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Influence zone around a closed-ended pile during vibratory driving

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ABSTRACT

This paper presents a numerical study based on vibratory driving of closed-ended piles. A set of axisymmetric finite element models were used to replicate the wave propagation during vibratory pile driving and to investigate the effect of wave propagation on the surrounding ground. The numerical modelling technique adopted for the analysis takes into account the large soil deformations around the pile during driving and is based on the Arbitrary Lagrangian Eulerian technique. It has the ability to drive a pile few pile diameters below the initial position without mesh distortions and the numerical model was verified using field data available in the literature. Soil was modelled as an elastic-perfectly plastic material. A parametric study was performed to determine the influence of change in pile driving force on the far field using different operating frequencies and amplitudes of the driving force, and rigidity index and material damping of the surrounding soil. The parameters for the driving force were extracted from the published specifications of commercially available vibratory piling rigs. Finite element results were compared with ground vibration measurements of peak particle velocities during vibratory sheetpile driving found in the literature. These results show that the material damping is an important parameter contributing to wave attenuation around the driven pile in addition to the geometric damping. The impact on the far field is discussed comparing the peak particle velocity distributions with the specifications given by the American Association of State Highways and Transportation Officials (AASHTO), Swiss Standard SN640312 and Eurocode 3 for acceptable vibrations to avoid damages to existing nearby structures. Finally attenuation relationships, and upper and lower bounds for the peak particle velocity distributions around a driven closed-ended pile are presented to determine the influence zones for different types of nearby structures.

1. Introduction

Rapid population growth in last few decades has drastically increased the demand for infrastructure, driving the modern day construction industry to utilise the land available adjacent to existing buildings. That is accomplished by constructing high-rise buildings spanning hundreds of metres above the ground level and also below the ground level, accommodating other requirements such as storage and vehicle parking. Pile foundations are used to transfer large design loads from these high-rise buildings to the ground. Also, when the soil conditions are poor closer to the ground surface, piles are used to transfer loads to strong soil layers deep below the ground surface.

Depending on the construction method, piles can be categorised into two groups: driven piles and drilled piles. Driven piles have relatively smaller diameter and are prefabricated and driven into ground using a pile driver. Drilled piles have larger diameters than driven piles and cast in-situ by drilling boreholes in the ground. Three widely used techniques to install driven piles are vibratory pile driving, impact pile driving and pile jacking. The present study focuses on vibratory pile driving.

In vibratory pile driving, a set of counter-rotating eccentric masses are used to generate the force driving the piles. According to Rodger and Littlejohn [21], the vibrations generated by the pile driver reduce the soil resistance, and accommodates to drive the pile with a smaller surcharge force than that generated during impact driving. Impact pile driving involves dropping a ram mass from a given height, which gives the pile energy to be driven into the soil, even in difficult soil conditions. However, due to the high noise and vibration generation, impact driving is less preferred in urban construction activities [23].

Woods [23] presented an illustration for wave propagation around a driven pile as shown in Fig. 1. According to his illustration, the shear stress waves are generated along the skin of the pile due to the friction between the pile and soil particles. Shear waves are first generated from the upper contact point and propagated out in a conical shape with a very shallow angle. Hence, the shear wave front is considered as cylindrical. Each impact on the pile creates a volume displacement at the tip of the pile, resulting in outward travelling compression and shear waves with spherical

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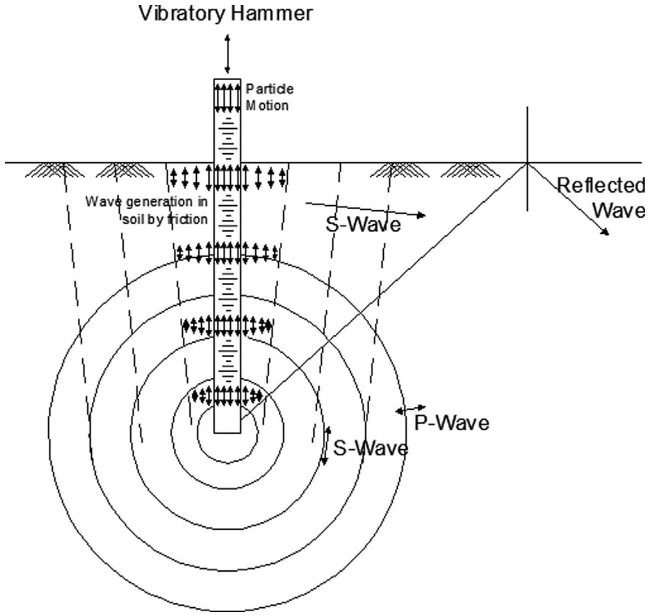

Fig. 1. Wave propagation in pile driving [23].

wave fronts. Once these waves reach the ground surface, part of the waves will be transformed to surface waves such as Rayleigh waves and rest of the waves are reflected back into the ground [3].

Vibration intensities are attenuated with increasing distance from their source and consequently their effect on sensitive structures. Dym [8] discussed about two types of vibration attenuation: geometric damping and material damping. Geometric damping occurs due to the expansion of the wave front with increasing distance from the wave source and material damping occurs due to the various physical parameters of the soil medium [15]. Peak particle velocity (PPV) can be used to discuss the intensity of ground vibration propagation. According to Athanasopoulos and Pelekis [3], the strains generated by propagating ground waves are proportional to the particle velocity of the medium. They summarised different approaches applied in numerous studies to derive PPV from the particle velocity measured in vertical, horizontal and transverse directions as follows:

(i) The peak value of velocity, out of velocities measured in three mutually perpendicular directions.
(ii) The peak value of the velocity in vertical direction.
(iii) The square root of the sum of squares (SRSS) of peak values of velocity in each direction.
(iv) The peak value of true vector sum (TVS) of velocities in three directions.

The fourth approach listed above is recognised as the most appropriate approach to describe the intensity of the vibration.

Different standards and design codes have published different vibration criteria to prevent building damages. Jones and Stokes [14] summarised the PPV criteria given by the American Association of State Highways and Transportation Officials (AASHTO) in 1990. Table 1 shows the limiting PPVs for different types of structures. A research report prepared by Jackson et al. [13] outlines the PPV criteria given in Swiss standard, SN640312, for vibration in buildings. SN640312 differentiates four building classes and two frequency ranges in each class for machines and traffic generated vibrations, as illustrated in Table 2. Eurocode 3 [9] provides guidelines for acceptable vibration levels to avoid structural damages to buildings. As shown in Table 3, Eurocode 3 is similar to AASHTO and does not differentiate PPVs based on frequency ranges as in SN640312.

Table 1
AASHTO: Maximum acceptable vibration levels to prevent structural damage [14].

Type of situation	PPV in/s (mm/s)
Historic sites or other critical locations	0.1 (2.54)
Residential buildings, plastered walls	0.2–0.3 (5.08–7.62)
Residential buildings in good repair with gypsum board walls	0.4–0.5 (10.16–12.7)
Engineered structures, without plaster	1.0–1.5 (25.4–38.1)

Table 2
Swiss standards (SN640312): maximum acceptable vibration levels to prevent structural damage [13].

Building Class	Frequency Range (Hz)	PPV in/s (mm/s)
I	10–30	0.5 (12.7)
	30–60	0.5–0.7 (12.7–17.78)
II	10–30	0.3 (7.6)
	30–60	0.3–0.5 (7.6–12.7)
III	10–30	0.2 (5.08)
	30–60	0.2–0.3 (5.08–7.62)
IV	10–30	0.12 (3.05)
	30–60	0.12–0.2 (3.05–5.08)

I- Buildings of steel or reinforced concrete, such as factories retaining walls, bridges, steel towers, open channels; underground chambers and tunnels with and without concrete lining.
II- Foundation walls and floors in concrete, walls in concrete or masonry; stone masonry retaining walls; underground chambers and tunnels with masonry linings; conduits in loose material.
III- Buildings as previously mentioned but with wooden ceilings and walls in masonry.
IV- Construction very sensitive to vibration; objects of historical interest.

Table 3
Eurocode 3: Maximum acceptable vibration levels to prevent structural damage [9].

Building type	PPV mm/s
Architectural merit	2
Residential area	5
Light commercial	10
Heavy industrial	15
Buried structures	25

Other standards such as German Standard, DIN4150; British Standards, BS7385 and BS5222-2; and Australian Standard, AS2187.2; also published PPV criteria but the guidelines are developed to use against the vibrations generated due to transient events such as blast loading. Since the occurrences of blast vibrations are transient and not continuous, the PPV values given are much higher than the limiting values given for continuous vibrations such as machine, construction and traffic generated vibrations.

Numerous studies have been carried out investigating free field vibration propagation due to dynamic pile installation methods. Thandavamoorthy [22] studied the intensity of ground vibrations from a hammer driven pile on the far field in sand by measuring the PPVs near and far from the driven pile. Masoumi et al. [18] conducted a low strain dynamic test using a hammer with a weight of 5.5 kg on a single pile to study the pile response and the vibration propagation in the free field. They compared the results with a numerical model developed by Masoumi et al. [19]. There was a reasonable agreement between the measured and predicted responses beyond 4 m from the driven pile. According to Masoumi et al. [18], the free field vibrations depend on the material damping ratio of the soil at high frequencies and at the distance from the