Michigan and California Highway Departments on in-situ curing of concrete are of special interest. The first case involved driving through sand within 0.75 m (30 in) of 5 m (15 ft) long, cast-in-place piles some 5 to 6 hours after pouring. After 46 days, these piles were extracted and cored to determine the strength. The ground motions produced by the pile driving showed that the vibration levels at these piles may have been as high as 100 mm/s. Also, piles subjected to vibration were statistically stronger than the non-vibrated comparison pile. The second case involved vibration of in-place cylinders by driving two 11 meter Raymond step taper piles over a curing time span; similar to that reported by (Esteves, 1978). Particle velocities at distances of 2.5, 5, 10, 20, and 40 feet from the vibrating piles recorded amplitudes of 3.9, 1.97, 0.5, 0.4, and 01.2 in/s, respectively. Once again, the California results showed that vibratory excitation by adjacent piling, even during the critical 12 to 14 hours period, did not reduce the strength of cast-in-place concrete piles.

It is apparent that enough has been learned about concrete vibration during the last 50 years to insure that low slump concrete can be placed successfully. However, a better understanding of the interaction of vibration and fresh concrete is still desirable. Knowledge gained from past experience on this subject has been utilized in the current study to investigate the extent of the effect of construction vibration on the concrete performance. The investigation also addressed the determination of the minimum distance where vibration in the vicinity of a freshly poured drilled shaft should not be allowed.

In view of the availability of well documented reports and books describing the state-of-the art on construction vibrations, the principal problem addressed is the development of updated construction vibration criteria based on research for application in practice.

2. METHODOLOGY

To characterize the type of vibration induced during the installation/construction of drilled shafts, full scale test was designed to study resulting effects. The installation consisted of 10 drilled shafts. The drill shafts were divided into five sets, including a control set. Each set is comprised of 36-in. and 24-in diameter with a centralized rebar. The 36-in construction included of a circular reinforced steel cage. The 24-in diameter drilled shaft design omitted reinforcement. The purpose of the smaller shaft was to document the effects within 3D distance from source of vibration, where D is the diameter of the vibration source, in this case the steel casing. The drill shafts extend to 15 feet below existing top of ground, and the layout followed the Florida Department of Transportation (FDOT) guidelines. The 36-in. shaft design is typical to field shafts in current use, while the 24 inch shaft was solely implemented as a secondary measure to quantify the degree of vibration experienced at the test site. A typical set layout is shown in Figure 1, which also depicts testing and sampling locations.

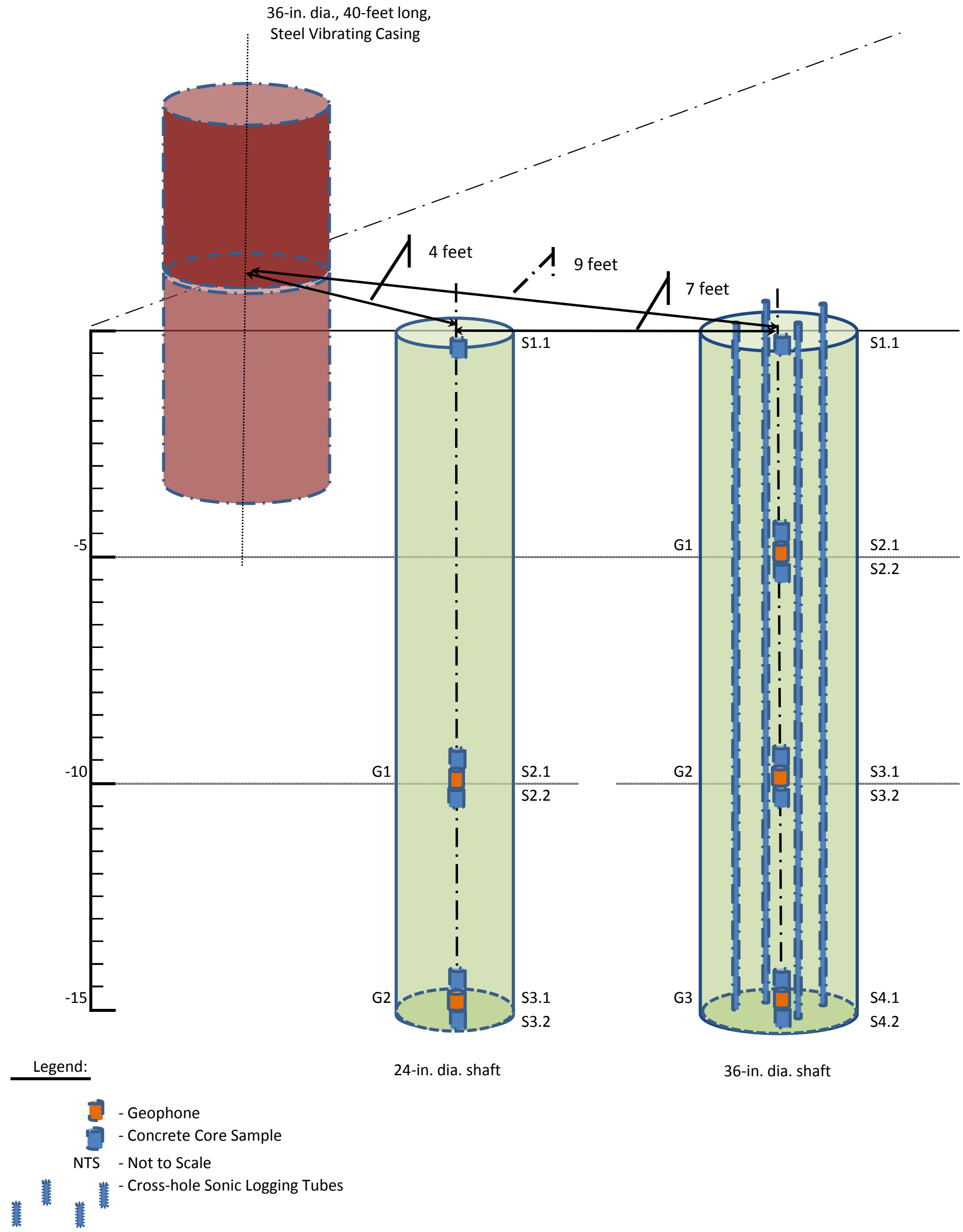


Figure 1. Full Scale Test Layout, Typical. (2, 4, 6, 12 hours, after initial concrete placement).

Monitoring of vibrations was conducted with instrumentation of the shafts. This included temperature sensors and geophones located on the centralized rebar, at varying depth locations to record levels of vibrations. The steel cage was installed with four PVC tubes for scheduled non-destructive testing.

Individual drilled shaft sets were subjected to excitation due to driving to 36-in. steel casing at time period: (2, 4, 6, and 12-hr) after initial pour. The steel casing was withdrawn after completion of each shaft construction.

Twenty-eight days or more after installation, the drill shafts were subjected to Non-Destructive Testing (NDT). The testing included: Pile Integrity Testing (PIT) and Cross-hole Sonic Logging (CSL). Additional testing included geophysical logging using neutron-neutron and gamma-gamma measurement to access shaft porosity and density, respectively. Drilled shafts were cored for the full shaft length. The cored samples and concrete cylinders (control) were subjected to compressive strength testing.

3. Test Results

The PIT showed definite full reflection of the transmitted wave from the shaft tip, indicating no structural damage in the shafts.

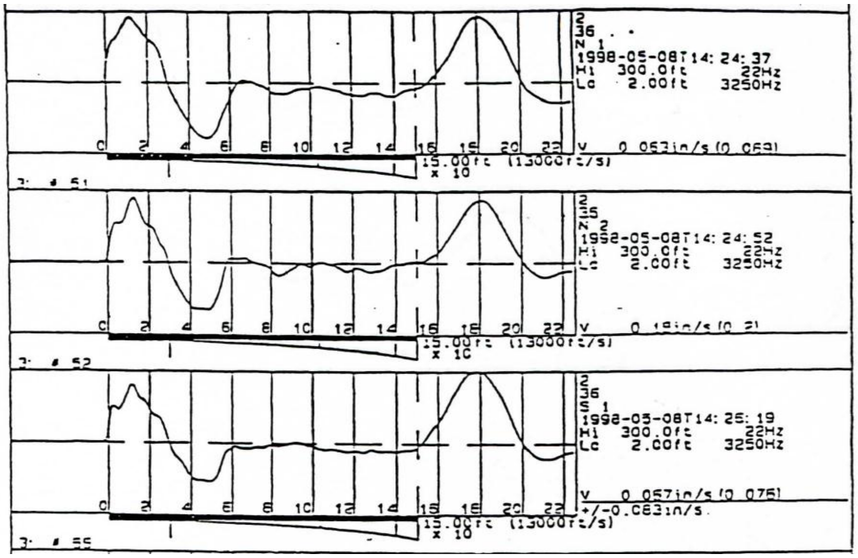
The CSL test showed continuity across the cross-sectional areas of the shafts, with the exception of the 2-hr, 36-in. shaft. However, the PVC access tube showed sign of impact, after construction (hurricane), which may provide the explanation for the anomaly.

Gamma-Gamma logging showed lower density profiles for the upper section relative to the bottom section for each of the shafts. Neutron-Neutron logging showed that porosity within the each shaft is relatively unchanged due to exposure to vibration.

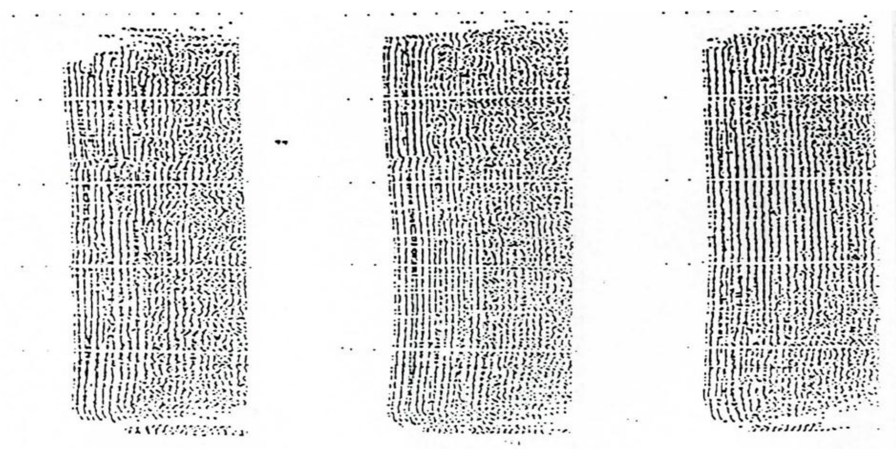
The geophysical data obtained is compared in relative terms to conclude the following: the upper 1/3 or 5 feet of the shafts showed some relatively weaker concrete properties. Typical geophysical testing results are presented in Figure 2. This can mostly likely be attributed to the segregation of the aggregate. The cores obtained were visually inspected and tested in compression. A summary of the core testing program is summarized in Table 1.

Table 1: Summary of Laboratory Unit Weight and Porosity, including Gamma-Gamma and Neutron-Neutron Field Values.

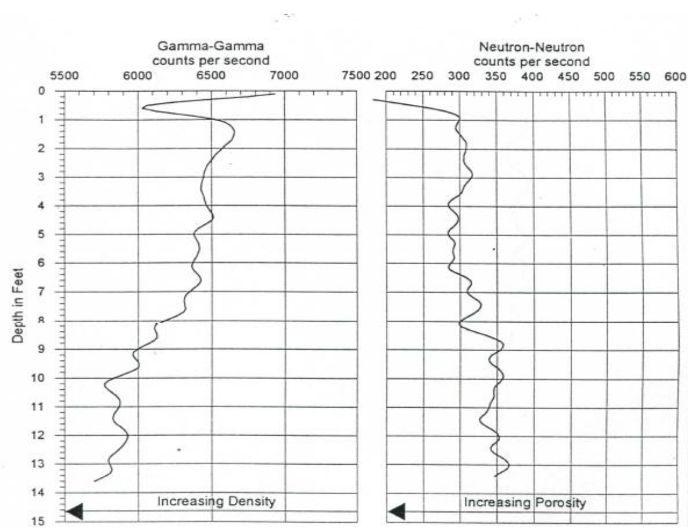
Shaft ID	Sample No.	Depth	Laboratory Saturated Unit Weight (lbs/ft^3)	Gamma-Gamma (counts per second)	Laboratory Porosity (%)	Neutron-Neutron (counts per second)
DS1-2	1	2.5	142.9	6212	17.55	354
DS1-2	2	12	145	6083	15.89	325
DS1-3	1	8	145.9	6051	15.4	388
DS1-3	2	11	144.4	5632	15.81	365
DS2-2	1	2.5	142.8	6238	18.41	350
DS2-2	2	6	141.3	5602	19.44	378
DS2-3	1	3.5	141	5836	19.22	321
DS2-3	2	7.5	139.8	5836	21.17	344
DS3-2	1	1.5	143.8	6370	18.59	343
DS3-2	2	13	143.1	5639	16.54	371
DS3-3	1	3	142.1	6444	19.37	316
DS3-3	2	12.5	143.5	5864	16.3	343
DS4-2	1	2	142.7	6241	18.38	363
DS4-2	2	9	142.9	5676	16.39	356
DS4-3	1	2.5	144.8	6662	18.75	277
DS4-3	2	6.5	140.1	6646	19.63	289



(a) Pile Integrity Tester Result, (typical)



(b) Cross-hole Sonic Logging Results, (typical)



(c) Gamma-Gamma & Neutron=Neurton Results, (typical)

Figure 2. Typical NDT Test Results, 36-inch Diameter Drilled Shafts.

The relative weakness of the upper shaft sections was further evidenced by the compressive strengths of the cored concrete samples, Figure 3.

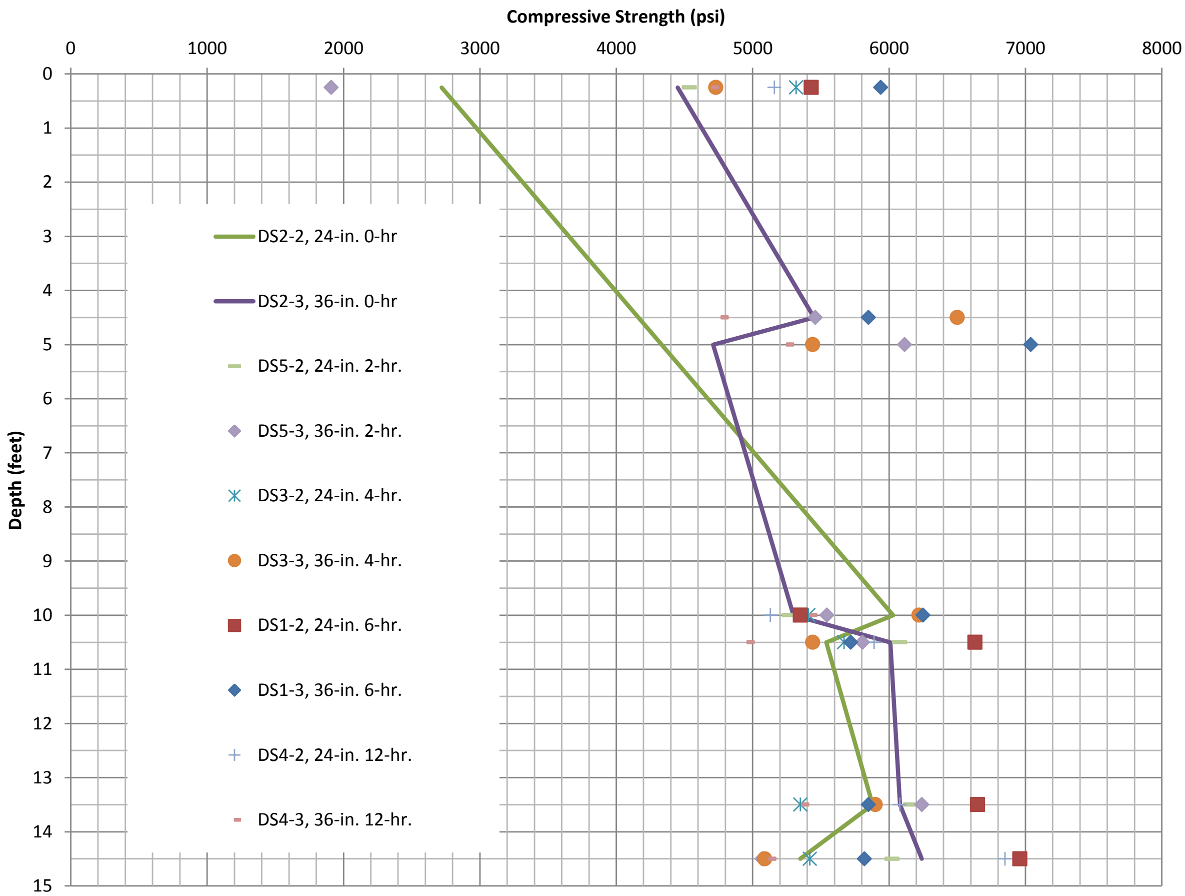


Figure 3: Coring Results, Compressive Strength (psi), of Drilled Shafts.

The geophysical data only served to show relative performance within each individual shaft, and no comparison were established with the other shafts, as no trend could be established in the correlation of the values between the compressive strength and the geophysical data. Nevertheless, the data shows that shaft integrity was not adversely affected, and though within each shaft relative weakness existed in the upper sections, it was not an indication of poor concrete.

Peak particle velocities activated during travel of stress waves, (i.e. 2.5 in/sec) were well below the threshold values of 8 in/sec known to cause damage in concrete structures.

These findings however, have limitations. Primarily, the data is true only for the subsurface conditions tested, i.e. loose soils. The loose soil condition aided to a great extent in the attenuation of the vibrations induced, and consequently diminished the transfer of the higher peak velocities across the interface between the stratum and shaft.

4. Discussion and Conclusions

In the field investigation, the peak particle velocities during drilled shaft were monitored to determine their effect on "green concrete." The principal findings from the field study are as follows: i) Vibrations, with peak particle velocities of up to 2.5 in/sec do not cause damage to the "green concrete" at a distance of two times the shaft diameter and beyond; and ii) In general, a spacing of three times the shaft diameter would be a safe specification to ensure no concrete damage due to shaft vibration.

The concept of peak particle velocity, PPV, is used to control construction vibrations for almost all types of projects in civil engineering. Although the concept is helpful as a quality control factor during construction, particle velocity should not be used alone to assess the impact of construction vibration on surrounding structures. For a meaningful assessment, particle velocity should be translated into amplitudes. Even or the same construction material, but with different moduli value, the same particle velocity would result in different strain amplitudes and hence different affects. For example, "green concrete" would have lower compression and shear moduli as compared to age concrete. Therefore, the effect of PPV on the same material at different time levels may vary since the induced strain amplitudes are different.

It is important to conduct a preliminary assessment of the effect of vibrations before construction of deep foundations. Such an assessment requires the following:

- Determining the physical and mechanical properties of the in-situ soil layers
- Predicting generated waveforms
- Assessing the PPV based on the generated waveforms
- Determining the shear or compression wave velocity of in-situ layers
- Field testing for Part (c.)
- Determining the damping ratios of soil layers
- Determining the strain amplitudes at critical locations
- Predicting the damage due to obtained strain amplitudes

The concept of PPV is very helpful to estimate the impact of construction vibration. However, the PPV concept is a transposition from mining engineering, where the applications are limited to certain practices. In Civil Engineering applications, the sources of vibrations are numerous. The types of vibration range from natural to man-made vibrations. Also, the waveforms range from deterministic to non-deterministic.

Construction equipment generates several different categories of vibration waveforms, to which structures may respond in ways determined by local soil properties and the structure's natural frequencies.

The foci of the majority of the studies and investigations have focused on the level of threshold for both humans and structures. The primary goal has been, and should continue to be the determination of acceptable limits to both with respect to attenuation over distance.

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