Vibration, Energy, and Pile Embedment Relationships during Driven Pile Installation

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Abstract

Installation of driven piles generate ground vibrations as the pile shears and displaces soil during its penetration. Typically, the magnitudes of ground vibrations from driven pile installations are greater as the pile penetrates stiff/dense soils than in soft/loose soils. For thirteen piles driven at six project sites in the Charleston, SC area, ground vibration and dynamic pile measurements taken during pile installation were compared to available insitu soil testing parameters. The results showed the following: (i) peak ground vibrations generally occurred during pile installation through the dense sands located above the Cooper Marl formation, (ii) the peak vibrations were typically observed along the longitudinal and/or vertical axes, and (iii) the average peak vector sum vibrations within the Cooper Marl were 68% of the average peak vector sum magnitude within the dense sands.

Introduction

It has long been understood that driven pile installations generate ground vibrations and that the source of vibration emission from driven piles depends strongly on the geotechnical conditions (Massarsch, 2005). Typically, the magnitudes of ground vibrations from pile driving are greater in stiff/dense soils than in soft/loose soils. This correlation between vibration magnitude and soil stiffness has been shown for individual pile installations by a variety of researchers (e.g. Thandavamoorthy, 2004, Hope and Hiller, 2000). However, these case histories do not present dynamic pile measurements in conjunction with the soil stiffness and ground vibration data.

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Measurements of ground surface vibrations, dynamic pile measurements, and insitu soil testing parameters for thirteen (13) driven piles at six (6) case history sites in and around Charleston, SC are presented. The presented measurements and subsequent analyses were performed to improve the understanding of the relationships between these parameters in order to refine vibration monitoring and mitigation techniques for future driven pile projects.

Case History Background and Data

The presence of soft clays and loose sands in the Charleston, SC area requires many of the newer structures under construction to be founded on deep foundation systems. Due to cost and other considerations, many of the deep foundation systems chosen are driven piles. Typical pile driving operations in the Charleston, SC region consist of installing pre-stressed concrete piles (PSC) and/or steel H piles into the underlying Cooper Marl Formation. However, for an increasing number of projects on the Charleston Peninsula, driven piles are founded on a dense sand layer located directly above the Cooper Marl. The majority of local pile driving contractors generally use air or hydraulic hammers with rated energies between 20 to 61 kN-m (15 to 45 kip-ft) to install PSC and/or H piles, although some open ended diesels with the same range of rated energies are used. Pre-augering with augers equal to the diameter/width of the driven pile is also commonly performed, with pre-augering depths varying depending on insitu soil conditions and pile design axial and lateral capacities.

Dynamic pile monitoring and ground vibration measurements were performed during installation of thirteen driven piles located at six project sites across the Charleston, SC area. Pile types varied from square Pre-Stressed Concrete (PSC) piles with widths of 254 mm (10 in) and 305 mm (12 in) to steel HP305x79 (HP12x53) piles. Subsurface conditions at the six project sites were explored using the standard penetration test (SPT), piezocone penetration testing (CPTu), and/or flat blade dilatometer testing (DMT). A summary of the pile types and sizes, hammer types and rated energies, and available soil information for the six project sites is presented in Table 1.

Table 1. Case History Summary.

Case No.	Available Soil Data	Pile Type	Bearing Layer[1]	No. Piles	Hammer	
					Model	Rated Energy[2]
C1	CPTu/DMT	254mm PSC	Sand	5	ICE 75	40.7
C2	CPTu	305mm PSC	Marl	2	ICE 75	40.7
C3	CPTu/DMT	305mm PSC	Sand	1	ICE 115	62.4
C4	CPTu/DMT	HP305x79	Marl	1	ICE 75	40.7
C5	SPT	HP305x79	Sand	1	Vulcan 06	26.4
C6	SPT	HP305x79	Marl	3	Vulcan 06	26.4

1. Sand = Dense sand layer above Cooper Marl. Marl = Cooper Marl Formation.
2. Maximum rated energy according to hammer manufacturer.

Each pile location was pre-augered prior to driven pile installation. Pre-auger diameters were equal to the width of the pile, while pre-augering depths varied.

Dynamic pile and vibration monitoring began after weight of hammer (WOH) pile penetration ceased. Distances from the driven pile to the vibration monitor varied from 3.0 m to 38.1 m (10 ft to 125 ft), with the vibration monitor locations dependent on nearby structures and site layout. Peak particle velocity (PPV) ground vibration measurements were taken on three axes relative to the pile driving operations: longitudinal (L), transverse (T), and vertical (V). Peak vector sum (PVS) vibrations were calculated from the three axes measurements. Correlation between pile penetration, dynamic measurements, insitu soil data, and ground surface vibrations was achieved via the pile driving records and time correlations between the dynamic pile monitoring and vibration data acquisition systems.

Typical pile blow count, transferred energy, and ground vibration measurements with respect to the insitu soil testing data and pile tip depth below the ground surface are presented in Figures 1 and 2 for a PSC pile and steel H pile, respectively. The data in Figures 1 and 2 shows that the peak vibrations generally correlated to the stiffest soil layer encountered (i.e. the dense sand layer above the Cooper Marl) and that the highest magnitude ground vibrations were generally in the longitudinal and/or vertical directions. Increases in soil stiffness also correlated to increases in pile driving blow counts. Since air and hydraulic hammers with constant strokes were used, consistent energies were delivered to the piles during installation. These trends were consistently observed within all thirteen driven piles.

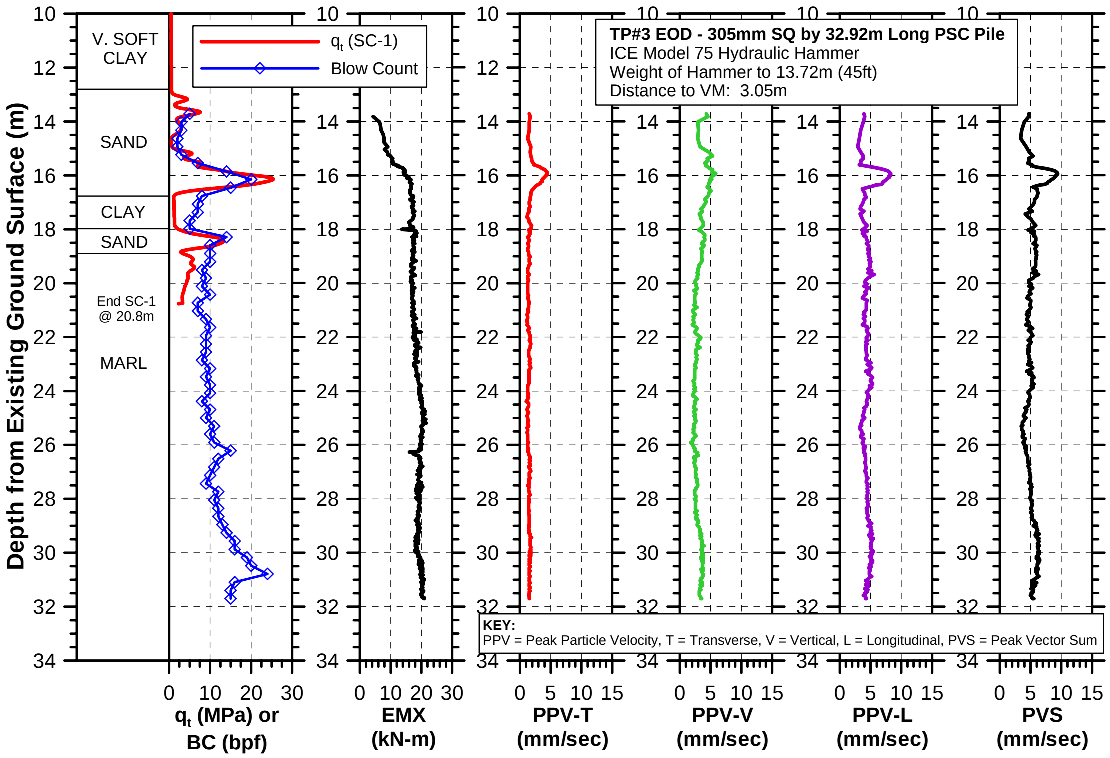

Figure 1. Typical Soil, Pile, and Ground Vibration Measurements for a PSC Pile.

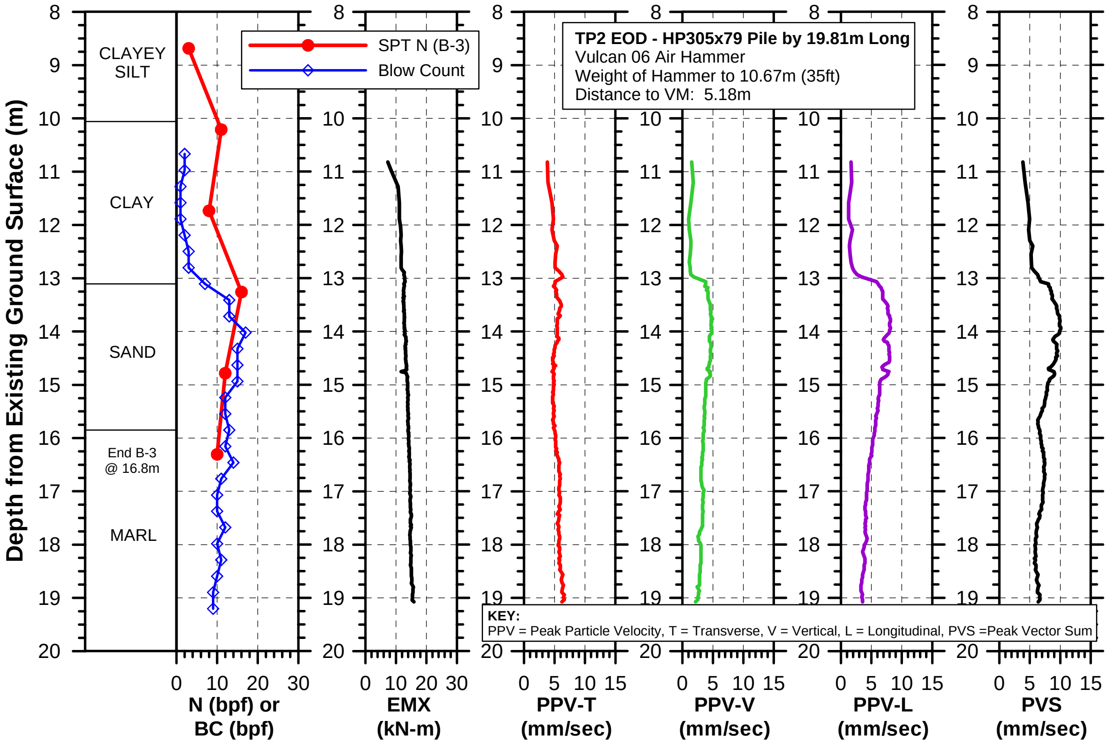

Figure 2. Typical Soil, Pile, and Ground Vibration Measurements for a steel H Pile.

Maximum ground vibrations were examined for three distinct soil layers during pile penetration: the loose to medium dense sands located within the upper 7 to 8 m (23 to 26 ft) (designated as upper soils), the dense sand layer above the Cooper Marl formation, and the Cooper Marl formation. Table 2 presents a summary of the maximum recorded ground vibrations and the corresponding measured maximum energy delivered to the pile (i.e. EMX) in these layers for the individual piles.

Comparison of the peak vector sum (PVS) vibrations within the three distinct soil layers showed that the vibration magnitudes within the upper soils ranged from 23% to 213% of the vibrations within the dense sand layer, with an average value of 88%. The vibration magnitudes within the Cooper Marl formation ranged from 26% to 101% of the vibrations within the dense sand layer, with an average value of 68%.

Scaled distance vibration attenuation relationships were also examined for the peak pile driving vibrations within the three distinct soil layers. The scaled distance concept is commonly used as a means of normalizing vibration attenuation to the rated energy of the hammer or the energy applied to the pile (if available). Refer to Wiss (1981) for additional information concerning vibration attenuation and scaled distance. Figure 3 presents the scaled distance vibration attenuation relationships for (a) the upper soils, (b) the dense sand layer above the Marl, and (c) the Cooper Marl. As shown in Figure 3, a distinct vibration attenuation relationship is only observed within the dense sand layer measurements. The lack of distinct attenuation relationships within the upper soils and Copper Marl is most likely due to a lack of data within these zones.

Table 2. Summary of Driven Pile Energy and Vibration Measurements.

Soil	Case No.	Pile	Pile Type	Dist. (m)	Pile Tip Elev. (m)	EMX (kN-m)	PPV-T		PPV-V		PPV-L		PVS
							(mm/s)	(Hz)	(mm/s)	(Hz)	(mm/s)	(Hz)	(mm/s)
Upper Soil	C1	TP1	254mm PSC	31.1	7.8	11.9	0.40	11	0.78	14	0.40	11	0.80
		TP2	254mm PSC	21.6	7.5	7.3	0.40	10	2.05	7	0.40	10	2.06
		TP3	254mm PSC	38.1	8.7	8.9	0.24	7	0.60	6	0.24	7	0.67
		TP5	254mm PSC	4.6	7.7	10.0	3.20	9	9.12	9	3.20	9	9.50
		TP6	254mm PSC	25.3	8.1	8.1	0.87	9	1.62	8	0.87	9	1.82
	C3	TP3	305mm PSC	3.0	4.6	12.1	5.87	21	15.90	10	5.87	21	16.84
Sand Above Marl	C1	TP1	254mm PSC	31.1	13.3	22.0	1.86	17	1.62	17	1.86	17	3.56
		TP2	254mm PSC	21.6	13.3	20.5	1.49	20	2.46	15	1.49	20	2.52
		TP3	254mm PSC	38.1	13.1	20.9	0.71	13	1.02	6	0.71	13	1.76
		TP5	254mm PSC	4.6	12.5	15.0	4.67	18	5.72	12	4.67	18	8.41
		TP6	254mm PSC	25.3	12.0	17.6	1.22	12	1.16	10	1.22	12	3.00
	C2	TP3	305mm PSC	3.0	16.0	14.4	4.45	19	5.33	23	4.45	19	9.40
		TP4	305mm PSC	9.1	16.7	18.4	1.40	18	2.41	17	1.40	18	8.46
	C3	TP3	305mm PSC	3.0	11.3	13.6	4.09	28	6.55	11	4.09	28	7.93
	C5	TP4	HP305x79	18.6	8.9	12.2	1.70	32	0.57	34	1.70	32	1.72
	C6	TP1	HP305x79	10.4	13.9	10.6	2.67	47	4.70	30	2.67	47	7.01
		TP2	HP305x79	5.2	13.9	12.9	5.46	51	4.83	34	5.46	51	10.08
		TP3	HP305x79	14.6	15.3	13.2	1.52	39	3.18	28	1.52	39	5.92
Marl	C2	TP3	305mm PSC	3.0	30.3	19.7	1.52	73	3.81	51	1.52	73	6.48
		TP4	305mm PSC	9.1	22.1	18.8	0.89	26	2.16	7	0.89	26	2.22
	C4	TP5	HP305x79	7.9	28.8	15.0	2.85	47	0.90	21	2.85	47	3.10
	C6	TP1	HP305x79	10.4	15.9	11.8	4.19	24	3.94	27	4.19	24	5.44
		TP2	HP305x79	5.2	19.0	15.3	6.60	51	2.54	37	6.60	51	6.68
		TP3	HP305x79	14.6	17.5	13.7	1.27	47	3.18	37	1.27	47	5.99

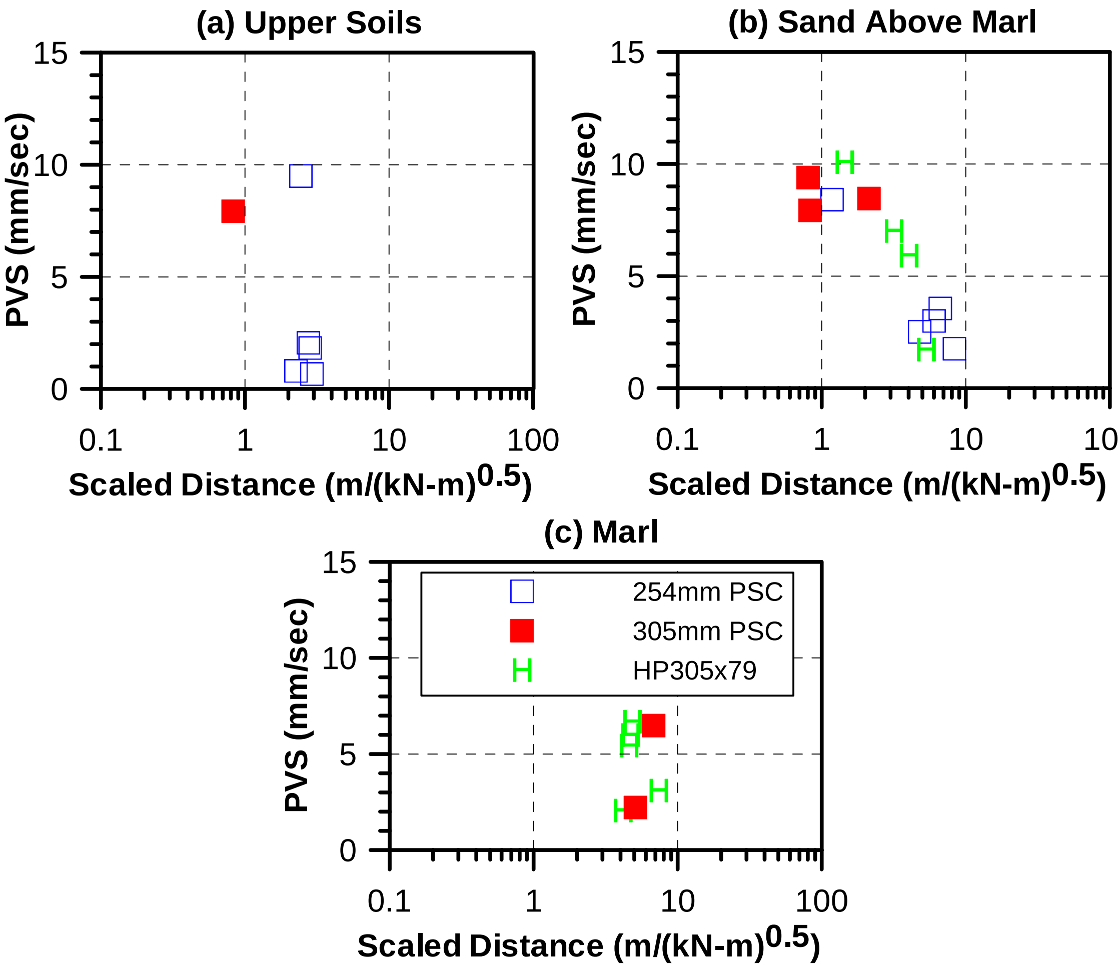

Figure 3. Peak Vector Sum (PVS) Ground Surface Vibration Attenuation Relationships.

Conclusions

Ground vibration and dynamic pile measurements during pile installation were compared to available insitu testing data for thirteen driven piles in the Charleston, SC area. In general, the data showed that pile penetration into or through the dense sands located above Cooper Marl formation produced the peak ground vibrations when consistent energy was delivered to the pile. The peak vibrations were generally in the longitudinal and/or vertical directions. Peak vector sum (PVS) vibrations within the upper soils and Cooper Marl formation were on average 88% and 68%, respectively, of the magnitude of the PVS vibrations within the dense sand.

By understanding where in the pile driving process the peak ground vibrations are generated, effective means to reduce the vibration magnitude can be implemented. The presented data suggests that driven pile vibrations in the Charleston, SC area can be decreased by reducing the soil stiffness in the upper sand layers and/or the dense sand layer above the Cooper Marl. This can be accomplished with the typical pile driving equipment used in the Charleston, SC area by pre-augering through these layers. This method of subsurface soil modification can alter pile axial and/or lateral capacities. Therefore, the pile design should be reviewed prior to implementation.

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