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PILE DRIVING CONTRACTORS ASSOCIATION

STEEL SHEET PILE GUIDES

BASIC PRINCIPLES OF HAMMERS FOR SHEET PILE INSTALLATION

Impact Hammer Technology

Hammer selection

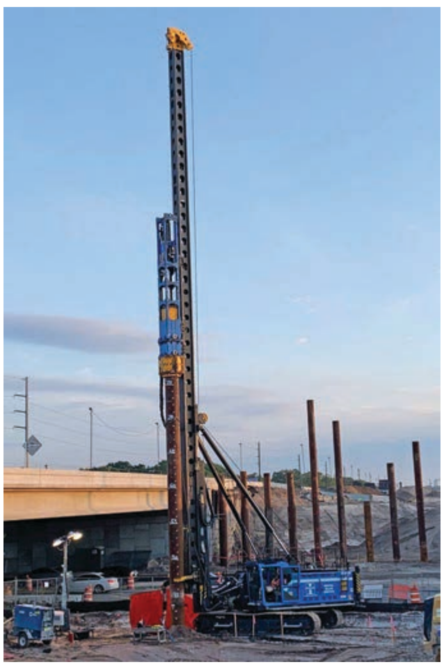
Hammer selection is the most important aspect of pile installation. In many cases only one hammer type may be applicable for the pile-soil combination, whereas others may require several hammers to cope with the varying conditions.

One major advantage of an impact hammer is that the blow count record during pile installation is a direct measure of the pile resistance. The **vertical advance of a pile under a given hammer blow is used as a measure of the pile's bearing capacity**. The hammer's interaction with the pile-soil system is both modeled before driving (wave equation analysis) and monitored during pile installation (Pile Driving Analyzer).

Vibratory hammers are widely used to drive and extract sheet piles, but they are less commonly used to drive bearing piles. Where bearing capacity is required, the use of impact hammers is the predominant installation technique employed.

Impact hammers are also essential to drive sheet piles when soil density increases. SPT 'N' values approaching 40 generally indicate the limit of vibratory hammer efficiency. Here, impact hammers come into their own by being able to shear through dense soils to reach the design penetration depth.

Impact hammers are usually supported by a leader rig or can be freely suspended by a crane.



Leader rig

Crane suspended hammer

What is an impact hammer?

An impact hammer is a specialty hammer used to drive sheet piles into the ground.

Impact pile driving hammers consist of a ram and an apparatus that allows the ram to move quickly upwards and then fall onto the driving system and pile. The ram must have a mass and impact velocity that is sufficiently large to move the pile.

A properly functioning hammer strikes the pile in quick succession. It transfers a large portion of the kinetic energy of the ram into the pile. The stroke of a pile driving hammer is usually between three and ten feet (900 to 3,000 mm).

How does an impact hammer work?

The most common forms of impact hammers in use today are hydraulic drop hammers and diesel hammers. While they operate differently, they are both used to drive sheet piles, pipe piles, H-piles and specialty wide flange piles by allowing a ram weight to fall onto the top of the pile.

Hydraulic impact hammers

Hydraulic fluid is applied to the piston to move the ram. A hydraulic power pack provides the pressurized fluid to operate the hammer. Hydraulic impact hammers can be single acting, double acting, differential acting or other variations. Most but not all hydraulic hammers employ the use of an electric valve operated with a variable timer. The timer allows for flexible control of the output energy. Others use a purely hydraulic system to control the valve and thus the cycling of the ram.

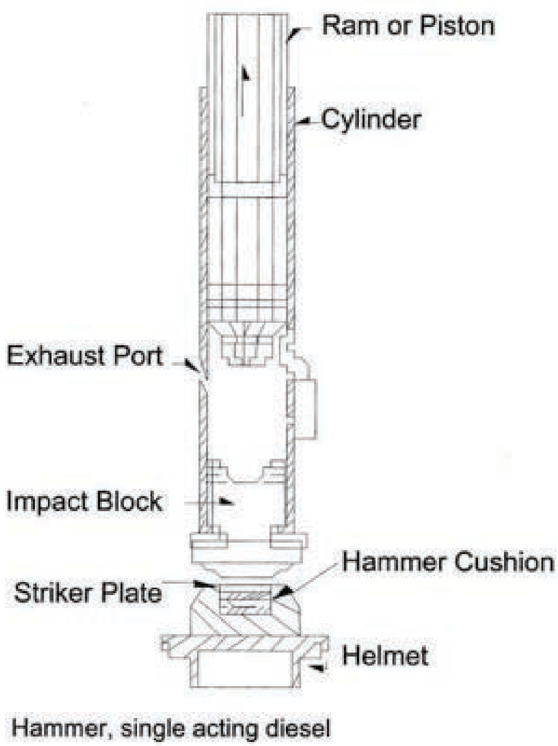
Most hydraulic hammer manufacturers claim high efficiencies for their hammers. Although there are many improvements in hydraulic hammers that enable a more efficient drop, the main reason for the higher efficiencies is that they have some kind of downward assist to equalize the hydraulic flow during the hammer cycle.

Hydraulic hammer

Diesel hammers

An **open-end diesel hammer** consists of a long slender piston (the ram), which moves inside a cylinder. The cylinder is open at its upper end, thus allowing the ram to partially emerge from the cylinder. The ram falls under gravity to the pile cap. Upon impact, the ram pushes the pile cap and pile head rapidly downward. The impact block separates from the ram within a very short time and the pressure of the combusting air-fuel mixture will cause further separation as the ram is forced upward.

A **closed-end diesel hammer** cylinder is closed at its upper end, thus causing the ram to compress the air trapped between ram and cylinder top. When the ram falls, it is subject to both gravity and the pressure in the *bounce chamber*, **hence called double acting**.



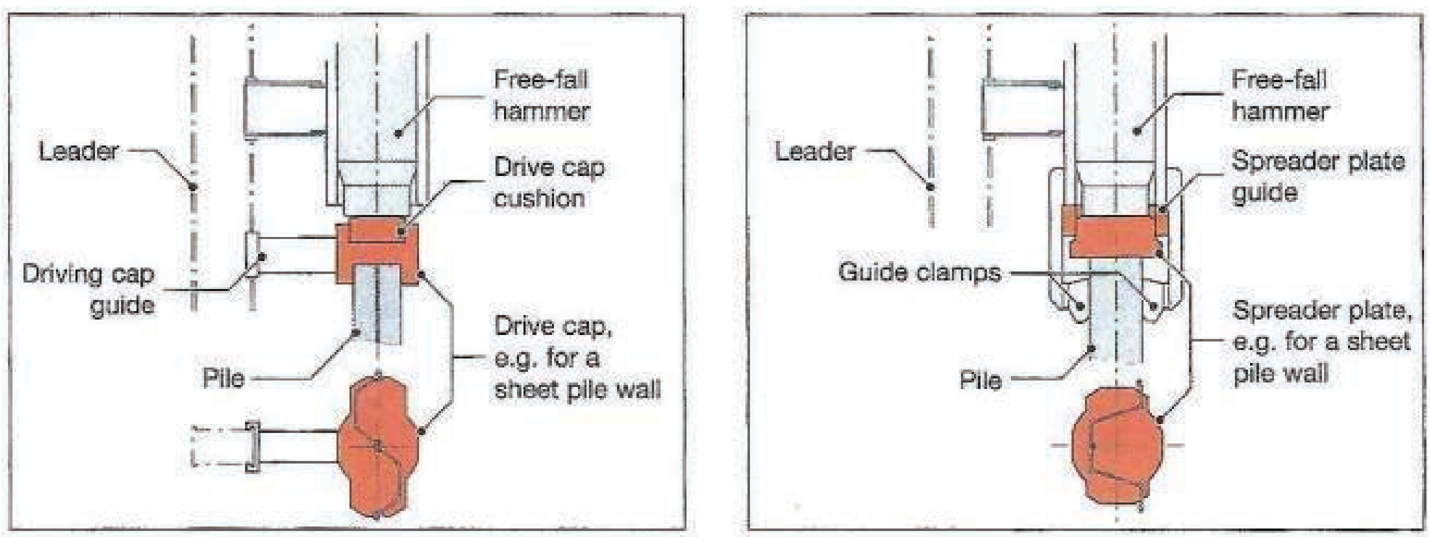
Diesel hammer

Pile cap

To ensure that as little energy as possible is lost in the transfer to the pile, the driving energy is transferred to the pile via a driving cap or spreader plate. The driving cap also ensures the hammer blows act centrally on the pile. The pile cap is matched to the shape of the sheet pile being driven.

A central connection between the hammer and the pile and exact guidance of the hammer on the leader are key prerequisites for accurate pile driving. If the hammer is not concentric with the pile, then the eccentricity may lead to pile head damage and/or pile lean.

Typical driving cap for Z-sheet piles



Typical driving cap and spreader plate detail

The form of driving cap must be matched to the sheet pile that is to be driven. It is attached to the underside of the hammer by a loose attachment and is guided by the leader where used.

Sizing the impact hammer

Impact hammers are of the size needed to develop the energy required to drive the piles at a blow count that **does not exceed 10 blows per inch** at the required ultimate pile capacity. The intent is to select the size of hammer at normal operating condition to be sufficient. Occasionally, it may be required to drive to a higher blow count to penetrate an unforeseen thin, dense layer or minor obstruction. Jetting or drilling may be a preferred means to penetrate a particularly dense layer. Overdriving often will damage the pile and/or hammer.

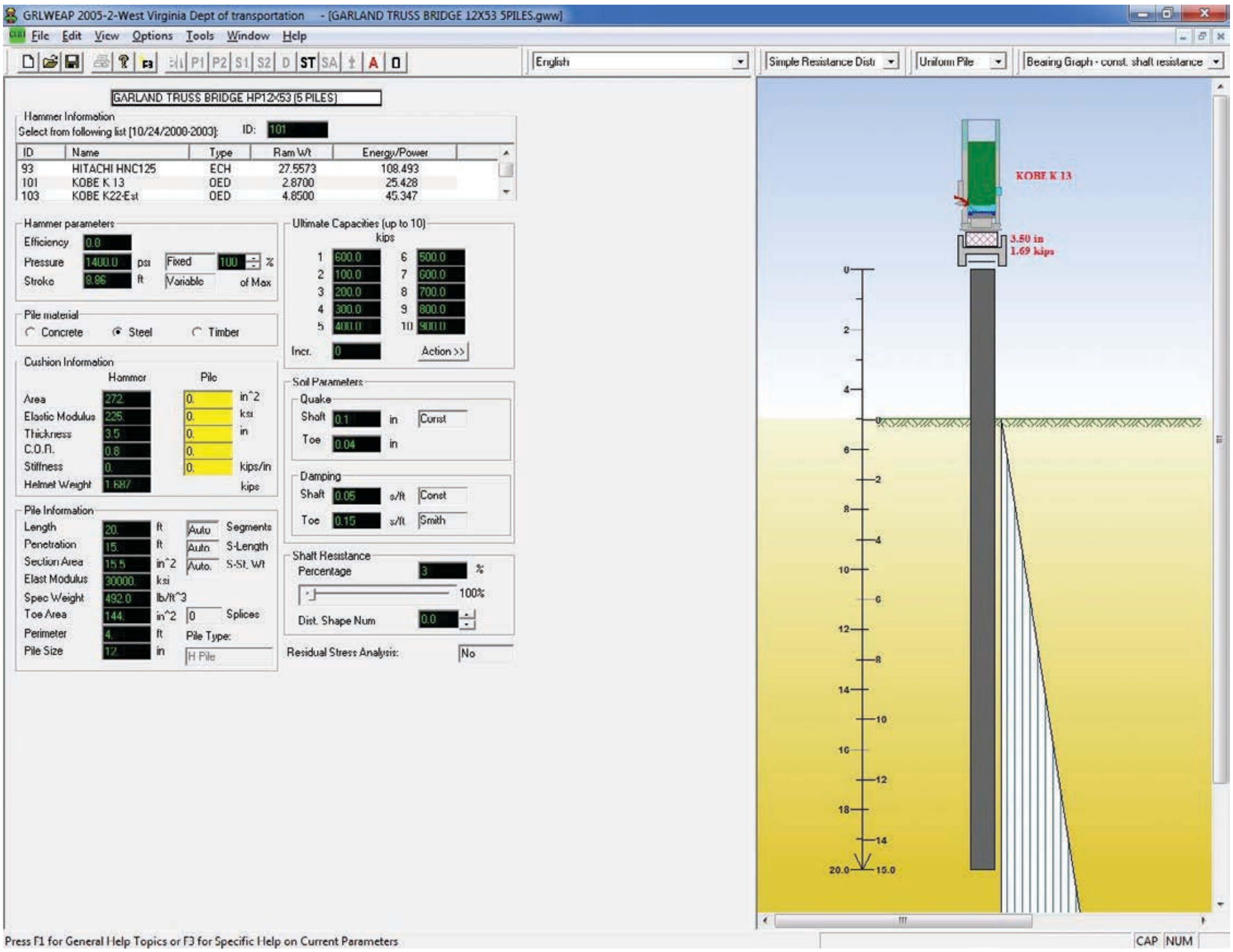
In its simplest form, the impact energy delivered per drop hammer blow is simply the weight of the ram times the fall distance to the pile cap.

A 3,000 lb. ram falling 10 feet (with no bounce on the pile cap) at impact would deliver 30,000 ft-lbs of energy. Twice the height of the bounce is deducted from the total drop height to determine the net drop and calculation of delivered energy.

A general rule of thumb for hydraulic drop hammers is to match the ram mass to the mass of the sheet pile being driven. Therefore, if a 50-foot-long pair of Z-26 sheet piles weighs 3.5 tons, then it would be reasonable to use a three-ton ram mass with a standard drop. As the drop height can be controlled by the operator, then the installation could begin with a small drop to get the pile penetration underway. Drop height would increase as needed to ensure a minimum penetration rate.

A more scientific and accurate approach is to use **wave equation analysis**. The industry has largely adopted wave equation analysis and it has become a well-used tool for pile driving evaluation. Contractors will often use the wave equation to optimize equipment selection and hammer makers often make equipment recommendations based on the wave equation analysis.

Wave equation analysis is a numerical method of analysis for the behavior of driven foundation piles. It predicts the pile capacity versus blow count relationship (bearing graph) and pile driving stress – for example, when a soft or hard layer causes excessive stresses or unacceptable blow counts. While popular, it is best carried out by an engineer familiar with the software to ensure appropriate results.



Vibratory Hammer Technology

What is a vibratory hammer?

A vibratory hammer is a specialty hammer used to drive sheet piles in or out of the ground. Impact hammers use a large weight to strike the pile. Vibratory hammers are relatively quiet and have many advantages, such as fast installation. They can also extract sheet piles, can be used underwater, are lightweight, protect the environment (especially animal life) and can be used in close proximity to residential areas without noise complaints. They are also relatively small and are easy to transport.

How does a vibratory hammer work?

Unlike traditional pile driving equipment that uses a large weight or ram to strike a pile, vibratory hammers use spinning counterweights to create vibration in the pile. The vibration sends the soil particles into suspension enabling the pile to slip through the soil.

The ability of a hammer to drive sheet piles is dependent on the sheet pile size, mass and the soil conditions present.

The vibratory hammer's ability to drive a pile is a combination of driving force, frequency, amplitude and free-hanging weight. The driving force of a hammer is determined by its **eccentric moment** and steady-state frequency.

- **Eccentric Moment** – The eccentric moment is calculated by the eccentric weight {M) and the distance from the center of gravity to the rotation axis (r).
  $M = (m \cdot r)$

- **Centrifugal Force** (F)

  $F = 0{,}011 \cdot N^2 \cdot 10^{-3} \cdot M$

- **Amplitude** (A)

  $$\frac{2 \cdot M}{M_d} \times 1000 \qquad M_d = \text{Dynamic Weight}$$

The size of the eccentric moment affects the driving force, attainable amplitude, operating frequency and power requirements for the hammer.

- Eccentric moment equals the distance from the center line of gravity to the center line of rotation, times the total number of eccentrics in the hammer.
- Amplitude is the vertical movement of the total vibrating system, and the direct result of the applied force generated by the rotating eccentrics.

$$\text{Amplitude} = \frac{\text{eccentric moment}}{\text{vibrating mass (hammer and pile weight)}} \times 2$$

Worked example:

A hammer weighing 8,750 lbs and with an eccentric moment of 2,600 in/lbs is driving a PZ 27 sheet pile 40 ft long. What will the amplitude be?

PZ-27 = 40.5 lbs/ft × 40' = 1,620lbs × 2 (driven in pairs) = 3,240 lbs (total weight of pair)

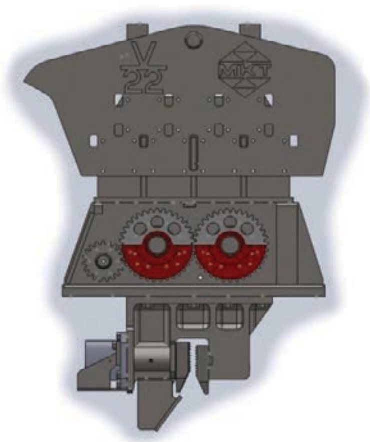
$$\frac{\text{2,600 in/lbs (eccentric moment)}}{\text{8,750 (weight) + 3,240 (pile weight)}} \times 2$$

$$\frac{(2{,}600)}{(11{,}990)} \times 2 = (.216) \times 2 = .432$$ amplitude, or **amplitude = 7/16"**

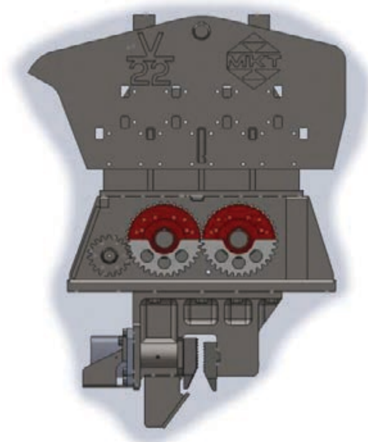
For effective driving, the hammer must have amplitude of equal to or greater than a quarter of an inch.

Generally speaking, the higher the amplitude, the more effective the hammer will be at driving piles in soils considered marginal to vibratory driving. Higher amplitudes may also increase risk of damage to adjacent structures.

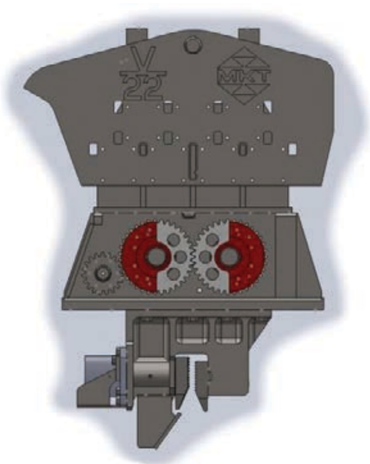
- The eccentrics of a vibratory hammer are attached to a shaft, and are mounted in pairs opposite one another, on a horizontal plane inside the gearbox. The pinion shaft(s) are connected to a hydraulic motor/motors mounted to the outside of the gear box. As the eccentrics rotate in opposite directions, their horizontal forces cancel one another out, leaving only vertical vibration.



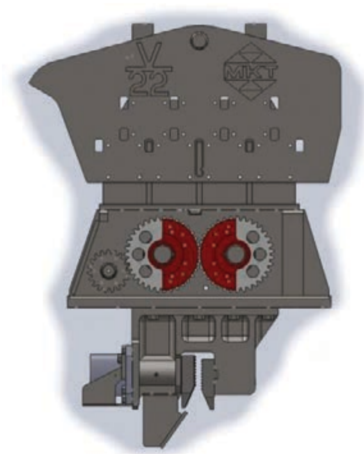
Position #1



Position #3



Position #2



Position #4

What is the difference between an electric and a hydraulic vibratory hammer?

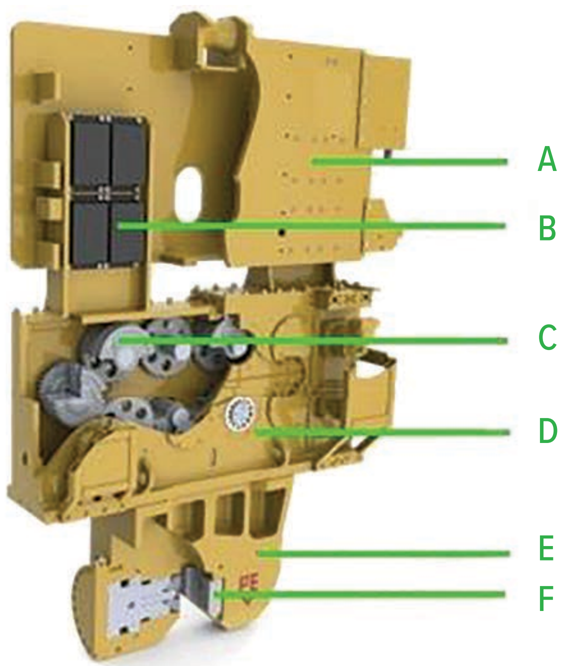
In the market today, there are two main types of vibratory hammers – electric and hydraulic. Electric hammers and hydraulic hammers have many differences but have similar traits.

Both electric and hydraulic hammers use a “power unit” that powers the hammer. Both have clamps allowing the hammer to connect to the pile. Both use wires or hoses to connect the hammer to the power unit.

Electric vibratory hammers use a large electric motor on top of the hammer to spin the counterweights. To power the electric motor, a large power unit with a diesel engine will turn a generator, giving enough power to the motors.

Hydraulic hammers use hydraulic motors to spin the counterweights. To power the hydraulic motors, a large power unit with a diesel engine turns hydraulic pumps, which flow oil out to the motors and back.

Hydraulic hammers are much more powerful than electric hammers and are half the weight. The other main advantage is that they can spin at a much faster speed. The higher the vibration speed, the less vibration will travel through the soil to surrounding buildings.



A suppressor

B elastomers

C eccentrics

D vibration case (gearbox / carter)

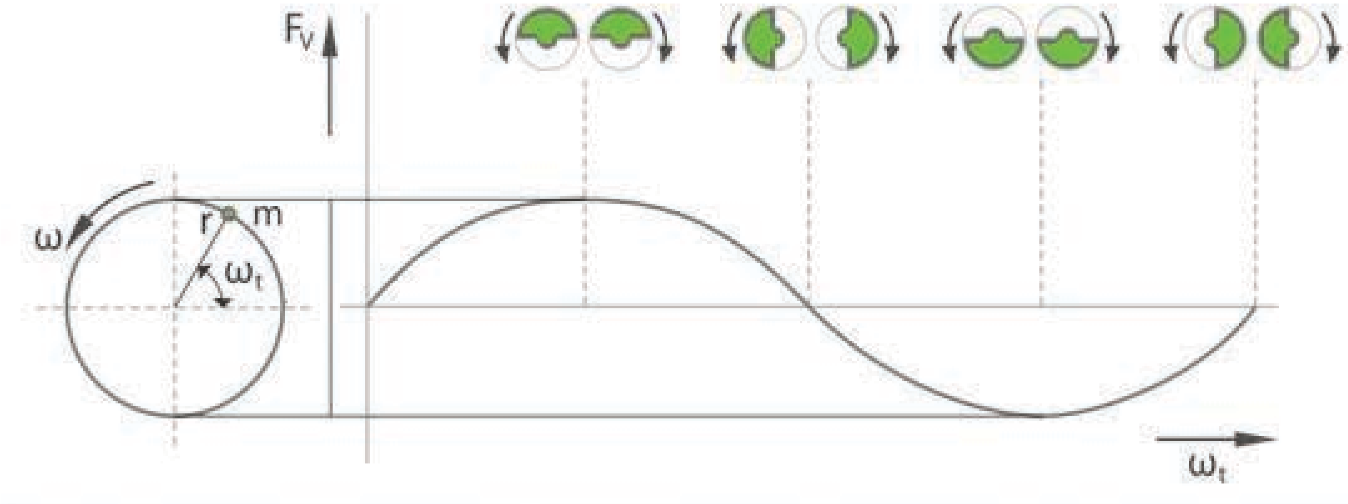
E clamp

F jaws

The design of a vibratory hammer

Vibration generation

The vibration case has two pairs of eccentric weights that rotate in a vertical plane to create vibration. This generates centrifugal force. When two unbalanced eccentrics maintaining the same moment are rotated in opposite directions, vertical (up and down) vibration of constant cycle is produced.



Fv	vertical force	r	rotations per minute
w	angular frequency	w_t	angular frequency π-radian
m	mass		

The weights are driven by hydraulic engines. The eccentrics are gear-connected to maintain proper synchronization. The eccentric shafts are mounted in heavy-duty roller bearings. The maximum capacity of the engines is hydraulically limited.

Suppressor

The extraction head contains rubber elements (elastomers) to isolate vibrations from the vibration case to the crane or pile driving rig.

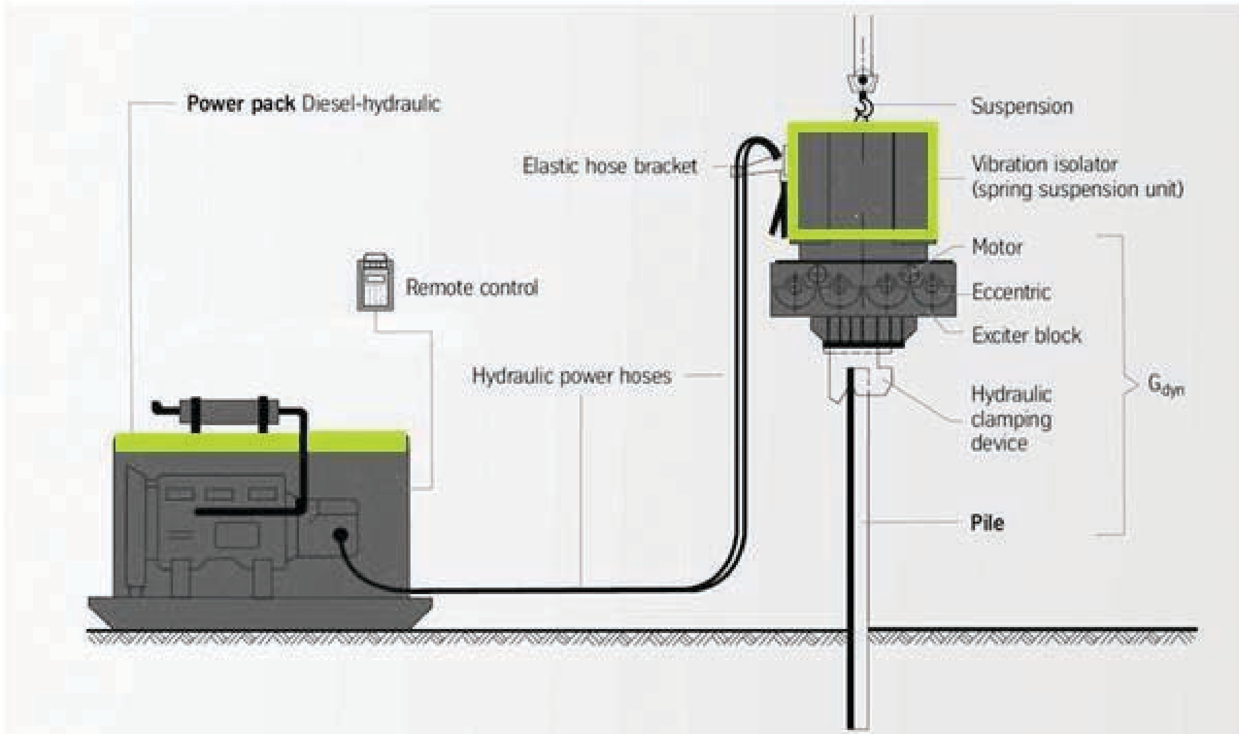
Clamp

The hammer has a hydraulic clamp containing two gripping jaws, one fixed and one moveable, that grip onto the sheet pile. A cylinder, integrated in the clamp body, operates the moveable jaw and has a pilot operating check valve that keeps the cylinder under pressure in case of hose damage. The clamp is operated hydraulically.

The hydraulic system

The classic pile driving setup includes a power pack and a vibratory hammer. The heart of any vibratory hammer is the exciter block, containing pairs of counter-rotating eccentrics.

The power pack is driven by a diesel engine and supplies the oil flow to the vibrator via hydraulic pumps to drive the piling into the soil.



Vibratory hammer technology explained

Variable moment technology

A vibratory **hammer** with a **variable** eccentric **moment** can be started and stopped without vibration. For this, the eccentrics are placed in a zero position with an adjustment motor (with opposite centers of gravity, resulting in a cancellation of the eccentric force).

After the vibratory hammer has reached full speed, the eccentric moment is set causing the vibratory hammer to vibrate. It is possible to set the eccentric moment at a value from 0 to 100%. The operational rpm of these vibratory hammers is higher than that of low frequency vibratory hammers. Where a low frequency vibratory hammer will rotate with approximately 1,500 revolutions per minute, a high frequency (HF) vibratory hammer will rotate with approximately 2,300 revolutions per minute.

Due to this high rotational speed, the vibratory hammer operates further away from the soil's resonance frequency – and due to the smaller amplitude, these vibratory hammers are less harmful to the surroundings. Tests have demonstrated that the vibration level of a HF hammer measured at a distance of 2m from the sheet pile equals the level of vibrations produced by a low frequency hammer at a distance of 16m.

Also, when vibrating a steel sheet pile into the ground, the adjustment motor can be adjusted to influence the eccentric moment and therefore the amplitude. This will allow optimum adjustment of the vibratory hammer.

Conventional vibratory hammers have a constant eccentric moment. When passing the critical frequency area during start-up and stop, the constant amplitude will cause disturbing negative vibrations in the boom of the crane and in the soil to a considerable perimeter distance.

Content and photos in this section are courtesy of American Piledriving Equipment, ThyssenKrupp/Müller and PVE-Holland.

Press-in Machine Technology

What is press-in piling?

Press-in piling is a unique method of pile driving that uses hydraulic force without the use of vibration or percussion to install piles. This method consists of a few different variations carried out by different types of equipment. These variations include installation with gravity-based machines, tall leader-masts with press-in attachments and reaction-based press-in piling machines.

Advantages of the press-in piling method include:

- Minimal noise impacts
- Imperceptible vibration (non-vibratory)

Of the aforementioned types of press-in variations, reaction-based press-in piling machines are by far the most prevalent. Additional advantages and capabilities of press-in piling with reaction-based press-in piling machines include:

- Installation into hard soil conditions (with attachments)
- Installation within very limited horizontal and vertical clearances
- Safe installation with controlled accuracy
- Installation within a small footprint
- Installation with controlled, measured and monitored static loads

How do press-in piling machines work?

Press-in piling machines are designed to install steel sheet and pipe piles without using vibration or percussion and do so by deriving its source of potential energy from the reaction of already installed piles that are essentially integrated with the ground (White et al., 2002). Press-in machines obtain this reaction by hydraulically clamping onto the tops of the installed piles, thereby using their reaction to create a press-in force in order to press in subsequent piles.

Figure 1 illustrates that with this mechanism, even a compact press-in machine can create a press-in force that is by far greater than its weight. Since these machines hold the sheet and pipe piles near or at ground level to press them in, hardly any press-in energy is lost that would otherwise generate unwanted noise, vibration or the deformation of piles with conventional pile driving equipment.

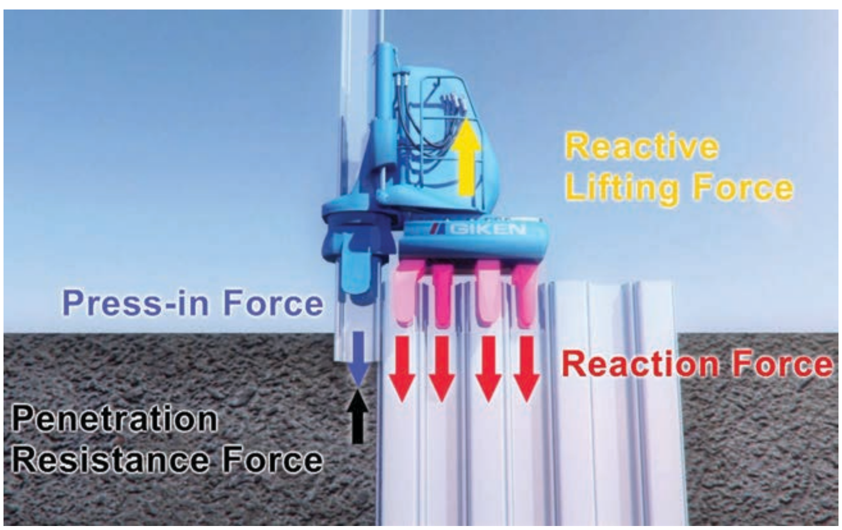


Figure 1

The safety of piling equipment handling is also enhanced since the point of contact between press-in machines and piles near or at ground level and is not suspended at a high elevation as it would be for the many types of conventional piling equipment.

Advantages and limitations of press-in piling machines

Press-in machines are ideally and commonly utilized on projects with challenges such as with noise and vibration sensitivity or restrictions. In addition to their non-vibratory and minimal noise attributes, press-in piling machines do not require a large footprint since these machines are designed to operate and advance along the top of installed piles. Therefore, press-in machines are also utilized for projects with space or access limitations. Since challenges differ from project to project, it is imperative that the conditions and parameters of challenging project sites are reviewed before a feasibility study is carried out in order to determine which press-in machine type is applicable. In addition to press-in machines being used to install piles for shoring, retaining walls, flood walls, seawalls, etc., press-in machines are also utilized to extract piles in many cases where impact or vibratory hammers alone may not be able to do so.

Although press-in piling machines are useful for the installation of steel sheet and pipe piles on challenging projects, press-in machines are not able to install or extract H-piles, concrete piles or certain sized cold-formed Z-shaped sheet piles. Although few and far between, there are certain sized hot-rolled Z-shaped sheet piles and pipe piles that are not compatible with press-in machines as well.

Basic press-in piling components

Figure 2 shows the basic press-in components of the press-in machine, power pack, pile laser and radio controller. The radio controller allows the machine operator to precisely control the machinery efficiently at a safe position/location. Since press-in machines use highly accurate infrared pile lasers placed 50 to 100 feet away from the location where the press-in machine is operating, conventional lead and driving templates are not required for press-in machines to install sheet and pipe piles.

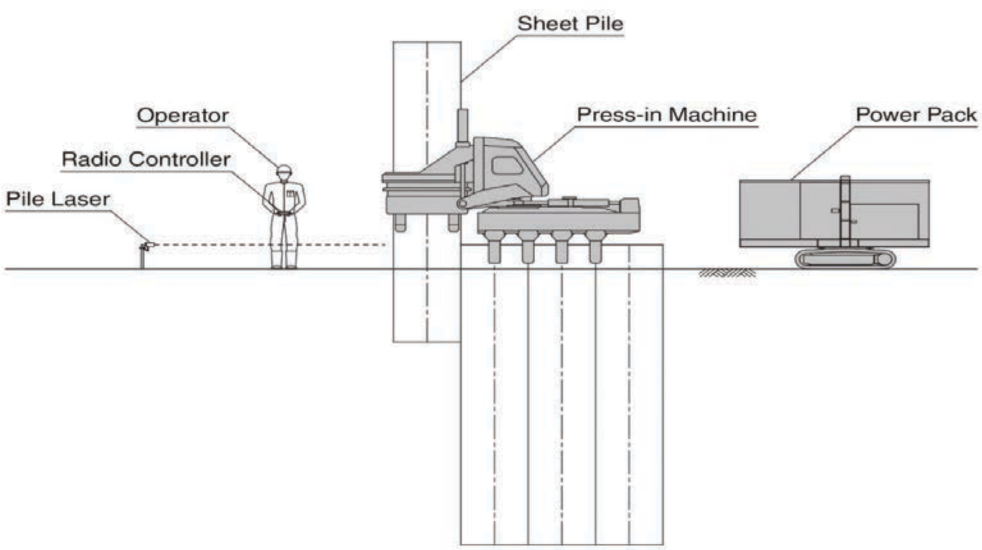


Figure 2

Non-vibratory pile installation with low noise

With the imperceptible vibration and minimal noise characteristics of press-in machines, the next two graphs will illustrate how low their levels typically are in comparison with conventional pile driving equipment. Figure 3 shows a comparison of ground vibration measurements among press-in piling, vibratory hammer piling and diesel hammer piling at *Site 2* (Site 1 was press-in piling only) where Peak Particle Velocity output for the press-in machine was between 0.3 and 0.7 mm/s (0.01 – 0.03 in/sec) from 7.15 meters (23.5 feet) away from the pile alignment (White et al, 2002).

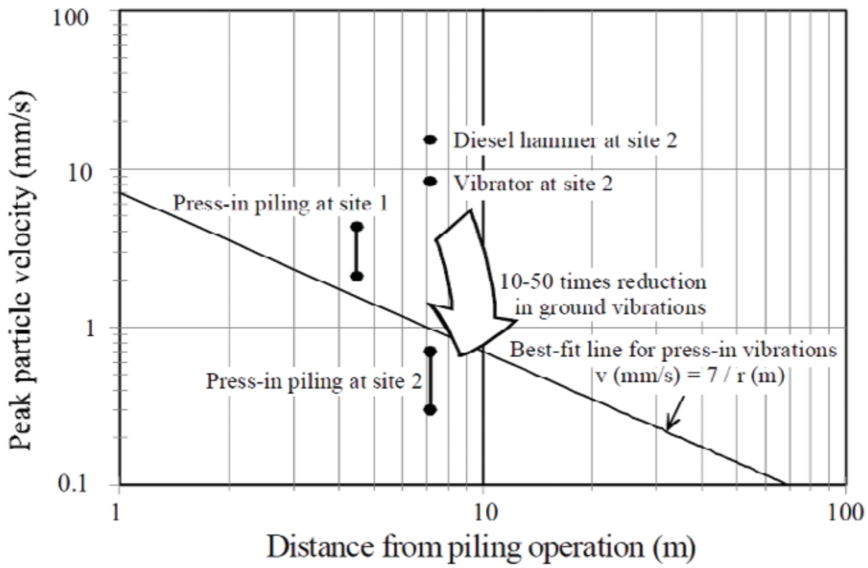


Figure 3

Figure 4 below displays noise data for a double acting diesel/air hammer, hydraulic drop hammer, enclosed drop hammer and a press-in machine (referred to as *Silent Piler*) within the graph. The graph shows that the *Silent Piler* does not exceed the rural noise limit of 70 dB at a distance of two meters (White et al, 2002).

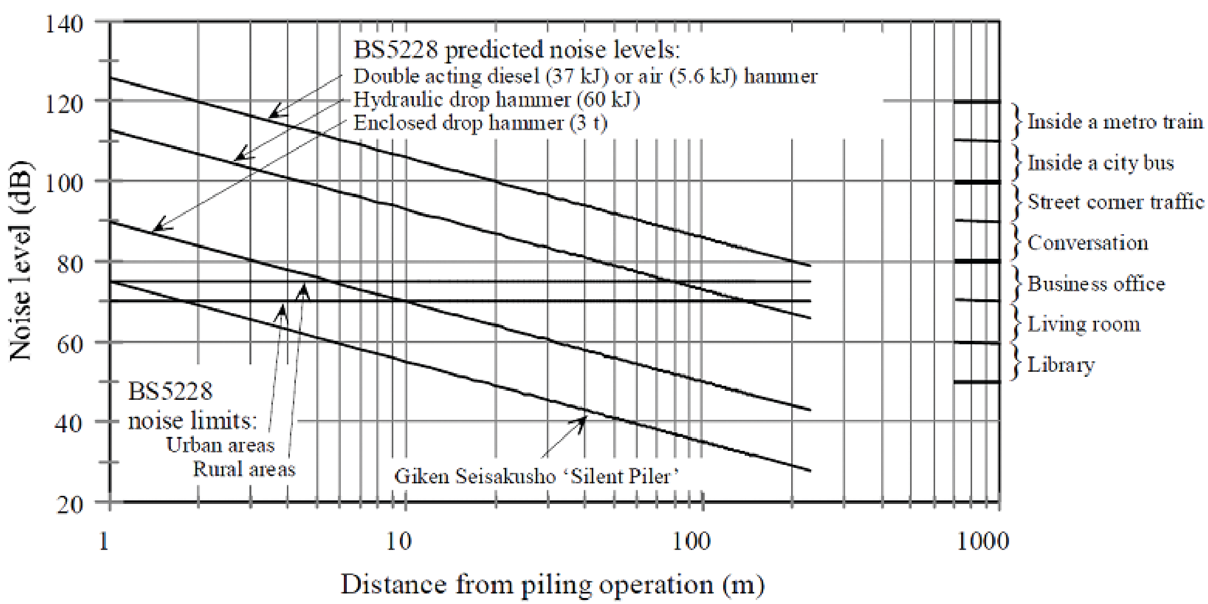


Figure 4

Capability to install piles in various soil conditions

Press-in piling machines utilize certain techniques to assist press-in machines in installing sheet and pipe piles into various types of ground conditions that range in various densities and depths. These techniques include:

- Standard press-in
- Press-in with water jetting
- Press-in with simultaneous augering
- Press-in with rotary cutting

Standard press-in piling is the press-in installation of piles without the need of the aforementioned water jetting, simultaneous augering or rotary cutting systems. In terms of steel sheet piles, standard press-in installation is typically performed where SPT N value is $N < 25$. For pipe pile installation, standard press-in installation is typically performed where SPT N value is $N < 15$.

Water jetting systems are designed to temporarily break up soil composition by loosening granular soils or lubricating cohesive soils with high pressured water to allow smoother pile installation into the ground. The image on the left in Figure 5 shows a press-in machine utilizing its water jetting system, which can be seen within the red circle as the reel affixed to the top of the machine. A water pump providing high pressured water would be nearby. The image on the right in Figure 5 illustrates what the operation would look like underground.

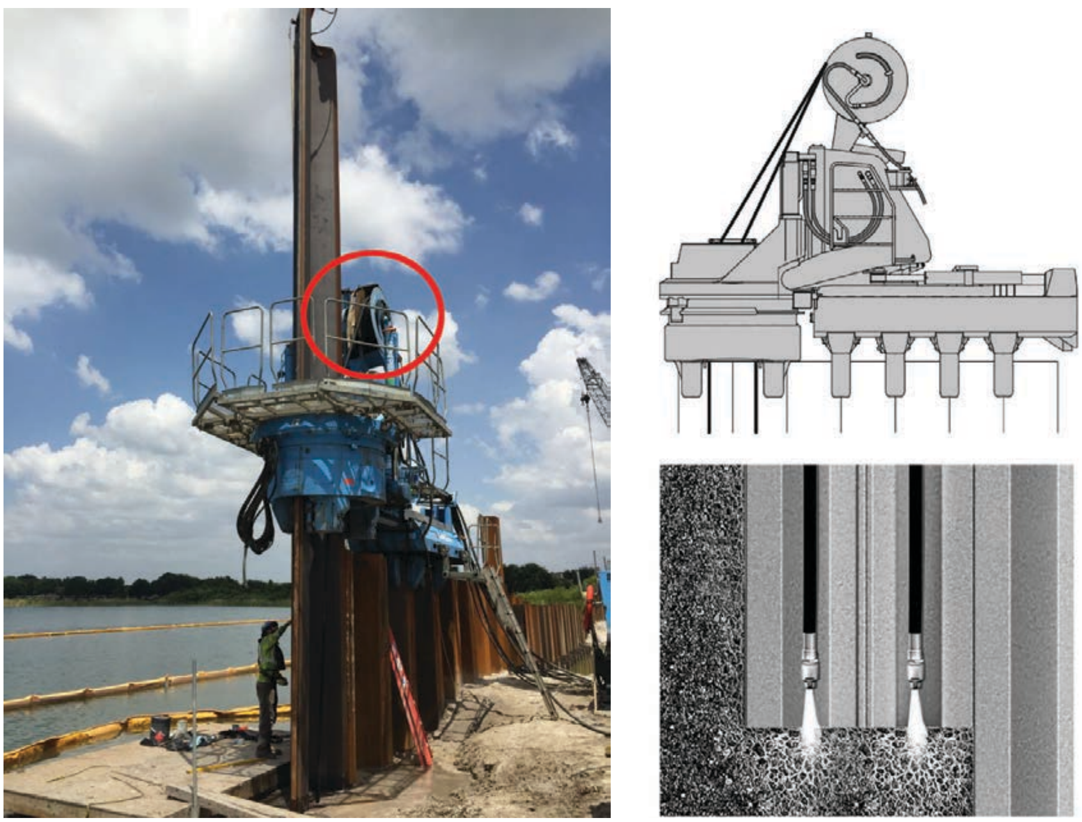


Figure 5

These systems are generally used for sandy soils or soils consisting of silty, clayey or gravelly dense sand where the SPT N value is $[25 \le N \le 50]$ for sheet piles and $[15 \le N \le 50]$ for pipe piles. In soils with this type of density and composition, the pile toe and interlock resistance can increase due to the consolidation of soil particles. By temporarily breaking up the soil composition around the pile toe while upstream water flow reduces skin friction and washes out soil within the pile’s interlocks, water jetting systems for press-in machines can reduce pile toe and interlock resistance, thus reducing resistance and preventing potential damage to the piles being installed.

Simultaneous augering systems for Z-shaped sheet piles like what is shown in Figure 6 are designed to drill ahead of sheet piles while pressing in sheet piles at the same time. The image on the left in Figure 6 shows that the continuous flight auger fits into the web of the sheet pile pair being installed. The image on the right in Figure 6 illustrates what the operation looks like underground.

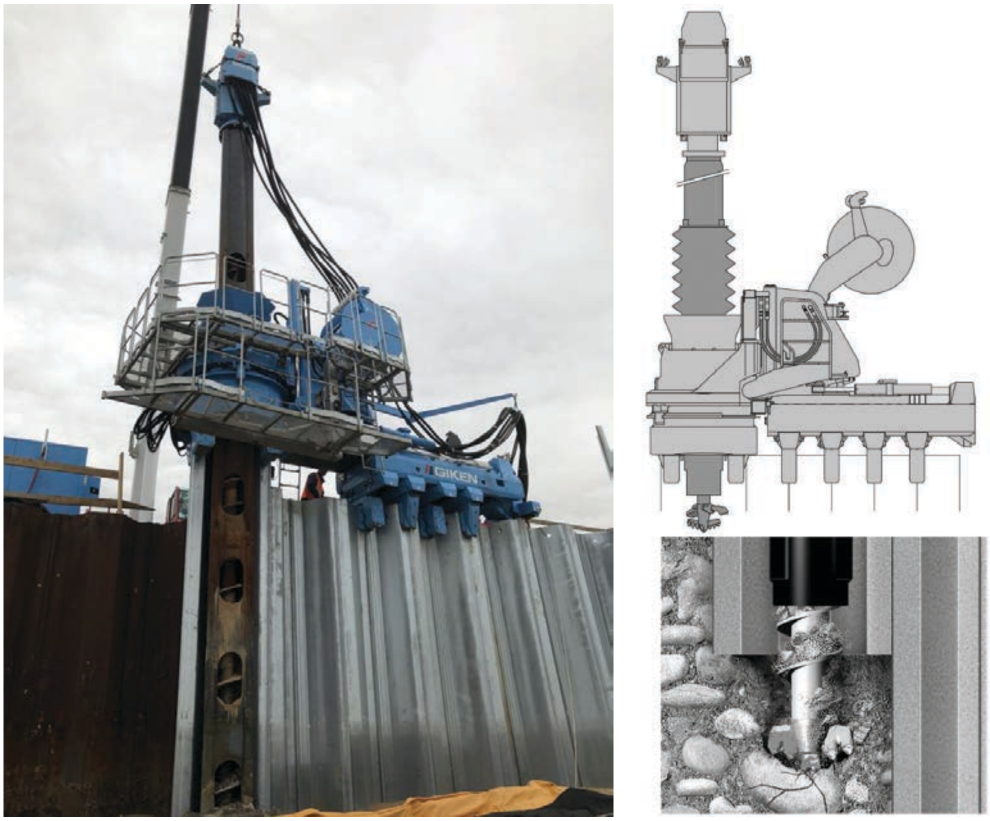


Figure 6

These systems are generally used for stiff cohesive soil, solidified sand/silt, gravels, cobbles, boulders and relatively soft rock/rock layers, etc., where the SPT N value is [$25 \leq N < 300$]. The drilling that takes place just below the toe of the sheet pile pair while the sheet pile pair is being pressed in at the same time prevents a pressure bulb from building up at the pile toe. Different auger head diameter sizes can be utilized depending on the soil conditions and project parameters.

Rotary cutting systems for pipe piles, like what is shown in Figure 7, are designed for pipe piles to core through similar soil and ground conditions as the simultaneous augering system for pressed in sheet piles. This variation of press-in piling for steel pipe piles is designed to rotate and simultaneously press pipe piles into the ground. Sacrificial cutting shoes are welded onto the toes of each pipe pile for faster pile installation into hard soil, rock and even existing concrete (Takuma et al., 2013). The bottom image within Figure 7 illustrates what the operation looks like underground.

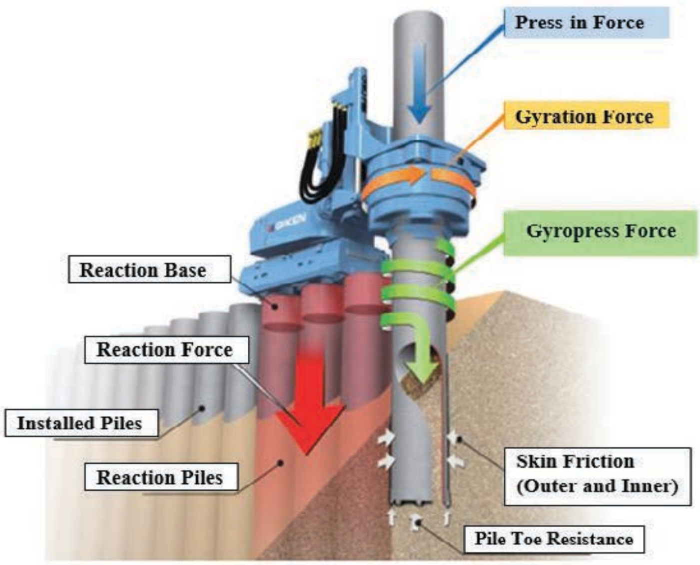


Figure 7

While long interlocking pipe piles can be pressed into dense sand with high pressure water jetting (Takuma et al., 2017), this simultaneous rotation and press-in action helps reduce press-in resistance without loosening the ground for pipe piles without interlocks. For pipe piles without interlocks, angular plates or smaller diameter pipe pile can be pressed in between the primary pipe piles for watertightness.

Capability to install piles with very limited access

In addition to the aforementioned basic press-in piling components, a method known as the non-staging method allows for press-in machines and the equipment needed to carry out pile installation to walk or advance on top of the sheet or pipe piles being installed, which enables the equipment to operate in limited access areas where conventional pile driving equipment cannot reach. Examples of limited access areas include slope embankments or water. Figure 8 shows the equipment designed to advance atop the installed piles to complete the operation which includes the press-in machine itself, a clamp crane, a power unit and a pile runner. The pile runner is designed to bring sheet or pipe piles to the piling operation from a remote access point.

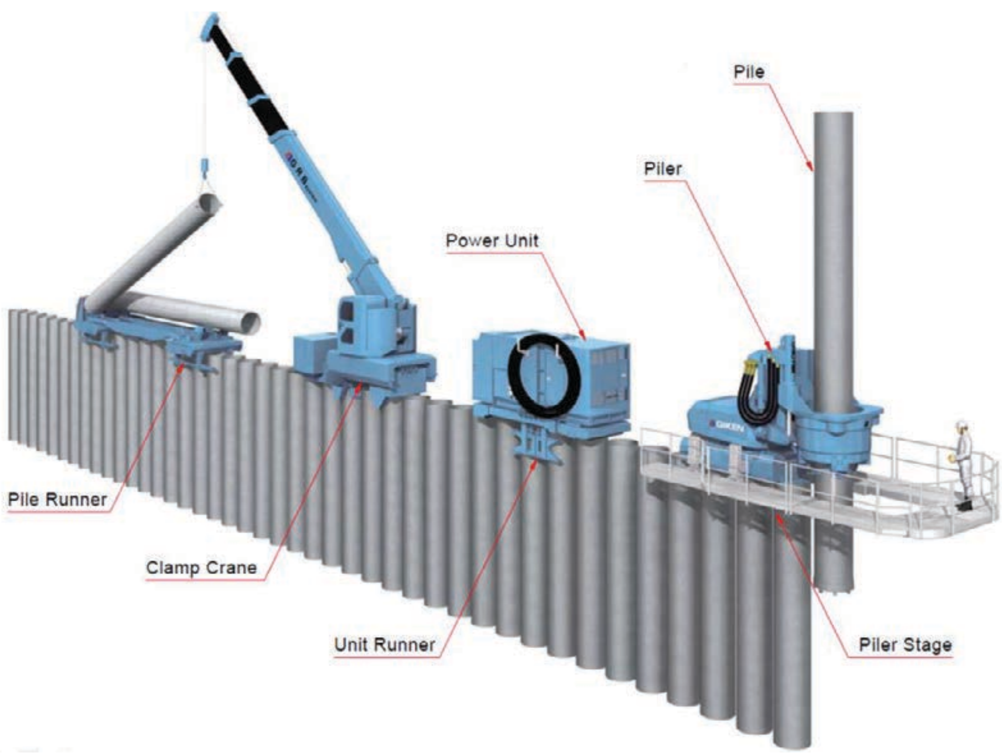


Figure 8

Capability to install piles in low headroom

While there is conventional pile driving equipment that is able to drive piles within limited vertical clearances, press-in machines are also designed for pile installation where vertical access is limited. Figure 9 displays how press-in piling machines are able to install sheet piles within low headroom conditions. Both sheet pile and pipe pile press-in machines can install within 13 feet of headroom, although there are limitations for sheet pile installation within low headroom conditions depending on the density of the soil that the sheet piles will be pressed into.

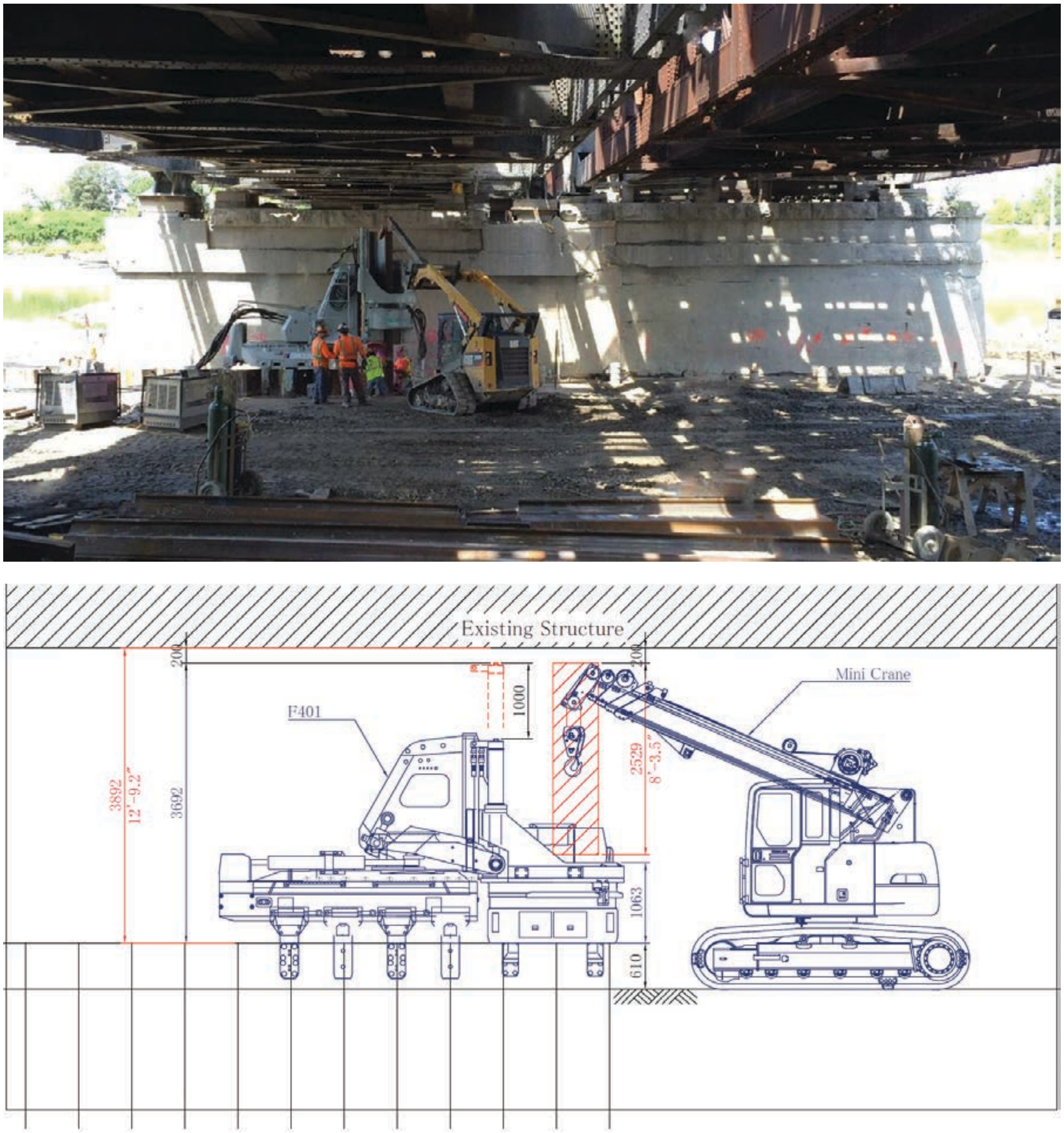


Figure 9

Press-in monitoring system

Another notable advantage of press-in machines is that with each pile pressed into the ground with an electronically controlled static load by using a series of hydraulics, real time conditions, skin friction, toe resistance, penetration depth and operation time of the press-in force can be monitored. These readings can also help determine axial load capacities during press-in pile installation, hence their advantageous use for the installation of vertical load-bearing piles. This monitoring is described through the illustration in Figure 10 below.

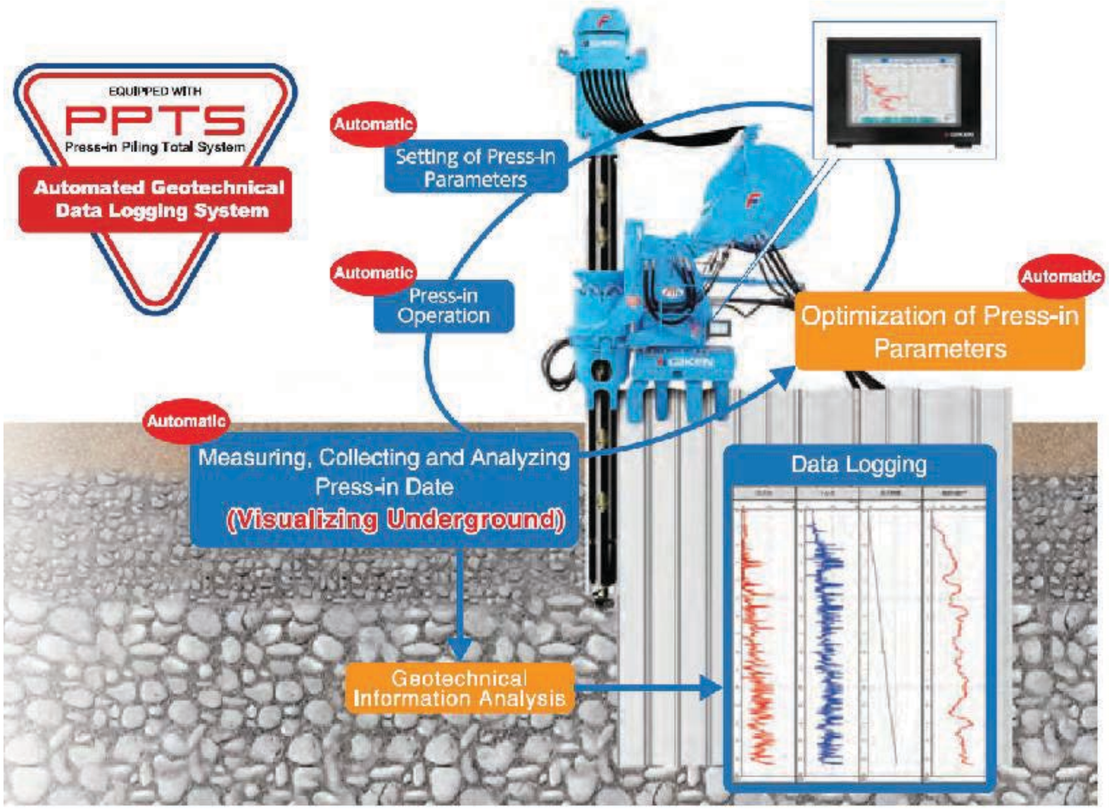


Figure 10

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