

Method of and driver for installing foundation elements in a ground formation

The invention relates to a method of installing a foundation element, in particular a (mono)pile, in a ground formation, such as a river- or seabed, by means of a driver, e.g. a hydraulic hammer, comprising driving the foundation element into the ground formation by means of blows delivered by the driver to the foundation element. The invention further relates to a driver for installing foundation elements comprising a reciprocable impact weight for delivering blows to the foundation element and an operating system configured to set blow energy and blow count of the weight.

In pile driving, an impulse-like force is applied to the top end of the pile by the impact weight of a hammer. The resulting compressive stress wave propagates downwards, towards to the tip of the pile. If resistance at the tip is high, such that the possible motion of the pile tip is close to zero, it will be reflected as a compressive stress wave. If the tip resistance is very low, such that no force can be exerted from the pile to the soil, the reflection will be a tensile stress wave. In practice, the soil resistance will vary between these extremes.

It is an object of the present invention to provide an improved method of pile driving in particular to reduce negative effects on fatigue life and/or to reduce sound emission especially when installing a foundation element in an underwater ground formation.

To this end, the method according to the present invention is characterized by estimating or measuring stress waves that are generated by the blows and reflected from the tip of the pile and, if a reflected stress wave is a tensile stress wave, reducing the blow energy.

During driving, the pile is continuously loaded with alternating compressive and tensile stresses. This causes lateral vibrations of the outer surface of the pile in turn resulting in the emission of sound pressure. It also has a negative effect on the fatigue life of the pile, as the fluctuation of compressive and especially tensile stresses accelerate the growth of voids and micro cracks in the material of the pile. With the method according to the present invention the blow energy is reduced or ideally minimized, preferably such that the pile penetration per blow is reduced to a value where the reflected tensile stress is substantially dissipated by the surrounding soil during its upward propagation, towards the top. In quantitative terms, the reflected stress wave, e.g. in terms of strain, is preferably less than 5%, preferably less than 2% of the stress wave resulting from the same blow. Thus, the reflected wave has no or a limited effect on fatigue life and sound emission is further reduced. Other parameters that may serve as an indicator of reflective waves include (but are not limited to) sound or (other) vibrations measured at a predetermined distance from the pile and so-called "quake", i.e. the elastic component of pile penetration.

In another embodiment, in addition to reducing blow energy, blow count, which conventionally is in a range from 20 to 30 blows per 0,25 meter penetration, is increased, preferably to at least 60, e.g. to at least 70, e.g. to at least 80 blows per 0,25 meter penetration. Thus, if the reduced blow energy results in a lengthening of the time needed to complete pile driving, at least part of this lengthening is compensated. It is preferred that the energy delivered per 0,25 meter penetration is (incrementally) changed, typically reduced, by a total of 30%, preferably 20% or less.

In a particularly efficient embodiment, the strain in the pile is estimated from penetration of the pile resulting from a single blow, e.g. from earlier measurements or from the speed of sound in the pile (~5200 m/s in a steel pile), duration of the blow, surface area of the cross-section, and the fatigue endurance limit (e.g. 120 MPa).

Another embodiment comprises the step of measuring at least one of strain in the pile, acceleration, velocity or penetration (change in position) of the pile resulting from a blow. In particularly accurate embodiment, both penetration of and the strain in the pile are measured after substantially every blow. In another embodiment, said measuring is performed on a part of the pile that extends above the ground formation.

A further embodiment comprises establishing, e.g. for a specific ground formation or area, at least one blow energy and/or blow count where substantially no tensile wave is measured in driving a first pile and employing that blow energy and/or blow count to drive one or more further piles. Thus, the further pile in principle does not require equipment to carry out such measurements.

The invention also relates to a pile driver comprising a reciprocable impact weight for delivering blows to a foundation element and an operating system configured to set blow energy and blow count of the weight. The operating system is configured to estimate or measure the stress waves that are generated by the blows and reflected from the tip of the pile and, if the reflected stress wave is a tensile stress wave, reduce the blow energy.

In an embodiment, the operating system is configured to reduce the blow energy until substantially no reflected tensile wave is measured.

In another embodiment, the operating system is configured to, in addition to reducing blow energy, increase blow count. It is preferred that the energy delivered per

0,25 meter penetration is (incrementally) changed, typically reduced, by a total of 30%, preferably 20% or less.

The invention will now be explained in more detail with reference to the Figures, which show a preferred
5 embodiment of the present method and pile driver.

Figure 1 is a cross-section of a pile driver according to the present invention.

Figures 2 to 4 are diagrams of suitable modes of operating of carrying out the invention.

10 It is noted that the Figures are schematic in nature and that details, which are not necessary for understanding the present invention, may have been omitted.

Figure 1 shows an embodiment of a pile driver 1 according to the present invention, which comprises an
15 impact weight 2, a hydraulic cylinder 3, a piston 4 reciprocatingly accommodated in the hydraulic cylinder 3 and connected to or forming an integral part of the impact weight 2, high- and low-pressure accumulators 5, 6, and first and second valves 7, 8 for alternately connecting the
20 cylinder space beneath the piston 4 of the hydraulic cylinder 3 to the high and low-pressure accumulators 5, 6. The system further comprises a tank 9 for a hydraulic medium, such as hydraulic oil, a feed pump 10 for pressurizing the hydraulic medium connected via the high
25 pressure accumulator 5 and the first valve 7 to the hydraulic cylinder 3 and a gas spring or "cap" 11 above the piston 4.

When the first valve 7 is open and the second valve 8 is closed, the high-pressure accumulator 5 communicates
30 with the cylinder space beneath the piston 4 and the piston and impact weight 2 are lifted by the hydraulic medium against the action of the gas spring 11. When the first valve 7 is closed and the second valve 8 is opened, the hydraulic medium flows to the low-pressure accumulator 6 and
35 the tank 9 and the impact weight is accelerated by gravity

and the gas spring to deliver a blow to the pile. The pile driver 1 further comprises a sleeve 14 to position the driver onto an pile and an operating system 15 configured to set blow energy and blow count of the weight. Suitable commercially available hammer include IHC Hydrohammer S-class.

The pile driver 1 shown in Figure 1 is positioned on top of a monopile 16, by means of the sleeve 14 and an anvil 17, and comprises a position sensor 18, e.g. a GPS sensor or an air pressure sensor, mounted on the pile driver 1 and a strain sensor 19, e.g. a strain gauge, attached to the monopile 16.

For a given combination of hammer, anvil and ram, the force exerted by the impact weight on the pile is controlled by the impact speed. The blow energy is calculated from the measured impact speed (just before impact) and the mass of the ram.

The operating system 15 is configured to measure, by means of the sensors 18, 19, the penetration of the pile after each blow and the stress wave that is reflected from the tip of the pile.

Figure 2 is diagram of the operating system, which shows that the values measured by the strain gauge and position sensor are used as feedback for the setting of the blow energy. References are e.g. $s_{pile} > 0.0025 \text{ m}$ and $\bullet_{reflection} \bullet < 0$. After an estimated initial blow energy setting, the blow energy is adjusted to a setting where the pile penetration is sufficient with small reflected stresses.

This is a most effective set-up, as the actual strain and pile set is measured after every blow. The blow energy thus can be adjusted every blow, resulting in a piling process with minimal stress amplitude and lateral pile wall vibrations.

The position sensor is mounted on the hammer and thus can be used for multiple piles. The strain sensor is

preferably mounted on the pile and, in that case, can be used only once.

In a further example, shown in Figure 3, the values measured by the position sensor are compared to an empirically set reference values, without the need for a strain sensor. The reference values provide to the operating system or the operator a maximal pile set per blow, as a higher value could risk reflected tensile stresses. This method is suited e.g. for projects with many piles and consistent soil conditions and where it is sufficient to equip only one or a few piles with strain gauges.

In a further example, shown in Figure 4, the blow count is compared to an empirically set reference value, e.g. 125 blows per 0,25 m. The blow count is measured by counting the number of blows between two marking lines on the pile. It is standard procedure to record the blow count during pile driving, so this method can be implemented at virtually no extra costs. As with the previous alternative, Figure 3, this method is suited for projects with many piles and consistent soil conditions. The reference value for the blow count can then be checked and corrected using the data from strain gauges and used for the piles in the vicinity.

The invention is not restricted to the embodiment described above and can be varied in numerous ways within the scope of the claims. For instance, if instrumentation is impossible or unavailable, the reference value for the blow count can be set by making calculations using soil investigations, traditional wave equation piling programs and FEM-calculations.

CLAIMS

1. Method of installing a foundation element, in particular a (mono)pile (16), in a ground formation by means of a driver (1), comprising

driving the foundation element (16) into the ground formation by means of blows delivered by the driver (1) to the foundation element (16), and

characterized by

estimating or measuring stress waves that are generated by the blows and reflected from the tip of the foundation element (16) and, if a reflected stress wave is a tensile stress wave, reducing the blow energy.

2. Method according to claim 1, wherein the blow energy is reduced until substantially no reflected tensile wave is measured.

3. Method according to claim 1 or 2, wherein, in addition to reducing blow energy, blow count is increased, preferably to at least 60 blows per 0,25 meter penetration.

4. Method according to any one of the preceding claims, wherein the energy delivered per 0,25 meter penetration is changed by 30% or less.

5. Method according to any one of the preceding claims, comprising the step of measuring at least one of strain in the foundation element (16), acceleration, velocity or penetration of the foundation element (16) resulting from a blow.

6. Method according to claim 5, comprising the step of measuring penetration of and the strain in the foundation element (16) after substantially every blow.

7. Method according to any one of the preceding claims, wherein said measuring is performed on a part of the foundation element (16) that extends above the ground formation.

8. Method according to any one of the preceding claims, comprising the step of establishing a blow energy and/or a blow count where substantially no tensile wave is measured in driving a first pile and employing that blow energy and/or blow count to drive one or more further piles.

9. Method according to any one of the preceding claims, wherein the foundation element (16) is driven into an underwater ground formation.

10. Driver (1) for installing foundation elements, in particular (mono)piles (16), in a ground formation, comprising a reciprocable impact weight (2) for delivering blows to the foundation element (16) and an operating system (15) configured to set blow energy and blow count of the weight (2), **characterised in that** the operating system (15) is configured to estimate or measure the stress waves that are generated by the blows and reflected from the tip of the foundation element (16) and, if the reflected stress wave is a tensile stress wave, reduce the blow energy.

11. Driver (1) according to claim 10, wherein the operating system is configured to reduce the blow energy until substantially no reflected tensile wave is measured.

12. Driver (1) according to claim 10 or 11, wherein the operating system is configured to, in addition to reducing blow energy, increase blow count.

13. Driver (1) according to any one of claims 10-12, wherein the energy delivered per 0,25 meter penetration is changed by 30% or less.

14. Driver (1) according to any one of claims 10-13, wherein the operating system is configured to measure at least one of strain in the foundation element (16), acceleration, velocity or penetration of the foundation element (16) resulting from a blow.

15. Driver (1) according to any one of claims 10-14, comprising a sensor (18) for measuring penetration of the foundation element (16) and a sensor (19) for measuring

the strain in the foundation element (16), the latter preferably mounted on a part of the pile that extends above the ground formation, preferably at or near the top end of the pile.