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Surface wave development during impact pile driving

Développement des ondes de surface lors de l'enfoncement de tas

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ABSTRACT: Pile installation by applying an impact to the top of a pile appears to be a simple construction process but analysis of that process is complicated as it involves a source of energy, the structural member (pile), and the ground into which the pile is driven. Codes and regulatory standards suggest some basic guidance to analysis but much is still unknown. It is customary to monitor surface ground motions starting as close as 1.5 m from the pile and use the surface vibration data to interpret energy propagation. In this study, triaxial component geophones were placed on the ground surface during impact pile driving to monitor ground motion. Traditionally, researchers have assumed that the surface waves propagating from a vertical impact driven pile were Rayleigh waves and consequently, the vertical component of motion was only measured. The surface ground motion measurements obtained from this work revealed that the surface waves are not the classical Rayleigh waves that researchers have assumed so far.

RÉSUMÉ: L'installation d'un pieu en appliquant un impact sur le dessus d'un pieu semble être un processus de construction simple, mais l'analyse de ce processus est compliquée car elle implique une source d'énergie, l'élément structural (pieu) et le sol dans lequel le pieu est entraîné. Les codes et les normes réglementaires donnent des indications de base pour l'analyse, mais on en ignore encore beaucoup. Il est habituel de surveiller les mouvements du sol à partir de 1,5 m du pieu et d'utiliser les données de vibration de la surface pour interpréter la propagation de l'énergie. Dans cette étude, des géophones à composantes triaxiales ont été placés à la surface du sol lors de l'enfoncement de pieux à impact afin de surveiller les mouvements du sol. Traditionnellement, les chercheurs ont supposé que les ondes de surface se propageant à partir d'une pile entraînée par un impact vertical étaient des ondes de Rayleigh et que, par conséquent, la composante verticale du mouvement était uniquement mesurée. Les mesures du mouvement du sol en surface obtenues à partir de ces travaux ont révélé que les ondes de surface ne sont pas les ondes de Rayleigh classiques que les chercheurs ont assumées jusqu'à présent.

Keywords: Pile driving; Impact; H-piles; Ground vibrations; Surface waves

1 INTRODUCTION

Earthborne vibrations can cause direct structural damage to buildings and buried infrastructure. In addition, a combination of loose granular soils and ground vibrations can be the cause of liquefaction, densification, and ground settlement, and consequently damage a nearby building. The mechanisms of energy transfer from driven piles into the ground were postulated in the FHWA Synthesis 253 (Woods, 1997) as illustrated in Figure 1. Body waves (P-waves) radiate from the pile tip in a spherical wave front and shear waves (S-waves) move outwards from the pile shaft in a cylindrical wave front. Interaction of these two types of waves on the earth surface allows for the development of surface waves, which up to this point were thought to be Rayleigh waves (R-waves).

It is customary to measure vibration intensities during pile driving operations on the ground surface only, starting at approximately 2 m from the pile. There is a number of studies that focused on monitoring surface ground motions in an attempt to better understand how the waves propagate through the ground during pile driving. Among them, Clough and Chameau (1980), Woods and Jedele (1985), Nilsson (1989), Linehan et al. (1992), Kim and Lee (2000), and Hwang et al. (2001) are mentioned. Traditionally, only vertical componet amplitudes are measured on the surface during impact pile driving, because researchers assume that the vertical component has the greatest amplitude. In this study, ground vibration measurements were collected on the surface, close to impact pile driving activities. Vibrations were measured in the vertical, longitudinal and tranverse direction of wave propagation.

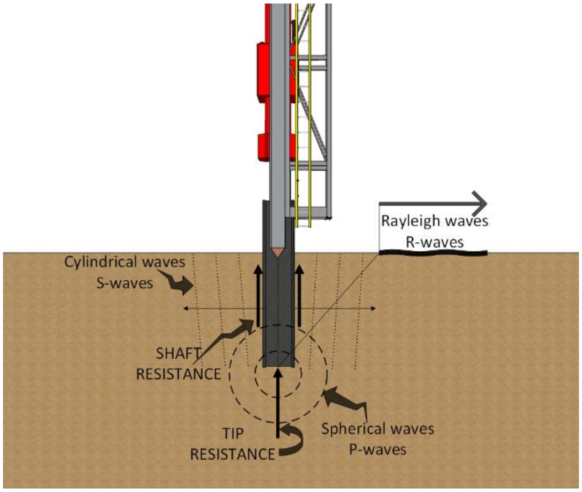

Figure 1. Mechanisms from energy transfer from pile to soil (from Grizi et al., 2016)

2 MONITORED SITE

Ground motion measurements during impact pile driving were monitored at five different project sites controlled by the Michigan Department of Transportation (MDOT). Results from one site collected along Highway M-139 are presented in this paper.

2.1 *Site description*

The M-139 site was associated with the replacement of a deteriorating bridge near the city of Niles in Michigan. A 16.8-m long 360 mm by 109 kg/m H-pile was driven using a Pileco D30-32 diesel hammer. The pile was driven to a depth of 16.2 m. Site characterization was performed by standard penetration tests (SPTs) and by the multichannel analysis of surface waves (MASW) technique (Park et al., 1999).

Subsurface conditions at site M-139 can be generalised as 1.8 m of loose-to-medium dense sand (SP) followed by 1.2 m of muck with silt (ML). Below the muck was 1.5 m of loose-to-medium dense sand (SP) followed by 1.8 m of medium dense silt (ML). Underlying the silt was 2.1 m of loose-to-medium dense sand (SP) followed by 3 m of medium dense sand (SP). Below the medium dense sand was 4.6 m of dense sand (SP) followed by 2.1 m of very dense sand (SP). Below the very dense sand was 3.3 m of dense silt (ML). The water table was encountered at 1.6 m below the ground surface. Figure 2 shows the soil conditions, SPT and shear wave velocity profiles, and pile penetration resistance.

2.2 *Monitoring procedure*

A line array of geophones (L4, Mark Products Inc., Houston, Texas) was placed on the ground surface at the locations shown in Figure 3. The two closest geophones (BG1 and BG2) were triaxial units, while G1 had two single component geophones (vertical and longitudinal), and the further out (G2) was a single vertical component geophone.

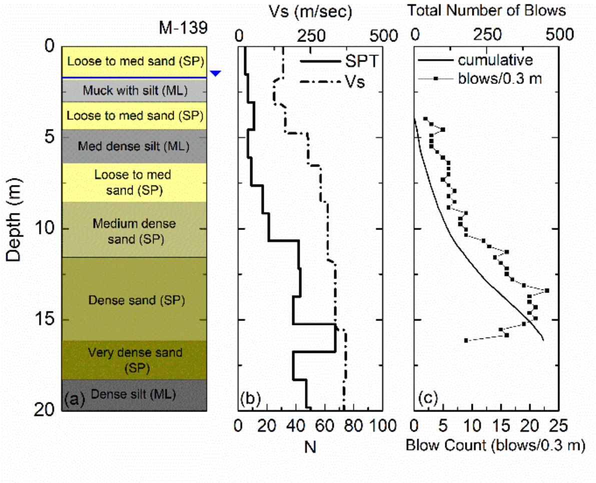

Figure 2. (a) Soil conditions, (b) Standard Penetration Test and Shear wave velocity profiles, and (c) Penetration resistance

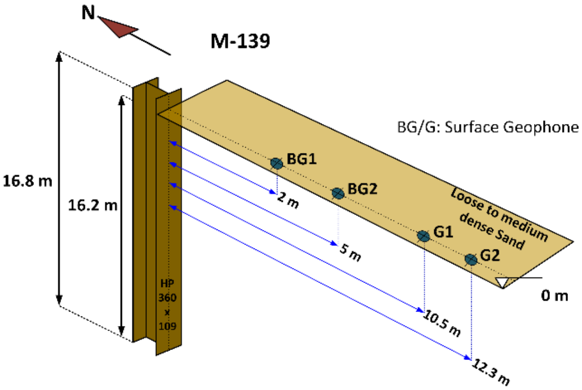

Figure 3. Perspective view of surface sensors

A video was taken during pile installation and an analysis was followed to determine the number of blows per 0.3-m pile increments. Output from all sensors was recorded by a multichannel data acquisition system (CDAQ-9178, National Instruments, Austin, Texas) and data logs were taken simultaneously for the entire duration of pile driving and stored in a toughbook computer. A sampling rate of 1 kHz was used for recording the signals.

In this work, embedded sensors were also pushed in the ground at different radial distances from the piles and different depths, in an attempt to better understand and characterize the wave field during impact pile driving. Results and analysis of ground motion measurements of the in-depth sensors have been documented in Athanasopoulos-Zekkos et al. (2013), Grizi et al. (2016), and Grizi et al. (2019). This paper presents ground motions collected only from the surface sensors in order to characterize the surface wave propagation.

3 GROUND MOTION MEASUREMENTS

Two triaxial seismometers, BG1 and BG2, were placed on the ground surface at 2 and 5 m from the pile, respectively. G1 and G2 were single-component seismometers that measured vertical and/or longitudinal motion directions, and were located at 10.5 and 12.3 m away from the pile, respectively.

The ground motion measurements are presented in terms of peak particle velocities versus pile tip depth. The maximum particle velocity amplitude per 0.3-m increments of depth was extracted and is plotted at the mid-depth of each pile penetration increment.

Figure 4 presents peak particle velocity amplitudes versus depth of the pile tip for the three measured directions, i.e., vertical, longitudinal, and transverse. It is observed, as expected, that the further the sensor from the pile the lower the peak particle velocity. There is a decrease in velocity amplitudes until the pile tip reached approximately a depth of 5 m, and an increase in amplitudes until the pile tip reached a depth of approximately 6.5 m. This is because the pile tip was penetrating into the medium dense silt layer and the penetration resistance increased.

4 ANALYSIS OF RESULTS

In order to compare the three-component response of the geophones, the maximum amplitudes for every 0.3-m of penetration of the vertical, longitudinal, and transverse directions for every surface sensor was plotted. Figure 5a and Figure 6a depict peak particle velocities of the three components for sensors BG1 and BG2, respectively. Figure 7a illustrates amplitudes of the vertical and longitudinal components for sensor G1.

It is also helpful to examine the relative amplitudes in the three directions of motion in order to define the type of motion occuring. Figure 5b and Figure 6b show the ratio of vertical to longitudinal (V/L) and vertical to transverse (V/T) components for sensors BG1 and BG2, respectively. Figure 7b shows the ratio of vertical to longitudinal (V/L) components for sensor G1. The red vertical line at the ratio value of one in Figure 5b, Figure 6b and Figure 7b is the boundary below which vertical components of motion are lower than either or both of the horizontal components of motion.

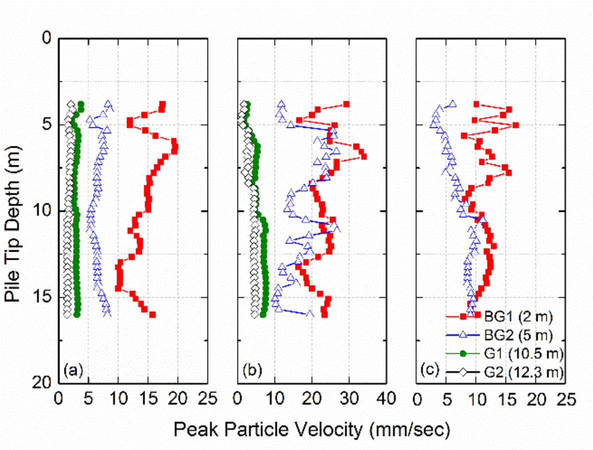

Figure 4. Peak particle velocities recorded by surface sensors versus pile tip penetration depth for (a) vertical, (b) longitudinal, and (c) transverse direction

For sensor BG1, nearest to the pile (2 m), the vertical component of motion is lower than the longitudinal component for the entire depth of pile penetration (Figure 5b). The opposite stands for the transverse component of motion which is lower than the vertical for almost the entire pile penetration depth.

The next further away sensor, BG2 (5 m from pile), has again ratios of V/L smaller than one for the entire penetration depth (Figure 6b). In addition, the transverse components of motion are greater than the vertical after the pile tip gets below 9 m.

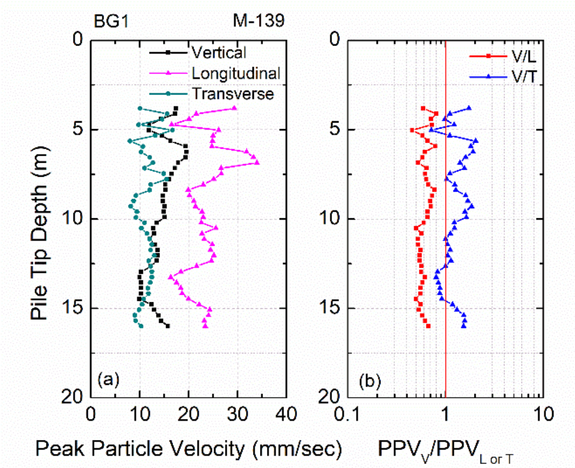

Figure 5. (a) PPVs of three directions of sensor BG1, and (b) Vertical to longitudinal and vertical to transverse components of PPV

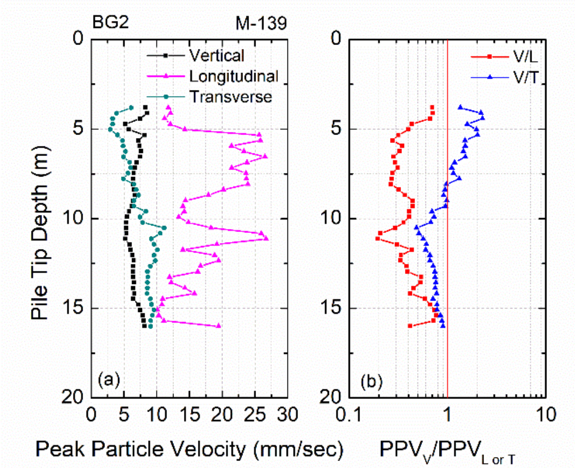

Figure 6. (a) PPVs of three directions of sensor BG2, and (b) Vertical to longitudinal and vertical to transverse components of PPV

Finally, the third sensor in the row, G1 (10.5 m from the pile) has longitudinal components of motion greater than the vertical components for the entire depth of penetration (Figure 7b) except for a depth range in the beginning of the pile installation (4 to 5 m).

It is of interest to note that the vertical components of motion are smaller than either or both of the horizontal components of motion indicating that the wave motion at these sesors is not a classic Rayleigh wave form as traditionally interpreted by researchers. This observation is very firm as there was no uncertainty with regard to sensor orientation. Furthermore, ratios V/L and V/T were lower than one for almost the entire pile penetration depth at all the other tested sites monitored by the authors (Gkrizi, 2017).

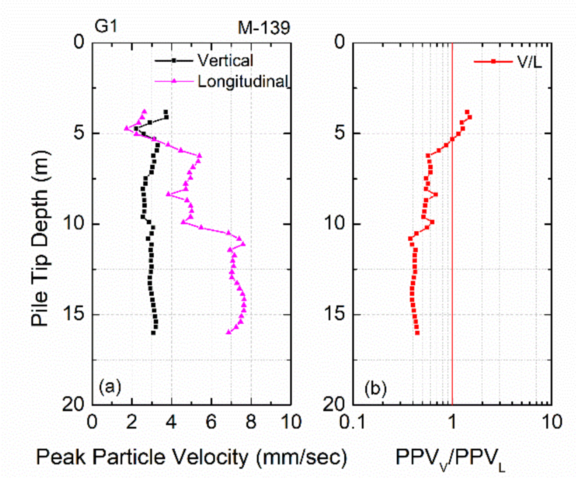

Figure 7. (a) PPVs of vertical and longitudinal directions of sensor G1, and (b) Vertical to longitudinal components of PPV

Another way of investigating the types of waves propagating away from a vibration source and recorded by a surface geophone is by plotting the variation of particle motions with time. Figure 8 shows vertical versus longitudinal and vertical versus transverse particle motions captured by geophone BG2. It is evident that the particle motion path does not have the form of an elliptical shape with higher vertical particle motion, which is typical for a Rayleigh wave motion. The same trend was found at greater distances from the source after analysing ground motions collected at the other tested sites. This finding contradicts the assumption that vertical component amplitudes are greater than horizontal components, thus a classic Rayleigh wave was not developed on the surface based on the surface ground motion measurements.

5 CONCLUSIONS

Ground motions were measured during the driving of H-piles with diesel hammers at five sites in Michigan, USA. Ground vibrations were recorded by installing sensors in the ground and by placing a line array of geophoned on the ground surface. This paper presents results from one of the sites regarding surface wave development.

Traditionally, researchers have assumed that the surface waves propagating from a vertical impact driven pile were Rayleigh waves and consequently, the vertical component had the greatest amplitude. However, this was not true for the surface measurements at this site and the other sites that were monitored by the authors. That is because the layered soil profile makes the wave propagation more complex than the assumed uniform isotropic half-space upon which the mechanisms of energy transfer are based. Similar trends were observed at other tested sites and will be reported in a future publication.

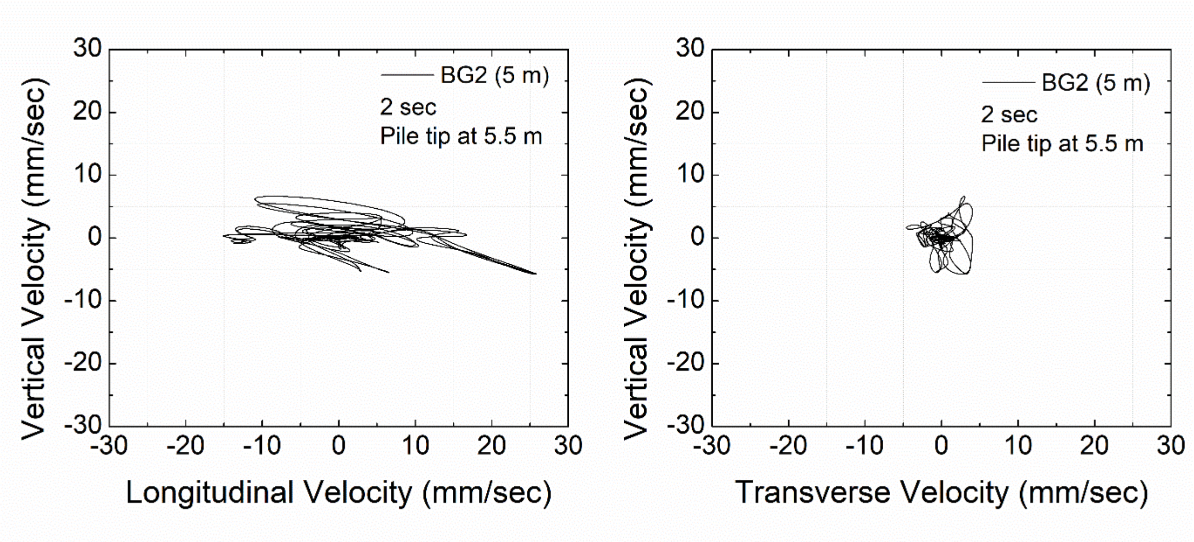

Figure 8. Particle motion paths during impact pile driving for pile tip being at 5.5 m – sensor BG2

6 ACKNOWLEDGEMENTS

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