Press-in piling: Ground vibration and noise during pile installation

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Abstract

Conventional dynamic piling methods are ill-suited to the urban environment. The press-in method offers an alternative technique of pile installation, which allows pre-formed piles to be installed with minimal noise and vibration.

Field measurements of noise and ground vibrations during press-in piling are presented and compared to existing recommended limits. Based on this initial database, tentative prediction curves are presented. Equipped with these tools, designers can assess the relative environmental impact of each installation method when planning piling works.

Introduction

Pile driving is an activity that is ill-suited to the urban environment. The noise and ground vibrations created during the installation of pre-formed piles by dynamic methods can lead to human disturbance and structural damage. Stringent regulations now virtually preclude the installation of steel tubular piles by dynamic methods in urban Europe, and bored cast-in-place piles have become the most common design solution.

Steel tubular piles offer a number of advantages over bored piles, particularly relating to issues of sustainability (Table 1). The embodied energy of a pile is the sum of the energy required to extract the raw materials, carry out any manufacturing or construction processes, and transport the material between and within these processes. A steel pile contains less embodied energy than a concrete pile of similar capacity.

This advantage can be extended if the pile is extracted and re-used. Chapman et al. (2001) report that many sites in the City of London already contain multiple sets of old deteriorating bored piles, with little remaining space for future new foundations. Re-use of the pre-existing layout of bored piles is inconvenient, extraction is virtually impossible, and the construction of fresh piles is unsustainable.

Historically, the noise and vibration pollution created by conventional pile driving methods has prevented the advantages of steel piles being realised. However, a novel technique for installing large tubular steel piles without noise and vibration has recently been developed. The technique of press-in piling makes use of hydraulic rams to provide the force necessary to jack pre-formed piles into the ground. The hydraulic rams form part of a robotic machine that uses previously installed piles to provide a reaction

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force (Figure 1). This technique of pile installation and extraction is known as the 'press-in method'.

Although originally designed to install sheet piles, a range of machines have been developed to install steel tubular piles up to 1500 mm in diameter with a maximum force of 400 tonnes (4 MN). Since a continuous measurement of jacking force is provided during press-in installation, the bearing capacity of the pile can be verified. The press-in method is relatively unknown in Europe and the US, but dominates the Japanese sheet pile installation market.

This paper presents the results of field monitoring from two job sites at which the press-in method was used. Measurements of noise and ground vibration are presented and compared with other pile installation techniques and current European recommended limits.

Table 1: Comparison of pile types

Pile type	*Stiffness*	*Embodied energy*	*Re-cycle / extract ?*	*Suited to urban construction?*
Steel tubular piles	High	Low	Yes	No: noise and vibration created by dynamic piling
Bored cast-in-place piles	Low	High	No	Yes: less noise and minimal vibration

Figure 1. A row of 914 mm diameter tubular piles being installed by a press-in piler (New York, USA).

Piling-induced noise pollution

Noise pollution created during construction operations can present a health hazard to site operatives and cause annoyance to neighbours. Noise levels are expressed in decibels, and are derived from the fluctuating air pressure (Equation 1).

$$\text{Air pressure, p } (\mu\text{Pa}) = 20 \times 10^{(\text{dB}/20)} \qquad (1)$$

If a standard pressure transducer is used to record noise, frequencies outside the range audible to humans will be recorded. Noise meters are usually 'A-weighted' to give measurements which are relevant to the sensitivity of the human ear. Noise levels decrease with the logarithm of radius, r, from their source. The noise level of a source, L_{source}, can be attenuated using Equation 2 to deduce the attenuated noise level which neighbours will experience ($L_{equivalent}$).

$$L_{equivalent} = L_{source} - 20 \log(r) - 8 \qquad \text{(Selby, 1997) (2)}$$

In the UK, British Standard BS5228 (1992) provides guidance on acceptable noise levels during construction. In urban areas, $L_{equivalent}$ should not exceed 75 dB at the outside of a noise sensitive building (i.e. a residential or office building), with a lower limit of 70 dB applying in rural areas.

Table 2 compares some environmental noise levels with the source noise levels (L_{source}) of typical piling equipment. Note that the logarithmic scale obscures the true variation in loudness. The human ear perceives a 10 dB increase in noise level as a doubling in loudness.

Table 2: Typical ambient and piling-induced noise levels

Environment (Selby, 1997)	*Noise level (dB)*
Inside a metro train	90-100
Inside a city bus	80-90
Street corner traffic	70-80
Conversational speech	60-70
Business office	50-60
Suburban living room	40-50
Library	30-40
Piling machinery (from BS5228)	*Noise source level, L_{source} (dB)*
Double acting diesel hammer (37 kJ)	135
Double acting air hammer (5.6 kJ)	134
Enclosed drop hammer (3 t)	98
Hydraulic drop hammer (60 kJ)	121
Press-in piler: Giken Seisakusho 'Silent Piler'	*Observed noise (dB)*
Power pack (loudest component)	75 @ r = 1m (Selby, 1997)

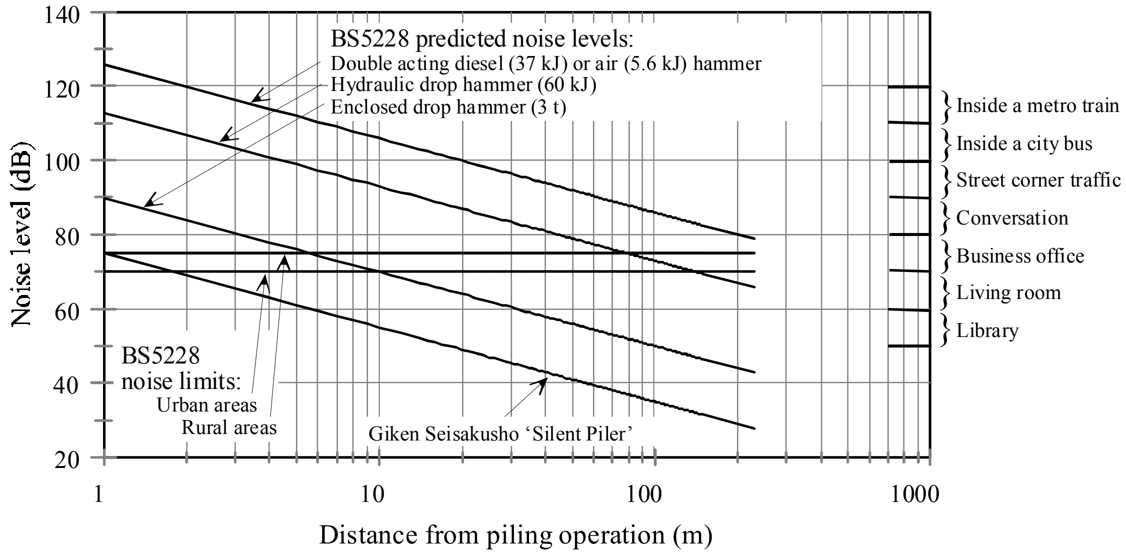

Figure 2. Variation of noise level with distance from various types of piling operation.

By combining Equation 2 with the data in Table 2 and the BS5228 acceptable limits, the minimum separation of piling works from a sensitive building can be estimated (see Figure 2). It should be noted that the layout of the site and neighbouring buildings will have an influence on the actual noise levels. Furthermore, the duration of piling during a typical working day, and the pre-existing ambient noise levels will influence whether the noise level is acceptable.

In order not to exceed the BS5228 noise limits, Figure 2 shows that diesel and air hammers should not be operated closer than 100m from a sensitive building. In contrast a press-in piler does not exceed the rural noise limit (70 dB) at a distance of 2m. The noisiest part of the press-in rig is the power pack, which can be located away from the line of piling and shielded to further reduce noise if necessary.

Piling-induced ground vibrations

Piling-induced ground vibrations can lead to human disturbance and structural damage. Ground vibrations are usually quantified by the peak velocity of particles in the ground as they are disturbed by the passing wave (peak particle velocity- ppv). Instantaneous particle velocity consists of three orthogonal components which are usually measured independently using a tri-axial geophone.

The most commonly used definition of peak particle velocity is the *simulated resultant* ppv; this is the vector sum of the maximum of each component regardless of whether these component maxima occurred simultaneously (Hiller & Hope, 1998). The vibrations induced by dynamic piling methods typically influence a zone stretching 10-50m from the operation, and can be easily measured using geophones.

The draft Eurocode 3 provides guidelines for acceptable human exposure to ground vibrations depending on the length of the construction period (Figure 3). Structural damage thresholds are also provided. These range from a maximum ppv of 2 mm/s for buildings of architectural merit, to 15 mm/s for industrial buildings (figure 4).

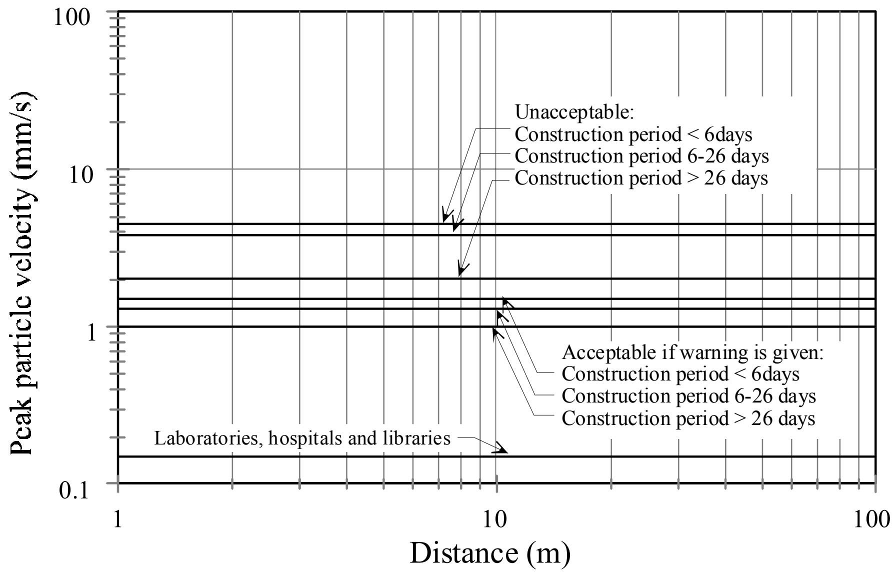

Figure 3. Eurocode 3: Maximum acceptable vibrations to prevent human disturbance.

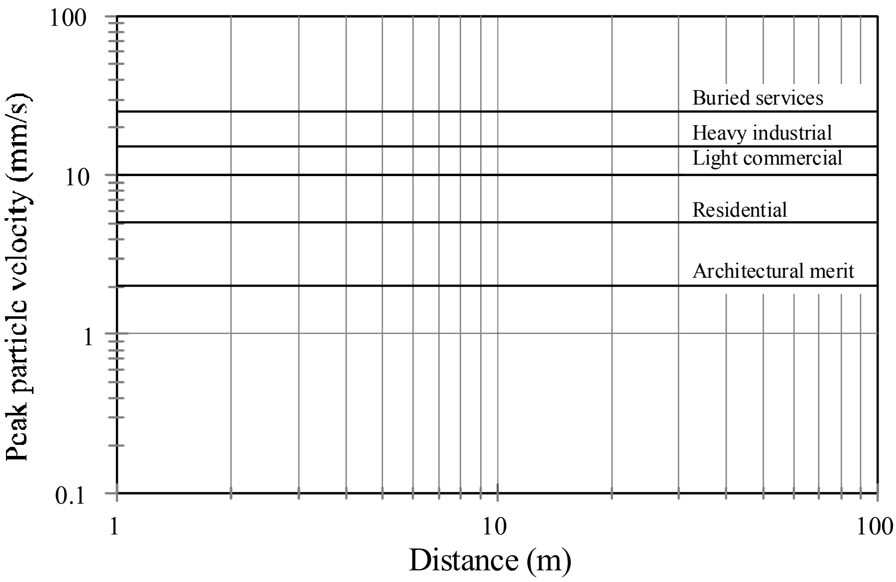

Figure 4. Eurocode 3: Maximum acceptable vibrations to avoid structural damage.

A database of previously published measurements of ground vibrations during dynamic piling has been assembled (Head & Jardine, 1992). These measurements are plotted in Figure 5 on the same axes as used in Figures 3 and 4. By overlaying these figures, the distance from the piling operation at which ground vibrations fall below the Eurocode thresholds can be found. The ground vibrations reduce in an approximately linear fashion with log radius. A number of empirical methods for predicting ground vibrations follow this trend, the most popular being that proposed by Attewell & Farmer (1973), and subsequently adopted by BS5228 and Eurocode 3 (Equation 3).

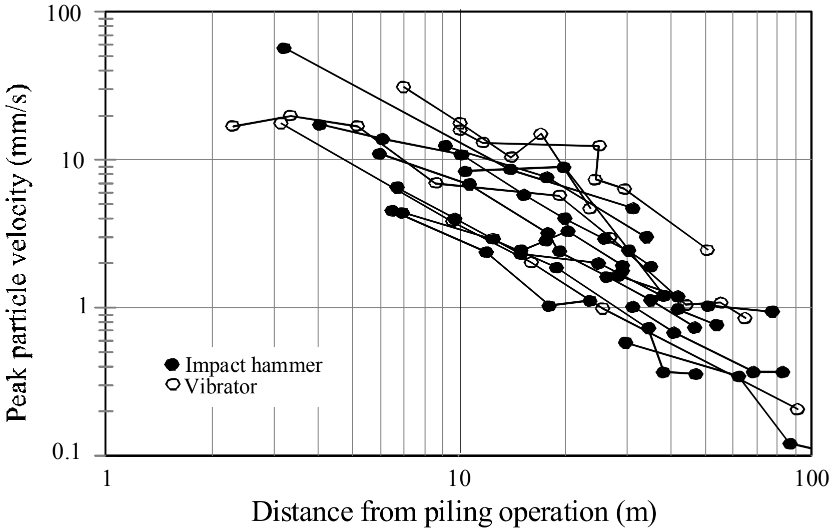

Figure 5. Measured ground vibrations during dynamic piling (data from Head & Jardine, 1992).

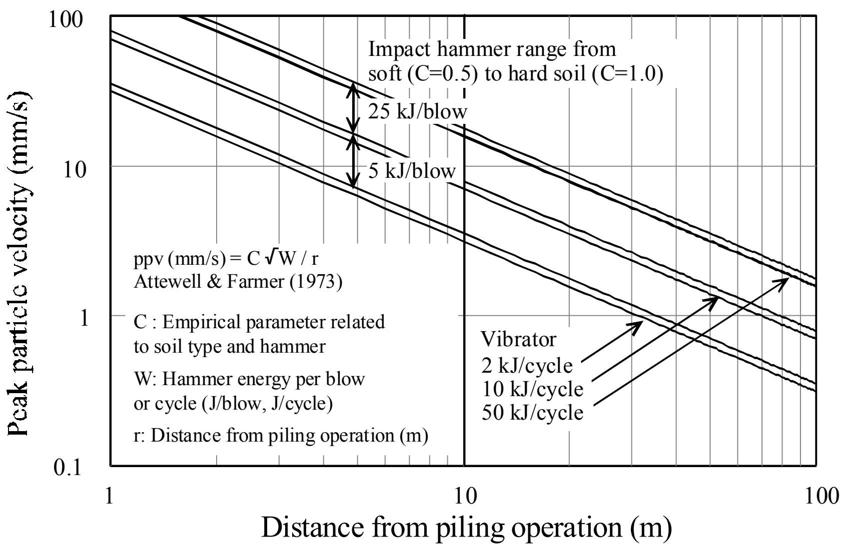

Figure 6. Predicted ground vibrations during dynamic piling (after Eurocode 3).

The empirical parameter C relates to soil and hammer type. Eurocode 3 recommends a value of 0.7 for vibratory piling, and values ranging from 1.0 in dense or stiff soil to 0.5 in loose or soft soil for impact piling. W refers to hammer energy per blow or cycle (J/blow or J/cycle). R is the horizontal distance from the piling operation in metres, and v is the predicted peak particle velocity in mm/s. The predicted attenuation of ground vibrations with distance for various types of piling are shown in Figure 6. These curves match well with the field observations shown in Figure 5 and thus represent a useful tool for engineers when planning piling operations in urban areas.

$$v = C\,(W^{0.5} / r) \qquad (3)$$

Field monitoring

Since the press-in method is a recently developed technology, no database of field measurements exists, and consequently no predictive method of the form of Equation 3 has been proposed. In order to provide a similar predictive tool for designers who wish to assess the suitability of the press-in method for a given job, field measurements of ground vibrations during press-in piling have been obtained. These form a limited database from which a tentative prediction curve is derived.

Site 1: New Orleans, USA

A demonstration of the press-in method was carried out by Giken America for the US Army Corps of Engineers in October 2000. A row of 30 interlocked U-shaped LX-16 sheet piles was installed along the west bank of the Grand Cross Canal in New Orleans using a UP-150 Silent Piler. A borehole investigation revealed ground conditions consisting of:

0m to 1m:	Soft brown and grey clay with silt lenses, roots and wood
1m to 4m:	Very soft grey and brown clay with organic material
4m to 4.5m:	Brown and black peat with clay lenses
4.5m to 10m:	Very soft grey clay with silt lenses (SPT N_{max} = 2)
10m to 20m:	Soft to medium stiff grey clay with silt lenses (SPT N_{max} = 10)

Vibration monitoring was carried out by Eustace Engineering (Metairie, Louisiana, US). Three monitoring stations were established close to the line of sheet piling. The most distant two locations, at 18 and 24m from the line of piling, did not provide useful data since the vibration amplitude experienced at these locations was similar to the resolution of the seismographs. The resultant peak particle velocities measured 4.8m from the piling operation were in the range 2.5-4.3 mm/s (Eustis Engineering, 2000) (see Figure 7).

Site 2: Utrecht, Netherlands

A wall of 500mm U-shaped sheet piles was installed beside Meester Tripkade, Utrecht, Holland as temporary works during the widening of the Utrecht to Blauwkapel railway line during July 1992. Vibration monitoring was carried out by Dutch Railways to assess any disturbance to the foundations of nearby properties (Dutch Railways, 1992). Tri-axial geophones were attached to the foundations of three houses 15 cm above ground level, located 7.15m from the piling line. Local regulations recommended that ground vibrations be limited to 3mm/s around residential buildings.

Construction of the wall commenced using a diesel hammer. However, the measured resultant peak particle velocity was 15.2 mm/s, significantly exceeding the local limit. A subsequent pile was installed using a vibratory method, with a resultant peak particle velocity of 8.3 mm/s being recorded. A press-in piler (Giken Seisakusho UP150 'Silent Piler') was brought onto site and the remaining piles were installed by the press-in method. Peak particle velocities in the range 0.3 to 0.7mm/s were recorded during this stage of the construction.

This field data provides a direct comparison of the ground vibrations created by different methods of piling. The influence of soil conditions and pile type can be ignored since identical piles were being installed in identical soil. Figure 7 shows that replacing the dynamic piling equipment with a press-in pile driver lead to a 10-50 times reduction in ground vibrations.

Prediction of press-in piling vibrations

This limited database of field measurements taken from two press-in piling sites allows a tentative prediction curve to be proposed. Although the ground vibrations during press-in piling are created through a different mechanism to dynamic piling vibrations, their attenuation with distance from source will be comparable since attenuation rate is a function of geometric spreading and soil damping.

Hence, a relationship of the form shown in Equation 3 is proposed. The empirical factor, C, and the energy per blow, W, are combined into a single empirical parameter. The best-fit line shown in Figure 7 is:

$$v_{press\text{-}in}\ (\text{mm/s}) = 7\ /\ r\ (\text{m}) \qquad (4)$$

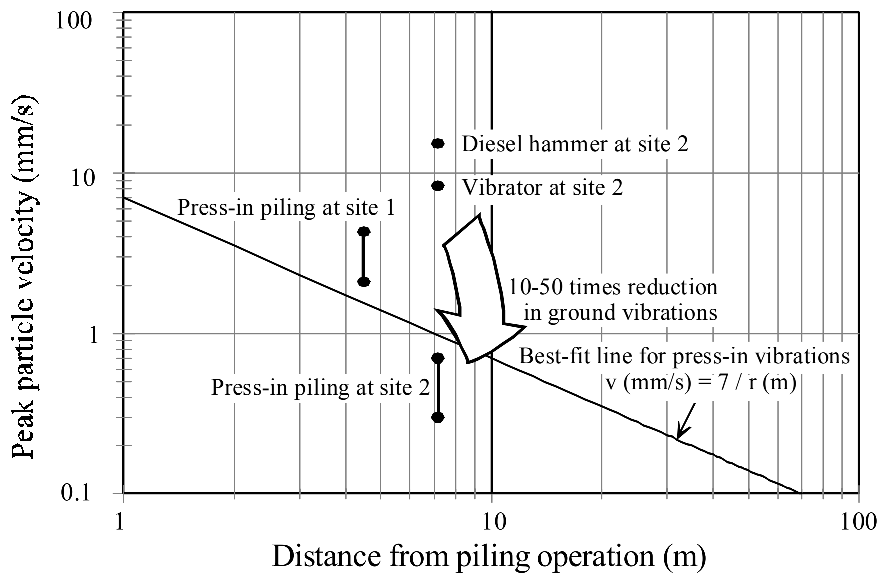

Figure 7. Measured vibrations at sites 1 and 2.

Comparison of this prediction curve with the Eurocode 3 limits shown in Figures 3 and 4 offers designers a tool to establish whether the press-in method is suitable for a given site (see table 3). It should be noted that the actual magnitude of vibrations will depend on soil properties and the local subsurface profile. Also, ambient ground vibrations, for example due to passing traffic or trains, could exceed both the press-in piling vibrations and the recommended limit.

Conclusions

Pre-formed steel piles offer a number of advantages over bored cast-in-place piles, particularly in relation to issues of whole life cost and sustainability. However, the noise and vibration created by conventional dynamic methods makes them ill-suited to the urban environment. The press-in method offers an alternative technique of pile installation, which allows piles to be installed close to existing structures and without disturbing human activity.

Field measurements of noise and ground vibrations during press-in piling are presented and compared to existing design codes. A direct comparison of dynamic and press-in piling at one site revealed a 10-50 times reduction in ground vibrations when using the press-in method. Based on this initial database, prediction curves for the noise and ground vibrations created by the press-in method are presented. Equipped with these tools, engineers can make an assessment of the relative environmental suitability of each installation method when planning piling works.

Table 3: Predicted minimum separation between piling operations and sensitive buildings

Building type (vibration limit from Eurocode 3)	Piling method					
	Press-in method (Eq^n 4)	Impact hammer (stiff clay / medium dense sand; (C=0.75) (Eurocode 3)		Vibrator (Eurocode 3) kJ/cycle		
		5 kJ/blow	25 kJ/blow	2 kJ/cycle	10 kJ/cycle	50 kJ/cycle
Architectural merit (2 mm/s)	3.5 m	26.5 m	59 m	16 m	36 m	78 m
Residential area (4 mm/s)	1.75 m	13 m	30 m	8 m	18 m	39 m
Light comercial (10 mm/s)	0.7 m	5 m	12 m	3.1 m	7 m	16 m
Heavy Industrial (15 mm/s)	0.5 m	3.6 m	8 m	2.1 m	5 m	10 m

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