Effect of Vibration on Concrete Strength During Foundation Construction

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EFFECT OF VIBRATION ON CONCRETE STRENGTH DURING FOUNDATION CONSTRUCTION

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By

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16. Abstract

Many studies have been conducted on the effect of construction vibrations on properties of freshly placed concrete. This study was concerned with the drilled shaft construction and its effect on the green concrete. The differences between the common construction vibrations and those produced during drilled shaft construction are the amplitudes and duration of vibrations. To characterize the type of vibrations induced during drilled shaft construction, a full scale field testing was conducted using a typical steel casing. The peak particle velocities (ppv) were recorded and empirical relationships were suggested to predict the velocity values on the surface and in the ground along the penetration depth of the shaft. Laboratory testing was conducted to determine the effect the ppv and different durations of vibration on green concrete properties. The duration of vibration used in this study included the initial and the final time setting. If vibrations took place before initial time setting, the concrete would suffer a noticeable segregation especially for samples subjected to ppv of 2 in/sec. However, the strength measurements were higher at this velocity. When the green concrete was subjected to ppv of 2 in/sec during the period of initial to final time setting, the strength was decreased. This trend was true for all samples subjected to other ppv values. Therefore, it was 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. Additionally, the ppv should not exceed 2 in/sec at the suggested distance.

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SUMMARY

Many studies have been conducted on the effect of construction vibrations on properties of freshly placed concrete. This study was concerned with the drilled shaft construction and its effect on the green concrete. The differences between the common construction vibrations and those produced during drilled shaft construction are the amplitudes and duration of vibrations. To characterize the type of vibrations induced during drilled shaft construction, a full scale field testing was conducted using a typical steel casing. The peak particle velocities (ppv) were recorded and empirical relationships were suggested to predict the velocity values on the surface and in the ground along the penetration depth of the shaft. Laboratory testing was conducted to determine the effect the ppv and different durations of vibration on green concrete properties. The duration of vibration used in this study included the initial and the final time setting. If vibrations took place before initial time setting, the concrete would suffer a noticeable segregation especially for samples subjected to ppv of 2 in/sec. However, the strength measurements were higher at this velocity. When the green concrete was subjected to ppv of 2 in/sec during the period of initial to final time setting, the strength was decreased. This trend was true for all samples subjected to other ppv values. Therefore, it was 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. Additionally, the ppv should not exceed 2 in/sec at the suggested distance.

CHAPTER 1

INTRODUCATION

One of the pressing issues that concerns the Florida Department of Transportation (FDOT) is the effect of vibrations induced during deep foundation construction on the green concrete of drilled shafts. Green concrete, which may be taken to mean freshly placed concrete or more specifically concrete having an age of less than 24 hours old **(Hulshizer and Desai 1984),** is particularly vulnerable to weakening its properties if subjected to intense vibrations that could disrupt the concrete matrix during the formative bond development process.

To minimize the adverse effect of excessive construction vibrations, the FDOT requires a halt on all construction activities around the concrete for a period of time needed for the fresh concrete to harden. The **FDOT Roadway and Bridge Specifications (2000)** require the contractors to "stop driving piles within 200 ft of concrete less than two days old unless authorized by the engineer." In some major bridge construction projects, the FDOT supplemental agreements require that within a distance of three times the shaft diameter vibrations be prohibited for a period of 12 hours to protect the green concrete.

On the other hand, the **FHWA (1999)** specifications for vibrating near a freshly poured concrete shaft disallow driving of piles or driving casing, or opening of boreholes for new drilled shafts, closer than about two shaft diameters clear spacing to the shaft with newly set concrete. Recommendations are that adjacent construction be stopped for a period of 24 hours. This period can possibly be shortened by using silica fume as an additive. However, the use of high early strength cement in the concrete mix is not recommended if the shaft diameter exceeds 5 ft because of the high heat of hydration and attendant cracking problems.

In a comprehensive survey of 26 state highway agencies, 20 consultants, and 13 piling contractors, **Wood (1997)** found that only nine agencies have standard specifications for controlling vibrations from pile driving operations. The vibration measurements that specified vary from one state to another.

Controlling vibration limits to protect green concrete were hardly mentioned in the vibration criteria of many states agencies. Most of the published limits are primarily selected based on the damage criteria for the surrounding structures.

Studies reported by **Bastian (1970)** indicated that nearby construction, such as drilled or pile installation, either by a vibratory driver or an impact hammer, do not normally damage a recently-placed drilled shaft while the concrete is still unset. He reports on a case where pile driving was being done 18 ft away from a shell pile that had just been filled with fresh concrete. Three days after pouring the concrete, cores were taken. Subsequent testing showed that the compressive strength of the cores was slightly higher than that of concrete cylinders that were taken at the time of casting of the concrete. Bastian reported on five other investigations by various agencies and groups. In each of the cases the results showed that the properties of fresh concrete were not affected by vibrations. Bastian reached the conclusion that vibration of concrete during its initial setting period was not detrimental and no minimum concreting radius should be established for this reason. No reasons exist to believe that vibrations due to a nearby pile driving even during the critical 12 to 14 hour time would influence the concrete in drilled shafts. Therefore, restrictions on driving piles near freshly poured concrete should be based on factors other than vibration.

In another study, **Esteves (1978)** tested the susceptibility of green concrete to blasting vibrations in the laboratory and found that crack development at peak particle velocity greater that 5.9 in/sec was most likely to occur between the first 10 and 20 hours. This vibration limit explained why other studies have shown that there was no loss of final strength from actual construction vibrations (**Howes, 1979; Orirad, 1980; and Wiss 1981**).

The possible effects of construction vibrations on freshly placed concrete, are very complicated and up to now, little is known about these effects. This complication is reflected in the large discrepancies in the vibration control requirements including the permitted peak particle velocity specified by different specifications.

Nevertheless, most published studies **(Table 1)** agreed that fully hardened concrete can withstand construction vibrations up to a peak particle velocities of about 4 in/sec without adverse effects on the concrete. Suggestions are that the resistance of green concrete to a construction vibration is proportional to its strength and thus the permitted peak particle velocity may be taken as proportional to the strength of the concrete (**Gamble and Simpson, 1985; Bryson and Cooley, 1985**). **Olofesson 1988**, on the other hand, proposed that within the first few hours before initial set, the freshly placed concrete should be able to withstand a vibration limit up to 4 in/sec. **Hulshizer and Desai (1984)** from their laboratory and field testing, suggested fairly high vibration limits of 0.4 in/sec, 1.5 in/sec, 2 in/sec, 4 in/sec and 6.88 in/sec for concrete cast in less than 3 hours, within 3 - 11 hours, within 11 – 24 hours, within 1 - 2 days and over 2 days, respectively. Thus, on one hand, the first 24 hours after concrete placement was generally regarded as the most critical period and caution must be exercised in controlling nearby blasting during this period, on the other hand, test results have indicated that the green concrete can, in fact, withstand fairly high intensity vibrations during the first few hours after placement.

From the presented values, it can be seen that very large discrepancies exist between the various recommended vibration limits, especially those being applied to concrete cast within a few hours. Consequently, these discrepancies in the specified values have frequently been the source of disputes between the agency and the construction industry.
Filed engineers have often considered that these limits seriously restrict the ability to conduct efficient and timely field operations and create serious scheduling problems when excavations and structural pours are on the critical path particularly if the concrete is poured daily. Such disputes combined with the lack of rigorous studies in the subject matter, necessitated the FDOT to delete the provision concerning the effect of deep

foundation construction on freshly placed concrete from **Section 455-1** of the **2004 version** of the FDOT Specifications for Road and Bridge Construction.

SCOPE

The selectivity of the vibration limits by many highway agencies was primarily based on the availability of limited published literature. Also, some published studies reported test conditions that may not necessary be applicable to drilled shaft concrete. For example, the type of concrete mixes used for drilled shaft construction may vary from one specifications to another and, hence, the initial and final time setting of the concrete will vary accordingly. In cases of highly plastic mixes (slump > 7.5 in) and at low temperatures, the final time setting for a green concrete may go on for more than 48 hours. Also, the modes of vibrations in most published studies were generally limited to blasting transient waves where the durations of the peaks range from 1 to 2 msec. These conditions may be true for cases of driven piles adjacent to drilled shafts. However, construction of drilled shafts generates different modes of vibrations. In these cases, the induced vibrations are continuous harmonic signals that last for periods of time measured by minutes rather than milliseconds **(Putcha et al, 1999).** Therefore, extrapolating values of peak particle velocities from transient vibrations and applying where the peaks may be lower and the durations of vibrations are much longer may not be convincing enough to set certain restrictions on the construction activities at the site. Like the efforts spent on pile driving conditions, a more realistic approach has to be taken to obtain limits that are applicable to the real drilled shaft construction.

Table 1: Suggested Peak Particle Velocities for Concrete at Different Ages

References	Permitted peak particle velocity (in/sec)					
	12hr	1 day	2 days	3 days	7 days	28 days
Gamble and Simpson, 1985	0.2	0.4	1	1.2	2	4
Bryson and Cooley, 1985	0.2	2	2	2	4	4
Olofesson, 1988 Curing at 5°C	4 (0-10 hr)	No vibration within 98 ft (10-70hr)	0.3	0.4	1.4	3
Olofesson, 1988 Curing at 21°C	4 (0-5 hr)	No vibration within 98 ft (5-24hr)	1.2	1.6	2.4	3.3

CHAPTER 2

TESTING PROGRAM

Field Testing

To meet the objectives of this study, laboratory and field testing were conducted under controlled conditions by which concrete samples were subjected to different amplitudes of vibrations and durations of time that resemble drilled shaft construction. Accordingly, a full-scale steel casing was driven in a sandy soil to characterize induced vibrations. The chosen testing site was in Boca Raton, Florida, where the soil was predominantly medium to fine sand. A 36 in diameter and 40 ft long steel casing was driven in the ground using a variable frequency vibrator. The scheme of the vibration measurements at the steel casing and in the surrounding soil is shown in **Figure 1**.

The vibration measurements were recorded using triaxial geophones lowered in 8 boreholes configured in a circular pattern around the driven steel case. The case was at the center of the boreholes circle where the sensors were lowered to depths ranging form 5 ft to 40 ft. Time-history records from each sensor were simultaneously collected using a multi-channel data acquisition system.

Another set of four accelerometers was used to record the steel casing vibration and the ground shaking. Shock accelerometers were placed on the steel casing at equally spaced distances of 5 ft center to center for the end of the case. The three other accelerometers were mounted on steel rods inserted in the ground. The ground accelerometers were also distanced 5 ft apart. This arrangement allowed a better insight of wave propagation in half-space sandy soil. All the signals obtained from the accelerometers were designated as Trace, and each Trace was given a number indicating the sequences of the stored records.

Laboratory Testing

After analyzing the characteristics of the ground vibrations from the driven steel casing, laboratory tests were conducted on concrete samples subjected to vibration amplitudes ranging from 1 in/sec to 9 in/sec. This range of velocities was selected based on some peaks obtained from the vibrated steel casing at different penetration depths. The variations of the duration of vibration from the field testing were not conclusive. It was found that several unpredictable factors could control the duration of induced vibration including the operating frequency of the hydraulic vibrator which may vary even at the same location. Generaly, the field construction necessitates the continuous production of drilled shafts at the site by moving from one shaft to another. In such cases, the intensity and the duration of the ground vibration may last for hours with some intermittent moments.

As a result of the difficulty in specifying the proper duration of vibration, concrete engineers at the Florida Department of Transportation suggested that concrete samples be subjected to continuous mode of vibrations. The duration of vibrations with variable amplitudes should last for a period of time equal to the time setting of the concrete mix. However, the setting time is divided into two periods including the initial and the final time setting and the differences between them may last for hours.

The initial time setting of the concrete is basically the elapsed time, after initial contact of cement and water, required for the mortar sieved from the concrete o reach a penetration resistance of 500 psi. On the other hand, the final time setting is required for the same mix to reach a penetration resistance of 4000 psi.

Sample Preparation

Concrete samples for this study were prepared from a design mix similar to the one used for typical drilled shaft construction in Florida. Because of the large number of samples needed for this investigation, it was decided to prepare two identical concrete mixes and test them simultaneously at the same laboratory conditions. Each set of samples consisted of 60 cylinders of 6 x 12 in. The concrete mix design of both sets is shown in **Table 2**.

To achieve a slump of 7 in or higher without increasing the water cement ratio, two additives were included in the design mix. The addition of these admixtures, however, would prolong the initial time setting of the concrete. The longest setting time that could be realized was during winter time at the lowest temperatures. Accordingly, it was decided to prepare and test the concrete samples during the months of January and February when the temperatures in Florida are at the lowest levels.

After completing the concrete mixes, the samples for the dynamic and the static testing were identically prepared in groups of 12 cylinders for each group. The first group was numbered and designated as no-vibration and was set aside for curing. The other four groups were also numbered and designated according to the vibration amplitudes that were used in testing. Each group of the dynamic testing cylinders was placed in a large container and placed on a calibrated vibrating table. Application of vibrations was started at the end of sample preparation and continued until the end of the final time setting for the first batch. Concrete samples of Set #1 were subjected to vibrations with velocity amplitudes of 1, 2, 3 and 9 in/sec. For Set # 2, the vibrations started at the initial and ended at the final time setting.

To control both the initial and the final time setting for both sets, the **ASTM C403** standard penetration test was used. This test was conducted on two representative samples of the concrete sieved through a No. 4 sieve and poured in cubical molds with 8 in each side. Measurements of penetration resistance were taken periodically until the initial and final time settings were reached.

Upon the completion of the vibration testing, the samples in each group were visually examined and transferred to the environmental room for curing. Three concrete cylinders from each group were tested for compressive strength at 3, 7, 14 and 28 days. The cracking patterns and the cross sections of the failed samples were also examined for possible signs of segregation or voids in the concrete matrix. Most of the failed samples were sectioned with an electric saw to facilitate such examination. The cross sections were digitally photographed and further processing was done on the images to quantify the segregation in each section.

MATERIAL	SOURCE	WT. PER CU.YD.(LB)	VOL. PER CU.YD.(CF)	WT. PER BATCH(LB)	ADJ. WT. PER BATCH(LB)	Properties
CEMENT, 40 %	Fla. Rock	310	1.58	160.7	160.7	
FLYASH	----	----	----	----	----	
SLAG, 60%	Rinker	465	2.30	241.1	241.1	
WATER	Local	321	5.14	166.4	140.9	
FINE AGG.	Rinker 05-455	1050	6.40	544.4	542.2	
COARSE AGG.	Rinker 87-090	1647	10.77	854.0	881.7	
AIR ENTRAINER	WR Grace Darex AEA	3.1 oz	0.81	47.5 ml	47.5 ml	
ADMIXTURE	WR Grace WRDA 60	24.8 oz		380.3 ml	730.3 ml	
W/C RATIO						0.41
Unit Weight						139.0 pcf
SLUMP (IN)						7 ¾”
AIR (%)						4.25 %
MIX TEMP						66° F
AIR TEMP						60° F

Table 2: Concrete Mix Design For Drilled Shaft Construction (Total Volume = 14

CHAPTER 3

RESULTS

Results from the field testing indicated that the maximum particle velocity that was recorded from the steel casing was about 10 in/sec. The ground vibration also exhibited similar pattern of vibrations with a peak particle velocity in the vertical direction of 0.8 in/sec at 5 ft from the casing. This distance equaled 1.66 times the shaft diameter. At 10 ft from the steel casing or at 3.33 times the shaft diameter, the peak particle velocity that was recoded was 0.268 in/sec. At a distance of 15 ft or 5 times the shaft diameter, the peak particle velocity in the vertical direction was 0.08 in/sec.

Values the peak particle velocity vs. distance constituted the following relationship:

$$\mathbf{v} = \mathbf{v}_{source}\ \mathbf{(0.65)^D} \qquad (1)$$

Where v = peak particle velocity at any distance from the steel casing, v_{source} = peak particle velocity at the source, and D = distance from the casing in foot. This relationship matched the wave attenuation equation described by **Bornitz (1931)** and showed by **Woods and Jedele (1985)**:

$$\mathbf{v_2 = v_1\ (r_1/r_2)^n\ exp[-\alpha(r_2-r_1)]} \qquad (2)$$

where v_1 = velocity amplitude at distance r_1 from source, v_2 = velocity amplitude at distance r_1 from source , r_1 = distance from source to point of known amplitude r_2 = distance from source to point of unknown amplitude, n = 2 for body waves at the surface.

The *n* values may vary depending of the type of the propagated wave. In this study, it was believed that waves generated from driving the steel casing were shear waves since the casing was an open pipe. The severity of the ground vibration from the induced shear waves was noticeable from the 3.5 ft settlement that took place inside the casing.

Wiss (1980), on the other hand, suggested another pseudo attenuation model to describe the variation of the peak particle velocity at the ground surface. His best fit relationship of field data was as follows:

$$\mathbf{v = k\,(D)^{-n}} \qquad (3)$$

where v = peak particle velocity of seismic wave, k = value of velocity at one unit of distance, D = distance from vibration source, and n = slope or attenuation rate. The value of *n* used in this equation was 1.0. **Figure 2** shows the estimated values of the peak particle velocity vs. distance from the source for the above three relationships. The first two equations seemed to fit the field test results. Wiss's equation, on the other hand, matched the other predictions at large distances form the source.

When the steel casing reached 40 ft penetration, the sensor in borehole G8 recorded peak particle velocities of 0.34, 0.264 and 0.077 in/sec in the vertical, transverse and longitudinal directions, respectively **(Figure 3)**. The duration of vibrating the steel casing varied based on the penetration depth. The average duration was about 18 sec. However, driving the casing was done on stages to allow time to review and store the records. Also, it was noticed that the peak particle velocity was reduced with the increase in the overburden pressure. **Figure 4** shows the variation in the peak particle velocities obtained from the eight sensors at different depths.

The best fitting relationship that describes the peak particle velocities, penetration depth and overburden pressure can be expressed as follows:

$$\mathbf{v = \alpha\, e^{-\beta\, \sigma o}} \qquad (4)$$

where v = particle velocity, α and β = penetration depth factors, σ_o = vertical effective stress. Values of α and β can be determined from:

$$\boldsymbol{\alpha = 0.85\, x^{-0.3}} \qquad (5)$$

$$\boldsymbol{\beta = 0.5(0.9)^{x}} \qquad (6)$$

where x = penetration depth of the steel casing.

As explained earlier, the recorded durations of vibration from the beginning to the end of the driving process was varied from one penetration depth to another. This variation in the durations necessitated the application of continuous vibration during the laboratory testing of the concrete samples.

Some concrete samples in Set # 1 showed clear signs of bleeding on the surface of the cylinders. After 21 hr from sample preparation the surfaces of the concrete samples were found to be covered with wet cement paste, which could easily be scraped to about 0.25 in. These samples were subjected to vibration amplitudes equal to 3 in/sec and 9 in/sec. The second set of samples that were subjected to vibrations from the initial to the final time setting, the concrete surface did not show any sign of bleeding.

The time setting results for both sets are shown in **Figure 5**. Because of the low temperature and the high slump concrete, it was found that initial setting time for the first set of concrete samples took about 15 hours and an additional 6 hours to the final time setting. For the second set of samples the initial time setting was 11 hours with an addition of 4 hours for the final time setting. It was noticed that the laboratory temperature during the second set was slightly higher than the first one, and this explained the faster rate of hardening of that set.

The compressive strength values of samples subjected to vibrations until the end of the final time setting were found to increase as the vibration amplitude increased until it reached 2 in/sec **(Figure 6).** Beyond this limit, the compressive strength started to slightly decrease. This phenomenon was true for all the concrete samples tested at 3, 7, 14, and 28 days. However, after 28 days, the strength ratio of the samples subjected to 2 in/sec was about 1.1 **(Figure 7)**.

For Set # 2, the concrete strength after three days increased with the vibration amplitude. Unlike Set # 1, the strength continued to increase beyond 2 in/sec. For concrete samples at 28 days the compressive strength slightly reduced up to 2 in/sec peak particle velocity and then continued to increase afterward (**Figure 8)**. The lose of strength at 2 in/sec was about 9 percent as compared to the controlled values (**Figure 9**).

Immediately after completing the compressive strength tests, some samples were sliced using an electric saw machine to examine the final formation of the concrete matrix and the effect of vibration of the segregation of the aggregates. Additional digital processing was done on the sections by filtering the bitmap images using Gamma filters to quantify the segregation.

A thorough comparison of the cross sections revealed that samples of set # 1 which were subjected to 2 in/sec showed larger segregation than those of the 9 in/sec especially for the upper one third of the samples. When the cross sections of 1 in width by 12 in height of both samples were digitally filtered and the white formations of the images were traced and extracted it was found that samples with 2 in/sec had about 94 to 80 percent segregation and about 64 percent to 73 percent segregation for the 9 in/sec samples. These percentages represented the black areas (concrete paste) to the white areas (coarse aggregates) (**Figure 6**). Although samples of Set # 2 did not show any signs of segregation, the strength of concrete samples subjected to 2 in/sec peak particle velocity was less than the other samples. There is a possibility that some microcracks could have been developed in the concrete matrix when the samples were subjected to vibration between the initial and the final time setting. The 2 in/sec peak particle velocity used this study could have been the limit at which the samples reached the resonance mode and as a result endured more damage in the concrete paste which lead to the degradation in the compressive strength.

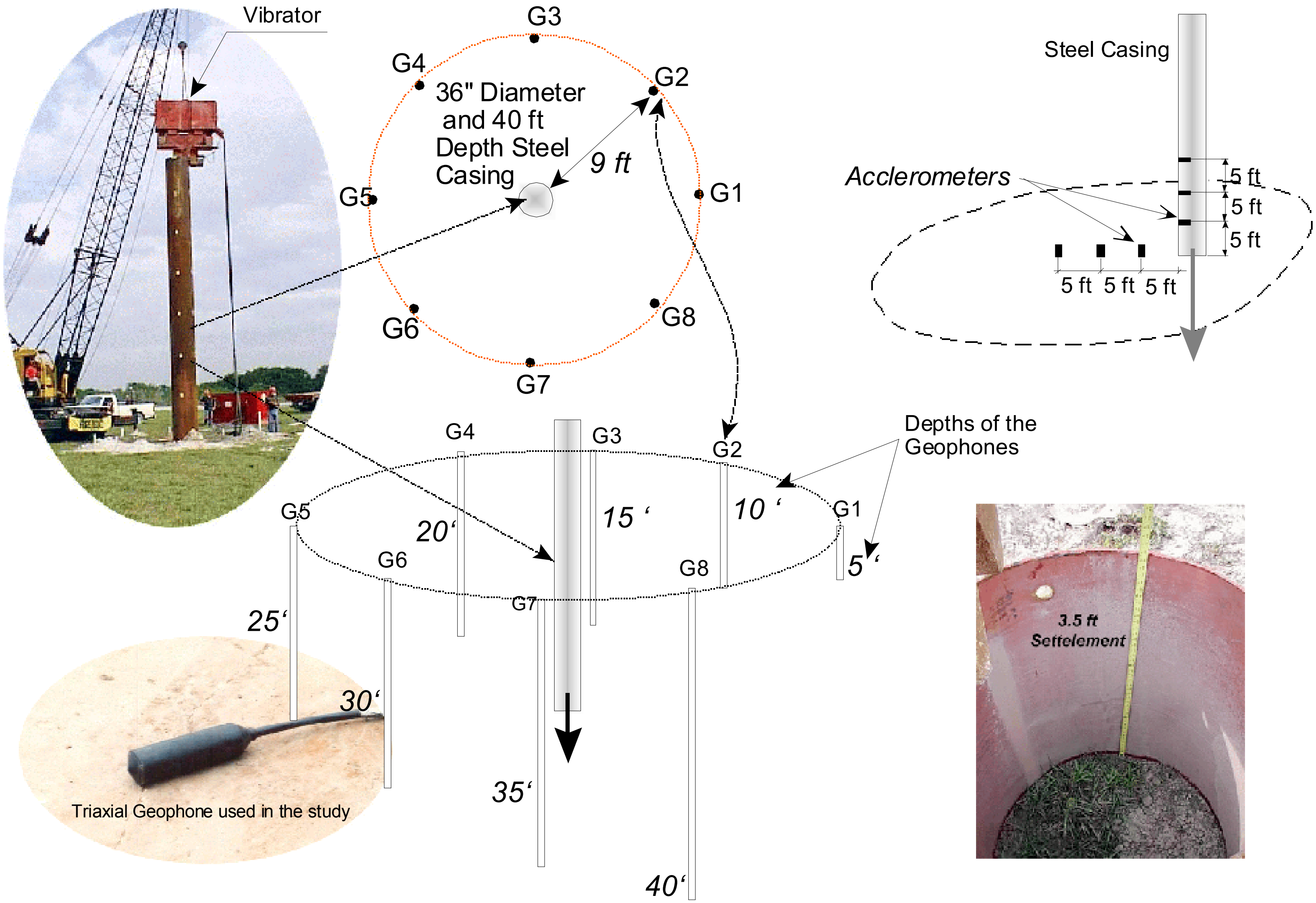

Figure 1: Field Testing on a Full-Scale Driven Steel Casing and the Arrangement of the Sensors.

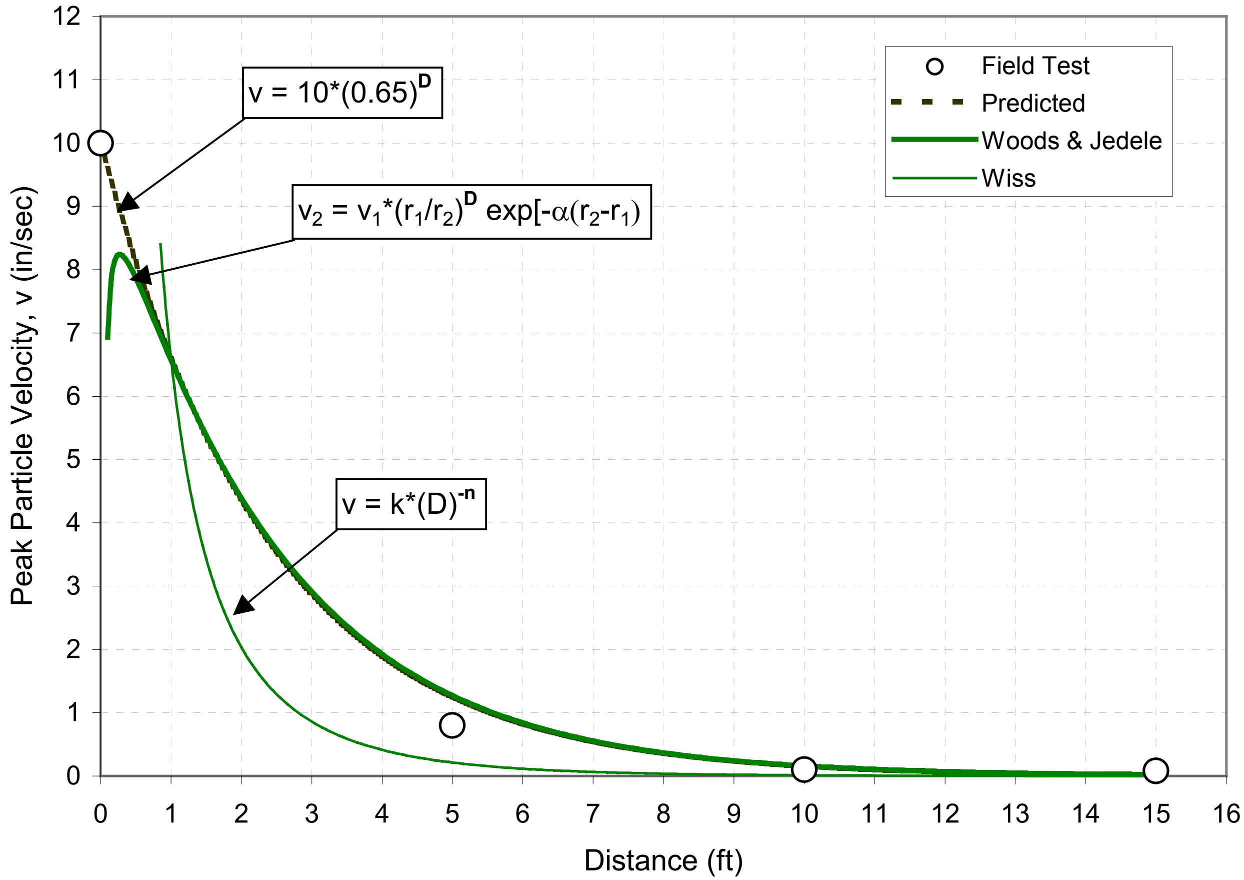

Figure 2: Measured vs. Estimated Peak Particle Velocity Attenuation From the Source.

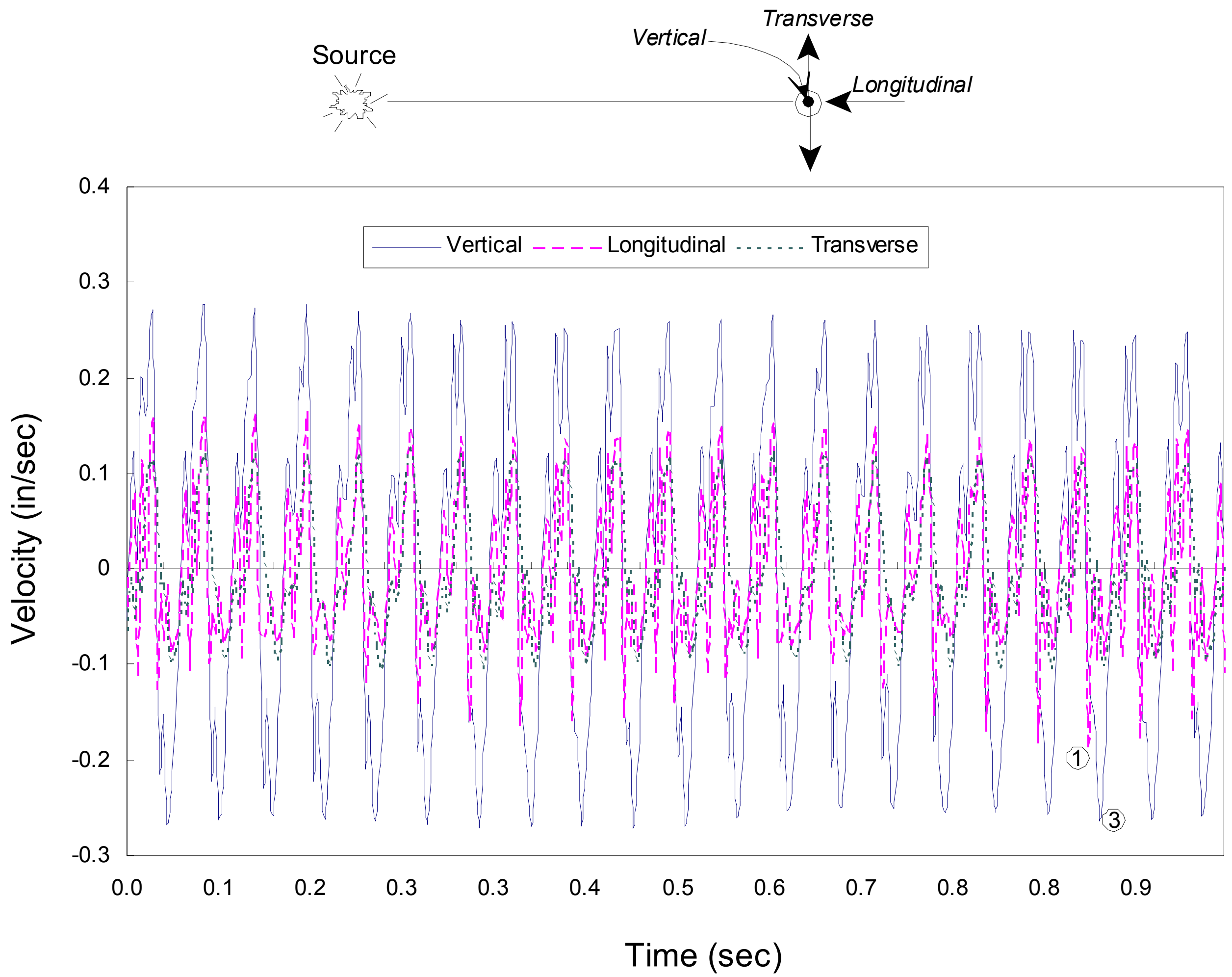

Figure 3: Vertical, Longirudinal and Transverse Mode of Peak Particle Velocity in the Ground

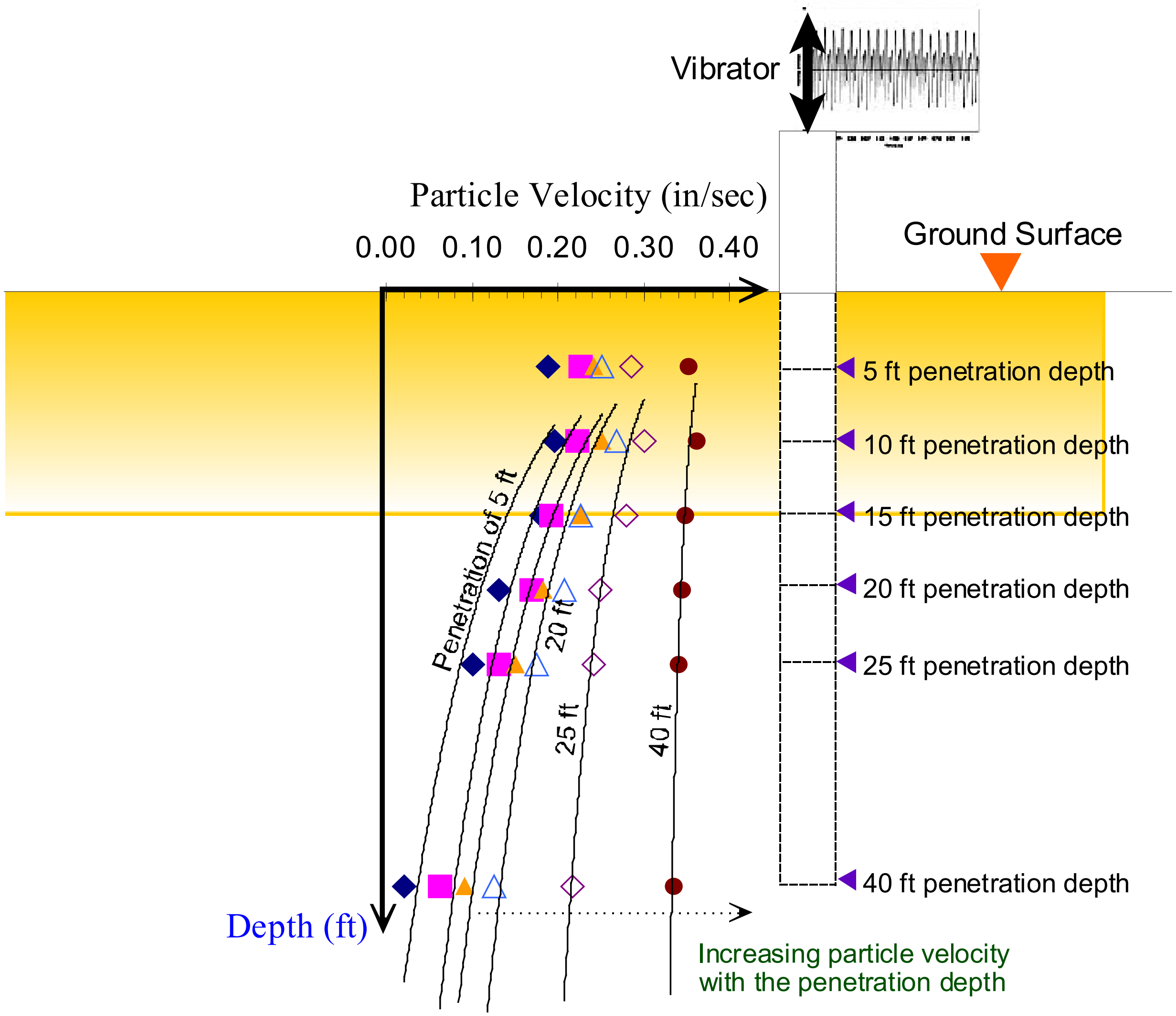

Figure 4: Change in the Peak Particle Velocity with Penetration Depth of the Dilled Shaft Casing

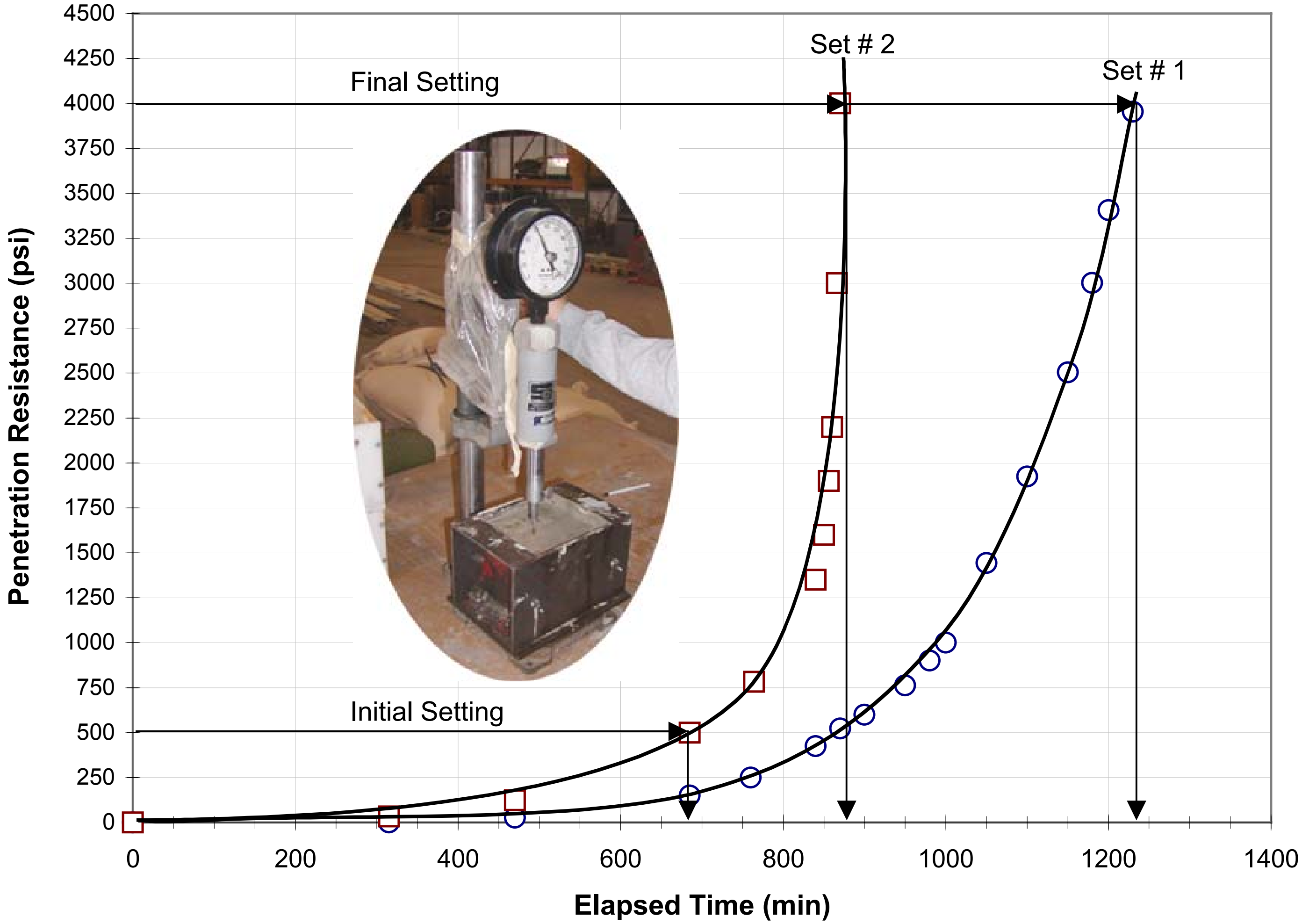

Figure 5: Time Setting of the Two Sets Used in this Study

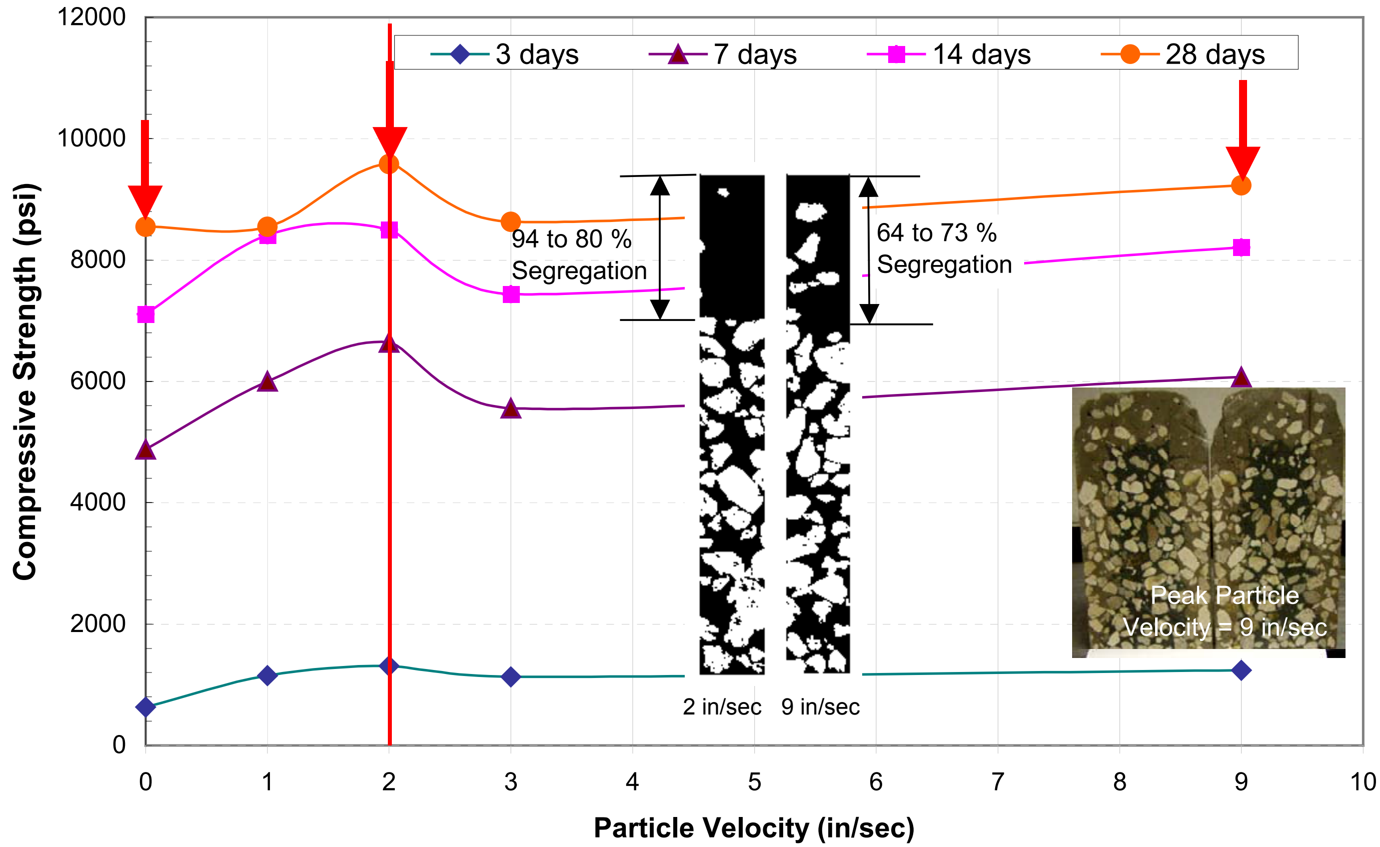

Figure 7: Concrete Strength of Set #1 (Duration of Vibration = zero to final time setting)

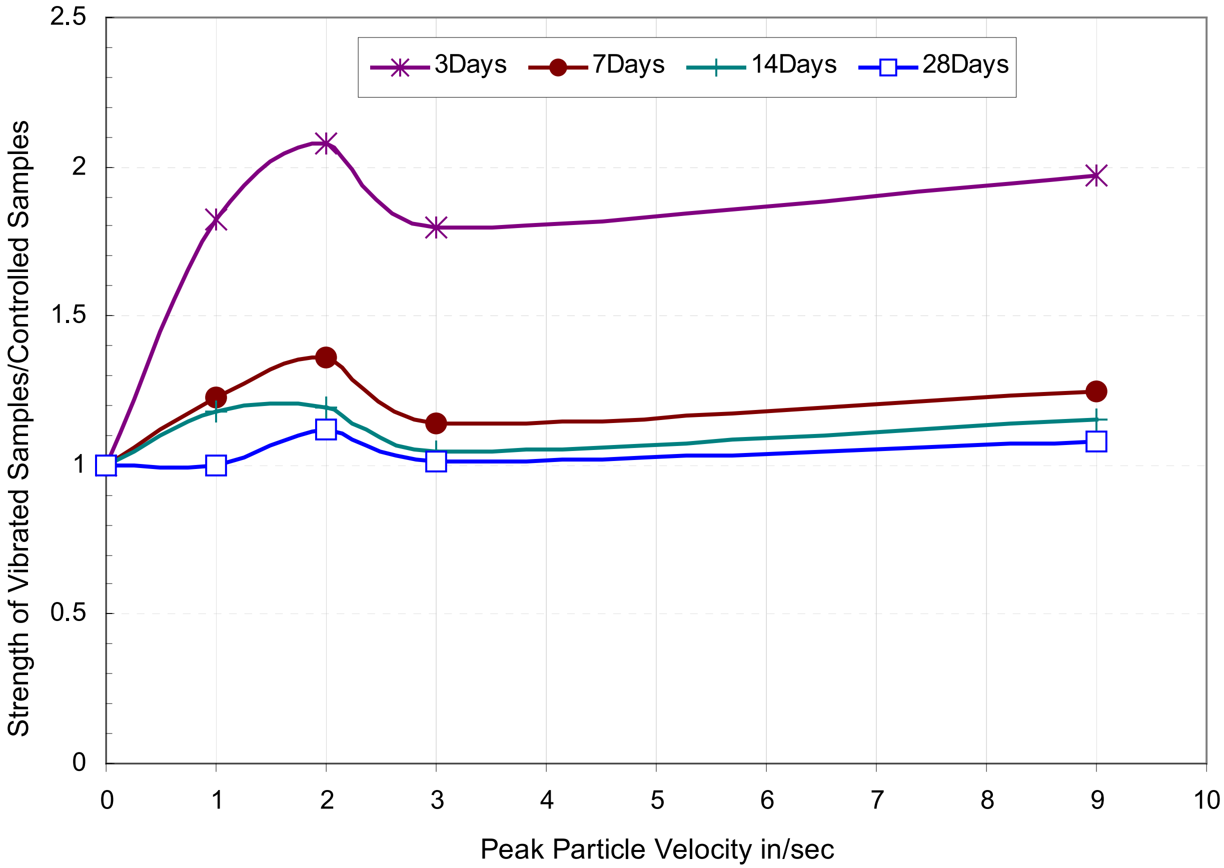

Figure 7: Normalized Concrete Strength for Set #1 (Duration of Vibration = zero to final time setting)

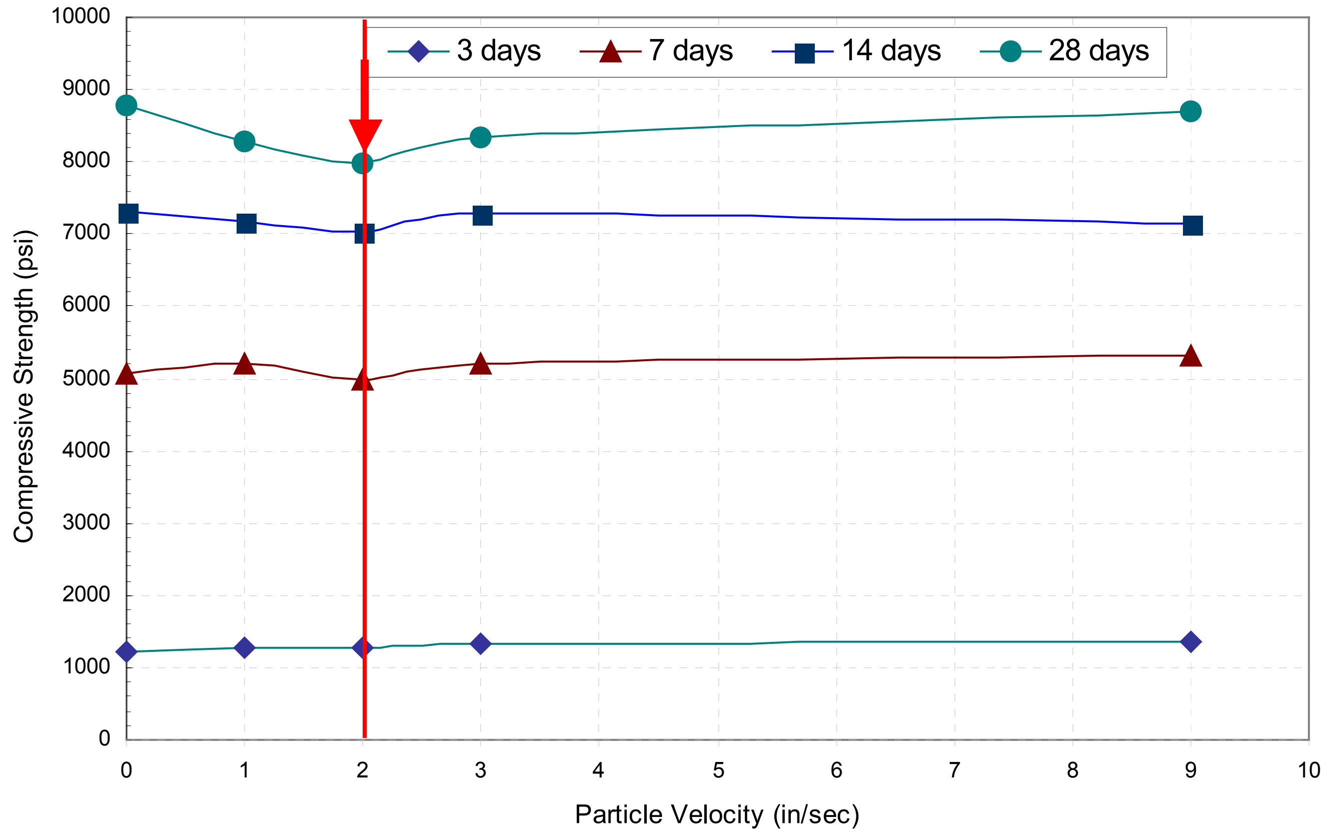

Figure 8: Concrete Strength of Set #2 (Duration of Vibration = Initial to final time setting)

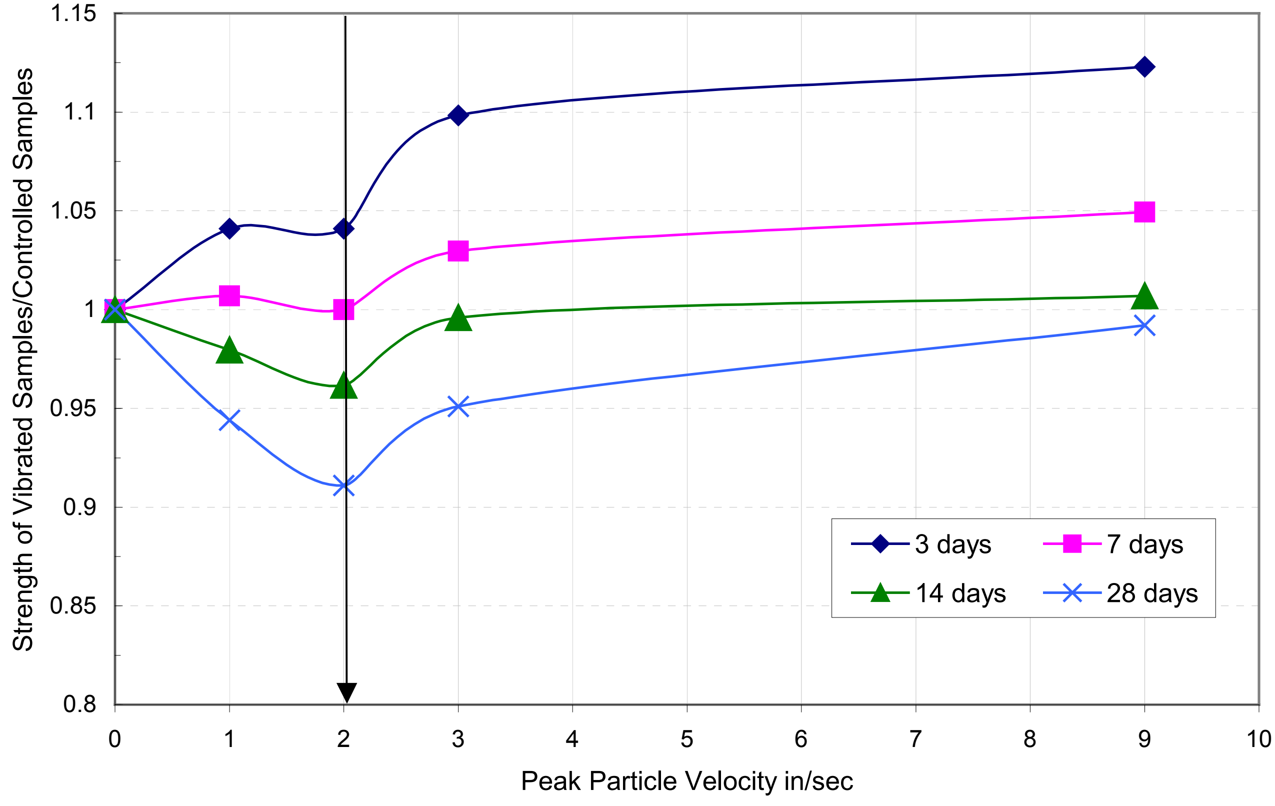

Figure 9: Normalized Concrete Strength for Set #2 (Duration of Vibration = Initial to final time setting)

CHAPTER 4

CONCLUSION

The findings of this study showed that vibrations induced during drilled shaft construction may produce large peak particle velocities in the ground as the driven case advances in the subsurface. The largest peak particle velocities, however, were rapidly damped within short distances from the driven casing. In this study, two correlations were obtained to estimate the peak particle velocities in a half space sandy soil. The surface peak particle velocity correlation conformed to Bornitz's relationship. The recorded durations of the induced vibrations were very scattered, and it was not possible to define a suitable duration from the field testing. Therefore, it was decided to subject the concrete samples in the laboratory to vibrations that last for the duration of the final time setting for Set # 1. For the second set of samples, the duration of vibration equaled the period between the initial and the final time setting. Results from the laboratory testing showed that the effect of the peak particle velocity on the second set of samples was more sever than the first one. However, more bleeding and segregation took place in some samples of the first set.

As a result, it can be concluded that no vibration should be allowed within a distance equal to 3 shaft diameter and for a duration equal to the final time setting of the concrete. During this period, the ppv limit suggested at the 3 shaft diameters should not exceed 2in/sce. Using Equation 1, the velocity amplitude at the green concrete can be determined for a distance of 3 shaft diameter and ppv of 2 in/sec. For 3ft shaft diameter, the vibration at the green concrete would be about 0.04 in/sec. This amplitude is considered too low to affect the green concrete.

RECOMMENDATIONS

Based on the outcomes of this study it is recommended that green concrete be protected from excess construction vibrations to avoid any detrimental effects on the concrete properties. Although controlled concrete vibration is desirable to improve physical and mechanical properties, construction vibrations can simply be categorized under uncontrolled vibrations which include both durations and amplitudes. Therefore, deterring any construction vibrations around the green concrete in drilled shafts would eliminate effects such as segregation, bleeding, and reduction in concrete stiffness and strength. The threshold values of the ppv of 2 in/sec and a distance 3 shaft diameter should be used in the absence of the exact measurements of resonant frequency of the freshly cast concrete drilled shaft. This study showed that ppv 2 in/sec was the most critical velocity for the concrete samples used in the investigation. Increasing the ppv beyond 2 in/sec did not reduce the strength of the samples which indicated that the concrete samples reached resonance where the vibration amplitudes in the concrete matrix was the maximum and hence produced the most detrimental effect.

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