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RESPONSE OF A FRESHLY PLACED FULL SCALE CONCRETE DRILLED SHAFT TO VIBRATIONS INDUCED BY ADJACENT SHAFT INSTALLATION

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Abstract. *A number of studies have been conducted in an effort to understand wave attenuation and sound response during installation of deep foundations. This research stems from the need to better understand the effect of vibration on 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 durations. The study focuses on effects during the installation of deep foundations through vibratory methods and the age effect of the vibrations on freshly placed concrete. The installation followed the Florida Department of Transportation (FDOT) guidelines. During the drilled shaft casing installation, vibration is transmitted from the source of installation to the surrounding soil causing ground motion affecting the adjacent structures. The intensity of the ground motion and the severity of the induced vibration depend on factors such as soil type, form of amplitude-time history of the vibration, polarity of certain type of waves and configuration of the adjacent structures. The field investigation monitored peak particle velocities during installation and their effect on freshly placed 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 the fresh 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.*

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.

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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 casings be removed except those intended to be permanently placed in the boreholes (FDOT Specification 455-15.4)[1]. If the permanent casing method is specified for certain site conditions, then the final shaft length needs to compensate for the reduced skin friction 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. According to article 455-1.1 of the FDOT specification, 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. 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 vibrations cease immediately when the structural settlement reaches 1.5 mm (0.06 in.), vibration induced velocity levels reach 13 mm/sec (0.5 in/sec), or damage is caused to the 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 vibration induced velocities 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 when as required to remove the 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 the 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

To study the effects of vibration on the maturing, freshly placed concrete within twenty-four hours of initial placement.

To develop recommendations for mitigating age effects of vibrations on fresh concrete, the criteria for distance from the source, and acceptable levels of vibration.

1.3 Background

During 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[2] 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 and 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 (Rayleigh) 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 depends 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[3]. Typical vibration criteria for building damage have been summarized by Amick and Gendreau[4], with particle velocities widely ranging from 100 in/s to 2 in/s depending on building categories. However frequencies were not addressed.

Literature does not present any conclusive evidence that construction-induced vibrations would significantly affect concrete properties. Bastian, 1970[5], indicated that "there are no detrimental effects due to vibration of concrete during its setting and curing period". There is evidence that even beneficial effects may be derived" ASCE[6]. 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. Tawfiq[7] suggested 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". Also, the maximum peak particle velocity should be limited to 2 in/sec at the suggested distance. In slight contrast, the spacing of 3 times the diameter was indicated by Reddy et al[8]. Reddy et al. also concluded that "concrete cured up to 24 hours is not damaged due to vibration.

The ACI Committee 609[9] has given specific recommendations for vibrator characteristics applicable to different types of construction and field practices. The frequencies of early vibrators were limited to 3000-5000 cycles per minute (50-80 Hz). L'Hermite and Tournon[10] reported that the 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. Walz[11] showed that the reduction in internal friction is primarily the result of acceleration produced during vibration. Olsen[12] 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 the 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[13]; Alemo and Grandas[14]; and, Stark)[15]. Forssblad and Sallstrom suggested that the duration of vibration in concrete of 60 to 70 percent of the total casting time or the vibration effort can be obtained as follows:

$$V_e = 1800/C \tag{1}$$

where:

V_e = vibration effort, s/m^3

C = casting capacity m^3/hr

It was also found that the optimum vibration effort ranged between 200 s/m^3 to 325 s/m^3. Using this relationship, a drilled shaft of 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[16] 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. To simulate a field blast condition laboratory testing was conducted by Esteves[17] on concrete prisms subjected to transient impact loading. At different intervals of curing time, the development of microcracks versus the amplitude of the particle velocities was monitored. 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:

$$\varepsilon = \frac{v}{c} = \frac{150mm/sec}{3{,}000m/sec} = 50\mu \tag{2}$$

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 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 (Howes[18]; Oriard and Coulson[19]) have also shown that there is no loss of final strength from transient vibration. Hulshizer[20] suggested some vibration acceptance levels for freshly placed and maturing concrete. And, found that 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, as expected, piles subjected to vibration were statistically stronger than the non-vibrated comparison pile. The second case involved vibration of adjacent in-place fresh concrete cylinders by driving two 11-meter Raymond stepped taper piles over a curing time span; similar to that reported by Esteves. 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 the 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, a full scale test was designed to study resulting effects. In advance of the full scale test setup, a geotechnical exploration was conducted to determine the soil type and characteristics. Soil sampling included Standard Penetration Testing and soil analysis. Additionally, a preliminary driven set up was tested to characterize the specifics of the steel casing and motion propagation at ground level and at depth.

The preliminary test set up, Figures 1(a) and 1(b), consisted of the installation of 8 geophones at depth, at five foot intervals in a circular array centered on a 36-in diameter steel casing. The driving of the steel casing established a record of peak particle velocity in the in-situ soils.

The installation of the full scale set up consisted of 10 drilled shafts. The drill shafts were divided into five sets, including a control set. Each set was comprised of one 36-in. and one 24-in diameter shaft. A centralized rebar was placed in each shaft. 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 extended 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 of 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 2, which also depicts testing and sampling locations.

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 vibration levels. 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 periods: (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 along the full shaft length. The cored samples and concrete cylinders (control) were subjected to compressive strength testing.

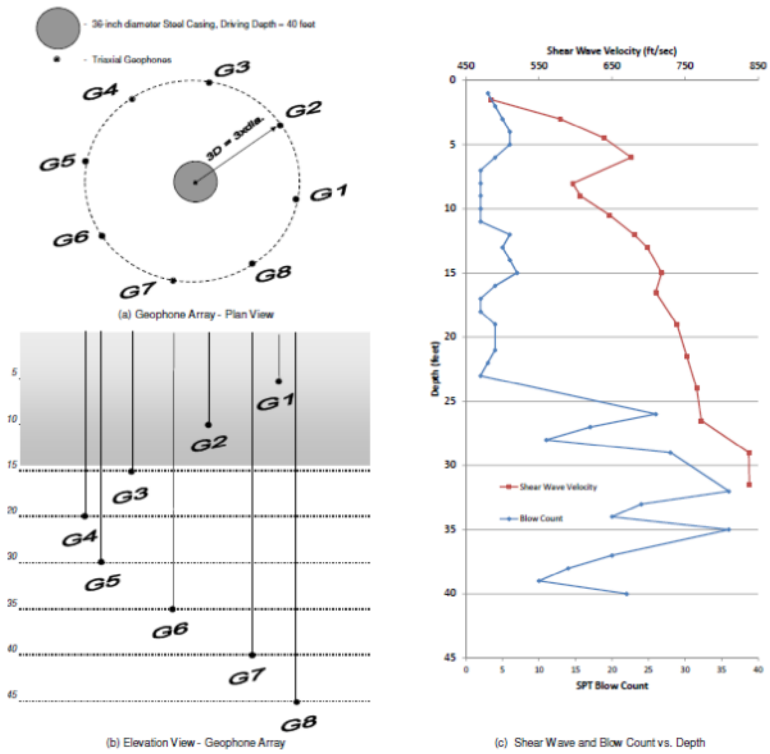

Figure 1. Preliminary PPV Determination, and Geophone Array.

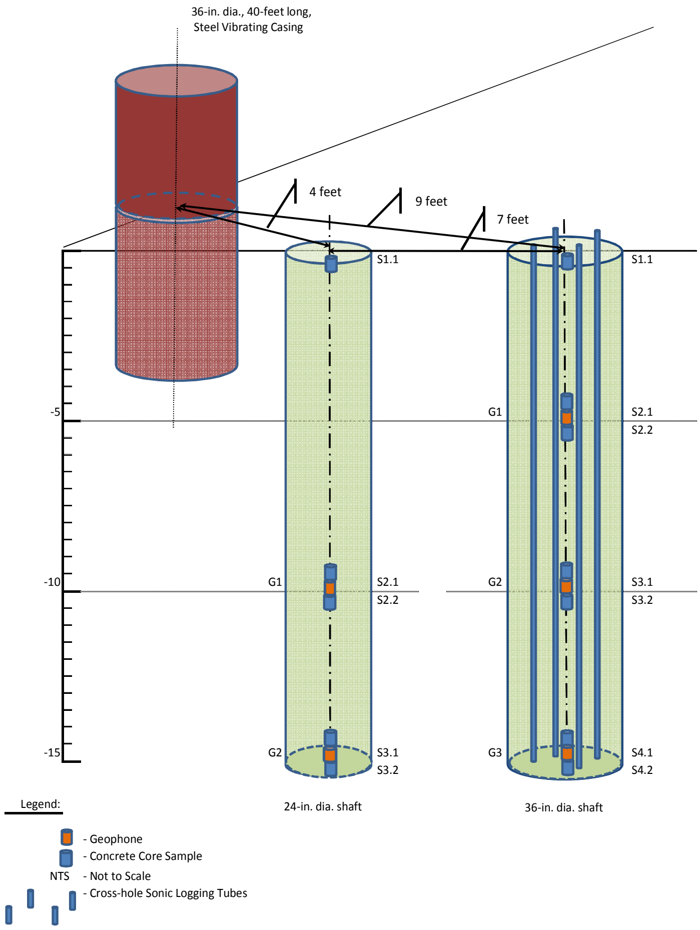

Figure 2. Full Scale Test Layout.

3 RESULTS

3.1 Geotechnical Exploration, Soil Properties/Characteristics, and Peak Particle Velocity

The soil conditions were primarily characterized via visual classification and SPT blow count. The soils present at the site, extremely fine sand, unconsolidated, were not conducive to the worst case scenario, or optimum propagation of detrimental wave velocities. The nature of the soil indicated attenuation to a large extent in the subsurface, specifically as depth/distance from source increased. The condition present at the site is generally observed or typical to South Florida subsurface.

The objective of driving a steel casing centered on the geophone array was to monitor the ground response of the in-situ soils. The geophone installation was limited to placement of a single geophone per borehole. A total of eight geophones were installed at successive five foot interval. Each borehole was cased via PVC tubes. The geophones were lowered to depth below the tip of the PVC tube and backfilled five feet or greater with native material and/or silica sand. Upon completion, the in-placed geophone array simulated a fully instrumented single drilled shaft.

The embedded accelerometers (geophones) monitored peak particle velocities. The data collected was limited by two malfunctioning geophones 6 and 7, embedded at 30 and 35 feet, respectively.

Peak particle velocities obtained from testing indicated that some components might have dominated the maximum values. These components were in the longitudinal and the transverse directions. Generally, the readings showed the vertical component to prevail. One possible explanation for the escalation of the longitudinal and the transverse components may be due to the eccentric vibration applied on the steel casing by the vibratory hammer. It is possible, and somewhat likely, that the gripping of the steel casing may not have been uniform.

The selection of the vertical component (shear mode) of the peak particle velocity necessitated the re-examination of all the time-history records collected in the field. Such examination is time consuming and impractical in industry practice. It is customary to record, as a final result, the peak particle velocity from any of the three orthogonal directions. Typically, the maximum velocity is reported regardless of direction. Therefore, the mode of vibration is typically missed in construction vibratory monitoring reporting.

In this effort it was important to attempt to properly identify the primary mode in order to assess the type of dominant type in the system. For example, if the PPV was for the vertical mode, then the conclusion is that the type of vibration would mostly be of a shear type. This would only be true for the driven steel casing. The reason is that the generated vibrations in the ground would predominantly be due to the friction between the casing surface and the surrounding soil. However, it is expected that soil displacement may occur. Lateral displacement could give rise to the development of longitudinal or compressive vibrations. Since the lateral displacement in this case is very low, as compared to the large displacement caused by pile driving, the longitudinal and the transverse modes are expected to be comparatively low, accordingly.

Reference to PPV without identification of the mode of vibration is a self-defeating concept. One of the main objectives of specifying the particle velocities in monitoring construction vibration is to be able to relate the strain levels that the vibrations induce in the system. In this regard, soil samples obtained from the boring logs were analyzed to determine the shear wave velocities on representative layers. In addition, water content, void ratio, and unit weight were established on 52 samples, and summarized in Table 1. The blow count and shear wave velocity are shown graphically in Figure 1.(c).

The peak particle velocities recorded by the geophones showed that as the casing was driven into the ground, the PPV values increased with depths. This trend is presented in Figure 3

Table 1. Determination of Damping Characteristics at Depth for the FAU Site. (Tawfiq, 2000)

Depth (ft)	SPT, Blow Count (typical)	Effective Unit Weight (pcf)	Void Ratio, e	Vertical Effective Stress, σ_0 (psf)	Shear Wave Velocity (ft/sec)
1.5	4	78.0	0.289	117.00	484.78
3.0	5	87.0	0.332	261.14	579.02
4.5	6	80.5	0.300	362.23	639.30
6.0	4	94.2	0.400	565.34	676.42
8.0	2	43.7	0.410	349.44	596.39
9.0	2	37.4	0.364	336.96	606.40
10.5	2	42.8	0.378	449.47	646.65
12.0	6	43.3	0.352	519.67	680.25
13.0	4	51.1	0.415	664.37	698.32
15.0	7	36.1	0.270	541.01	718.05
16.5	4	36.1	0.336	595.11	709.87
19.0	3	36.1	0.327	685.28	738.96
21.5	3	34.1	0.325	733.86	752.53
24.0	2	32.8	0.325	787.74	765.98
26.5	22	30.6	0.324	811.92	772.21
29.0	26	42.5	0.367	1232.34	837.19
31.5	34	38.4	0.356	1208.84	838.25

Water Table at 5.9 – 6.7 feet.

Hardin and Richart 1963:

Shear wave velocity = vs = $(170-78.2e)*\sigma_0'^{1/4}$ for $\sigma_0>2000$ psf

Shear wave velocity = vs = $(170-78.2e)*\sigma_0'^{1/5}$ for $\sigma_0<2000$ psf

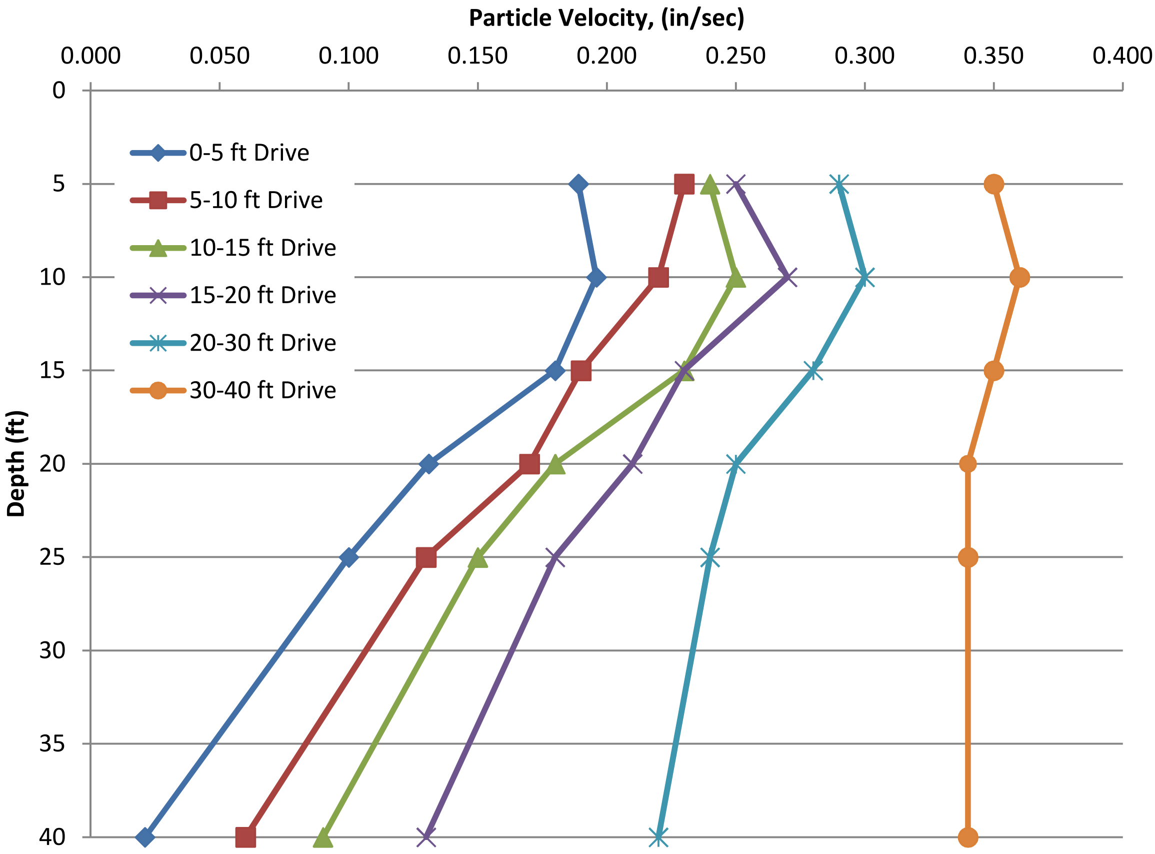

Figure 3. Measured Peak Particle Velocities due to Preliminary Driving of Vibratory Steel Casing (depicted in Figure 1).

3.2 Non-destructive Testing and Coring Results

A summary of the non-destructive testing program is summarized in Table 2. The geophysical data obtained from the non-destructive testing provided an indication, in relative terms, of the properties along the drilled shaft length.

The PIT results showed definite full reflection of the transmitted wave from the shaft tip, indicating no structural damage in the shafts (Figure 4), indicating no structural damage in the shafts.

The CSL test showed continuity across the cross-sectional areas of the shafts (Figure 5), with the exception of the 2-hr, 36-in. shaft. However, the PVC access tube showed sign of impact, after construction (due to 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 (Figure 6). Neutron-Neutron logging showed that porosity within the each shaft is relatively unchanged due to exposure to vibration (Figure 6).

The testing seemed to indicate that in the upper 1/3 or 5 feet, each individual drilled shaft showed signs of relatively weaker concrete. The weakening was attributed to the segregation in the aggregate, observed in the coring samples. The cores obtained were visually inspected and tested in compression. The relative weakness of the upper shaft sections was further evidenced by the compressive strengths of the cored concrete samples (Figure 7).

Table 2. 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

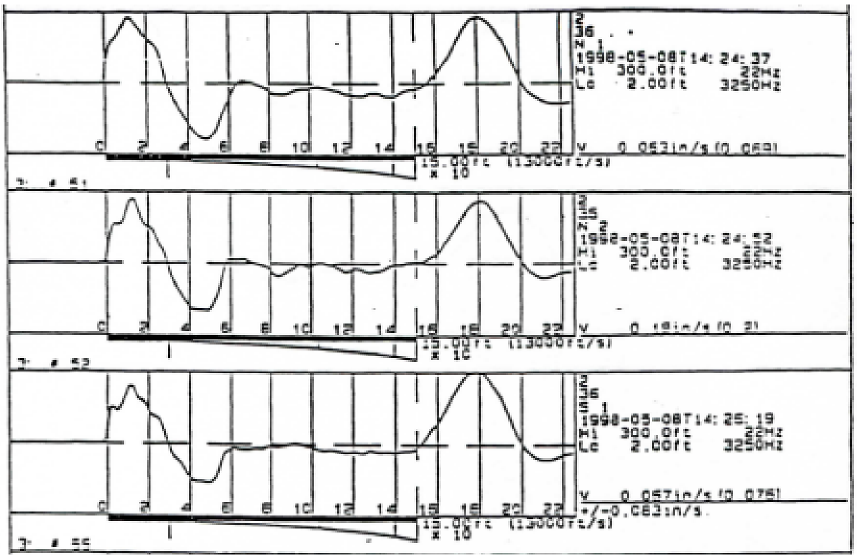

Figure 4. Pile Integrity Tester Results (typical).

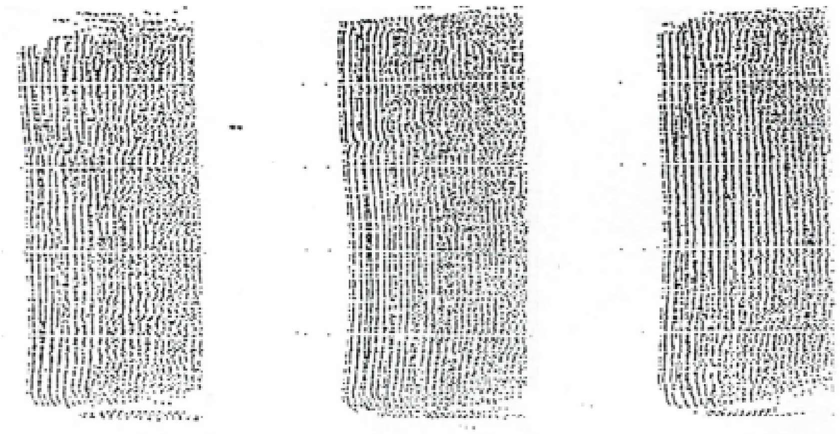

Figure 5. Cross-hole Sonic Logging Test Results (typical).

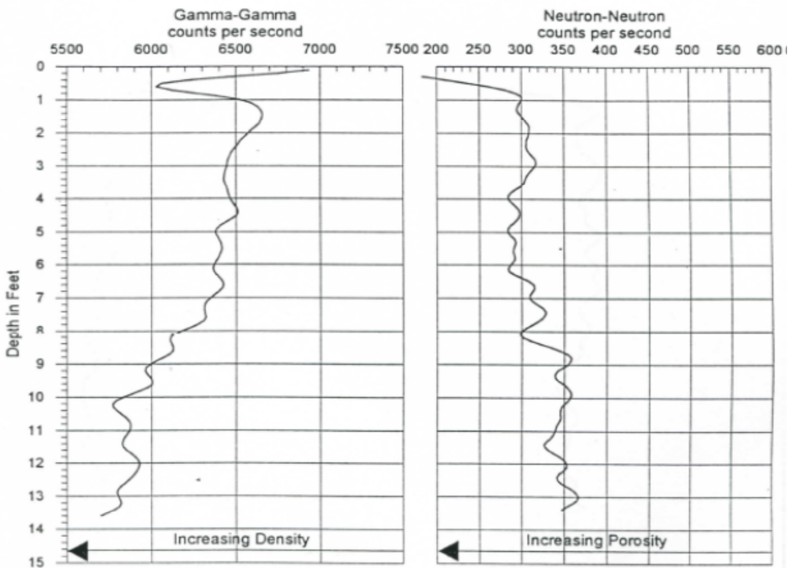

Figure 6. Gamma-Gamma and Neutron-Neutron Logging Results (typical).

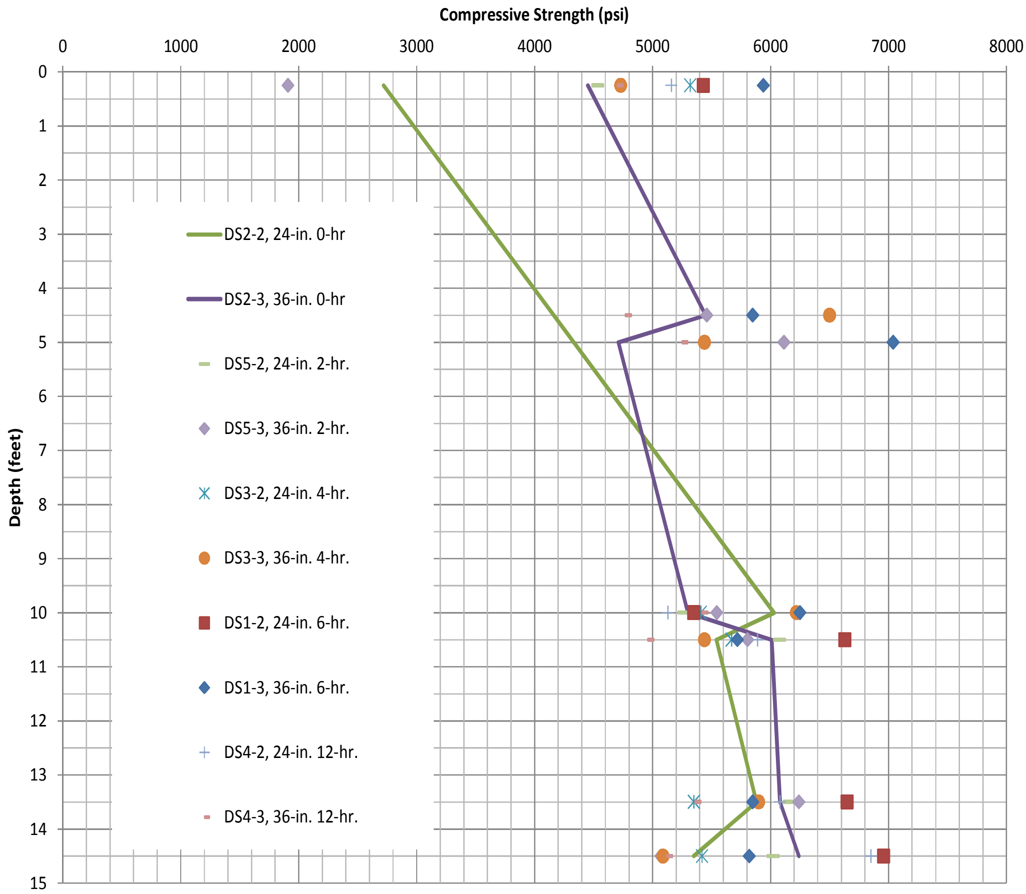

Figure 7. Coring Results, Compressive Strength (psi), of Drilled Shafts.

The geophysical data is limited as it only showed relative performance of individual drilled shaft. Therefore, no correlation was established between drilled shafts. No trend could be established in the correlation of the values between the compressive strength and the geophysical data. Nevertheless, the data showed that for each individual drilled shaft, integrity was not adversely affected. Although within each shaft, relative weakness existed in the upper sections, it was not an indication of poor concrete or anticipated performance as depicted in the compressive testing result of cored samples.

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 the shaft.

4 DISCUSSION AND CONCLUSIONS

In the field investigation, the peak particle velocities during drilled shaft were monitored to determine their effect on freshly placed 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 freshly placed 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 values, the same particle velocity would result in different strain amplitudes, and hence different effects. For example, freshly placed 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 the above item
- 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 addressed the threshold levels 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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