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Dynamic measurements of pile deflections as a source of underwater sound emissions during impact driving of offshore pile foundations

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ABSTRACT

Open ended tubular steel piles are used as a state of the art technique for the foundations of offshore wind turbines (OWT). The commonly used means of installation, impact driving, results in massive sound emissions into the seawater and the subsoil which are harmful for marine life. Current research carried out at the Institute for Soil Mechanics and Foundation Engineering of the Technische Universität Braunschweig covers wave propagation in and between driven piles, subsoil and water. This paper focuses on the properties and the propagation of the elastic waves through an impact driven monopile during its installation and the mechanisms of noise induction into water and subsoil. Within the scope of a research project funded by the German federal government measurements have been carried out during the erection of large diameter monopiles for an offshore wind farm (OWF) in the German North Sea. Axial and tangential strains as well as axial and radial accelerations along the length of the piles will be evaluated concerning the noise generating interactions between pile and water and pile and soil respectively.

Keywords: offshore wind farm, pile driving monitoring, hydro sound
I-INCE Classification of Subjects Number(s): 12.2.3, 14.5.4, 43.2.4, 54.3

1. INTRODUCTION

For the foundations of offshore wind turbines the installation of impact driven open ended steel pipe piles is the most common technique to realize a construction able to withstand impacts from wind, wave and current by transferring them to the subsoil. Due to a high amount of necessary driving energy impact driving leads to high noise emissions and ground vibration effects which can be harmful to marine life.

To understand the mechanisms taking place within the impact driving pile which lead to the hydrosound and ground vibration phenomena, the Institute for Soil Mechanics and Foundation Engineering of Technische Universität Braunschweig is undertaking a pile driving monitoring within a research project (short-term: triad) funded by the German Government.

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2. RESEARCH PROJECT 'triad'

2.1 Used offshore project OWF Amrumbank West

The project management organization is the E.ON Kraftwerke GmbH. The wind farm area is approximately 32 m^2, with water depths between 19.5 m and 23.6 m regarding LAT and is located north of Helgoland, 40 km away from the coastline, in the German Exclusive Economic Zone of the German North Sea.

The wind farm consists of 80 wind turbines of the 3.6 MW-class with an overall performance of 288 MW. The turbine constructions are founded on monopiles with a length between 53 m and 63 m, which have an embedded length between 27 m and 38 m. The diameter of all piles ranges from 5.2 m at the top to 6 m at the pile toe. The connection of the foundation to the tower is realized with a transition piece, which is connected to the monopile through a flange connection.

The monopiles are installed using the impact pile driving technique. To reduce noise emissions into the water by means of hydrosound and protect marine fauna, two different noise mitigation systems (NMS) are used during the installation of the monopiles, the hydrosound dampers (HSD) and the big bubble curtain (BBC).

2.2 Scope of research project

The 'OWF Amrumbank West' is one of the first OWF where two different NMSs are used in combination. Hence, the effectiveness of the two different systems plus their combined mode of operation is subject to investigation within this research project. In addition, analyses of the wave propagation in the water and the subsoil due to impact pile driving shall be derived from the recorded data (see Figure 1).

To realize these ambitious tasks, hydrosound and ground vibration measurements are executed from the installation vessel and from a separately operating measuring vessel. Furthermore, the monopile itself has been instrumented with several measuring devices to analyze the wave propagation through the pile which causes the hydrosound and ground vibration effects. With the time synchronization of the different measuring devices, conclusions about runtimes of the waves in water and soil can be derived. Additionally, the effects of strain and acceleration effects of the pile itself due to impact driving can be set into correlation with the characteristics of hydrosound and ground vibration phenomena.

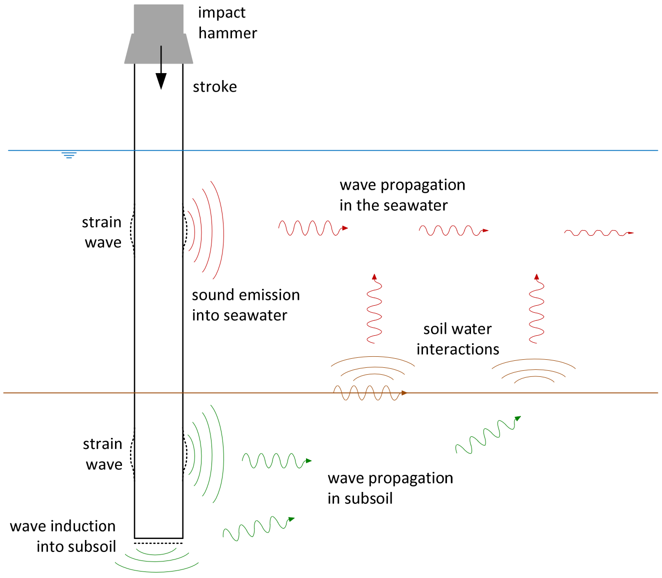

Figure 1 – Interrelations of strain wave, hydrosound and ground vibration

3. THEORY & BACKGROUND

An impact to an offshore monopile induces a force F and a particle velocity v at the top of the foundation (Figure 2.1). This causes a compression wave propagating along the pile in axial direction (Figure 2.2-2.4) with the speed c_p which is a function of the modulus of elasticity E and mass density ρ:

$$c_p = \sqrt{\frac{E}{\rho}} \tag{1}$$

On the basis of poisons contraction the compression wave causes an associated radial expansion of the pile by the increase of radius (1). The compressional wave propagates downwards to the bottom and pushes the pile into the ground (Figure 2.5). Depending on the resistance a tension or compression wave will be reflected at the pile toe. For the first blows a low resistance can be assumed and a tension wave propagates to the top of the pile (Figure 2.6-2.8). In this case an associated reduction of the radius occurs.

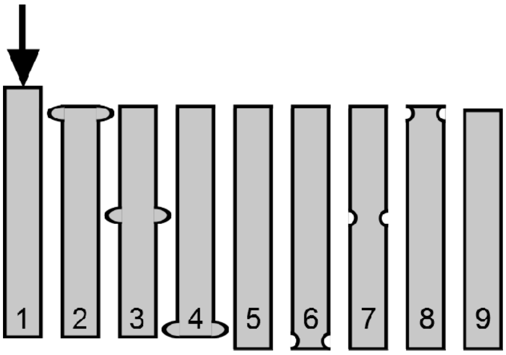

Figure 2 – Simplified model of wave propagation in a monopile with low resistance

The increase of radius during the compression phase of the impact produces an underwater pressure field in the water (Figure 3a). Due to the wave speed in water c_w this field propagates downwards forming a conical wave, also referred to as 'Mach waves' (2). The angle φ of the cone is defined as:

$$\sin\varphi = \frac{c_p}{c_w} \tag{2}$$

The up travelling tension wave and the decreasing radius induce a pressure wave in the water similar to the compression phase, with the shape of an uprising cone (Figure 3b).

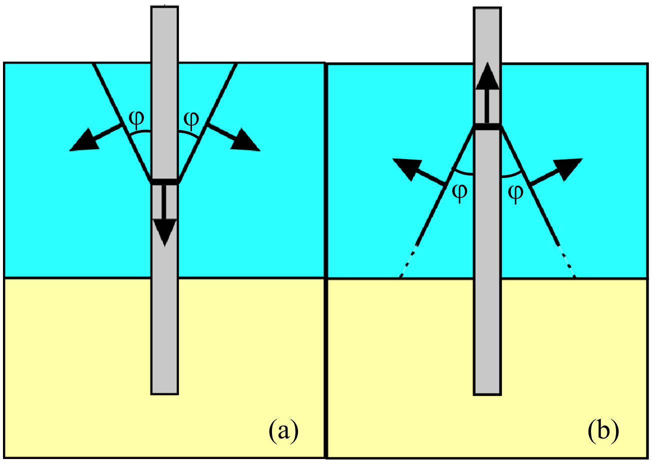

Figure 3 – Hydro sound propagation caused by
a) compression wave, b) tension wave

4. REALIZATION OF PILE DRIVING MONITORING

4.1 Measuring setup

During the research project one measuring campaign has already been carried out. Besides hydro sound and ground vibration measurements for all three piles of that installation load, one pile has been instrumented with several measuring devices. The properties of that pile are given in table 1.

Table 1 - Pile properties of instrumented pile

Length [m]	54.8
Diameter at top [m]	5.2
Diameter at bottom [m]	6.0
Wall thickness [mm]	60.0 - 75.0
Water depth [m LAT]	28.0
Embedded length [m]	29.5

The wave propagation through the pile in axial direction due to impact driving and its effect on acceleration and strain phenomena in lateral direction is accounted for the emission of sound waves into the water and the subsoil. Hence, a self-governed pile driving monitoring has been installed within the pile to carry out acceleration measurements in axial and radial direction as well as strain measurements in axial and tangential direction, both in several measuring sections (MS). Figure 4 shows a scheme of the measuring sections along the inner pile shaft of the pile. As can be seen, the measuring sections 1 and 2 remain above seabed level, while MS 3, 4 and 5 would penetrate into the ground during the pile installation. Hence, besides water tightness for all sensors, the sensors at MS 3, 4 and 5 including the main cables had to be protected from mechanical impacts by the soil, while penetrating the open ended steel pipe pile into the ground.

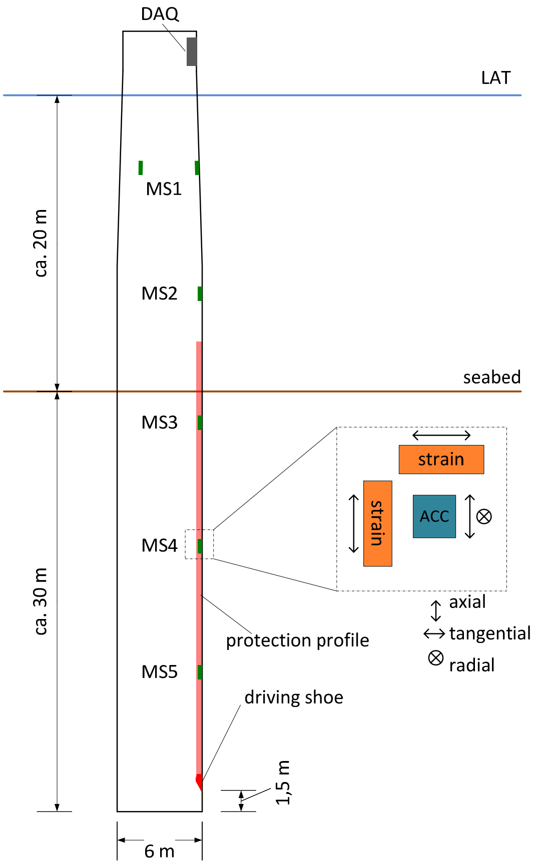

Figure 4 – Mounted strain and acceleration sensors

In table 2 the positions of the measuring sections along the inner pile shaft are shown. All values describe the distance of the MS to the pile top. The MS were supposed to be equally spread along the pile length while keeping a distance of 1.5 x diameter to the ends. Differences of the gaps between single MS result from modifications of the cables lengths to avoid measuring devices to be applied on cross-sectional jumps or welded joints of the cylindrical pipe sections.

Table 2 - Position of MSs

MS 1 [m]	9.60
MS 2 [m]	18.45
MS 3 [m]	27.50
MS 4 [m]	36.15
MS 5 [m]	45.00

As can be seen in the zoomed cutout of MS 4, every measuring section consists of two strain gauges and one tri-axial accelerometer. Both sensor types are needed to determine the properties of the elastic waves which run through the pile due to impact driving. For pile driving analyzes, these waves need to be characterized by means of their force and velocity propagations in axial direction. From deformation measures the force can be easily derived using the elasticity and cross section of the steel. The velocity will be calculated from the acceleration data by integration.

Regarding the noise emission due to pile driving, the deformation and acceleration of the pile in tangential and radial direction are of importance. Hence, one strain gauge is applied horizontally while the tri-axial acceleration sensor is able to measure in axial and radial direction.

4.2 Sensor application

All sensors were applied in advance to the measuring campaign while the pile was located at the project storage harbour in Cuxhaven. While the pile was stored in a horizontal position, the application works could be performed on the inner bottom of the pile. These works included the mounting of the strain gauges and the tri-axial acceleration sensors, measuring cables, protection plates and a driving shoe.

The work was done from the bottom up to the top by mounting the measuring devices and leading the cables upwards passing higher MS. To protect the cables and sensors from mechanical impacts within the embedded length of the pile, trapezoidal protection plates of steel were mounted to the inner shaft covering the MS and cables. The lower most protection plate was closed with a driving shoe of greater dimensions than the plates within the self-penetrating area of the pile. Thus, the necessary volume for the measuring devices including the protection plates was generated prior to the generation of high soil stresses due to the pile driving process. The following Figure 5 shows a zoomed view to one of the MS after application of the measuring devices to the cleaned steel surface of the inner pile shaft. The orientation of the strain gauges in axial and tangential direction as well as the mounted tri-axial acceleration sensor can be seen. The strain gauges are fixed to a thin metal ground plate which is then applied to the steel using a spot welding technique. The mounting of the acceleration sensor is done with the commonly usage of a thin layer of a non-elastic adhesive.

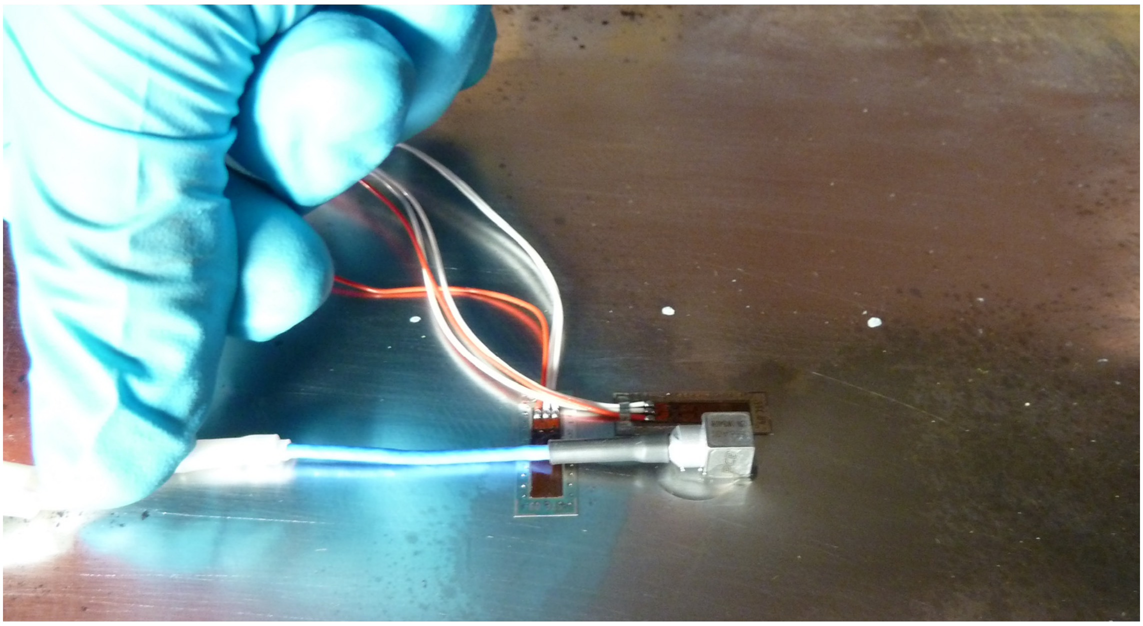

Figure 5 – Mounted strain and acceleration sensors

4.3 Data acquisition unit

It was neither possible to lead measuring cables from the pile to the installation vessel nor to use wireless data transfer from the inner side of the pile. Thus, an autarkic, automatically measuring system had to be attached to the inner shaft of the pile. Because the recording had to be started prior to the upending of the pile, the power supply for the DAQ had to be guaranteed for a minimum of 12 hours to ensure a recording of the whole pile installation process. These needs for some amount of batteries within the DAQ and measuring components to be able to measure up to 32 channels with a sample rate of 10 kHz each leading to an overall weight of the DAQ-containing box of more than 30 kg. Since no measuring component is able to withstand the high accelerations occurring during the pile driving of large diameter monopiles, the box had to be supported elastically.

This challenge was mastered by using elastic rubber bands to hang up the box within four suspension brackets above and beneath the box. By this, the high accelerations due to the pile driving were damped to an acceptable level, which every measuring component of the box could withstand. The following Figure 6 shows a laboratory picture of the box elastically suspended within the suspension brackets.

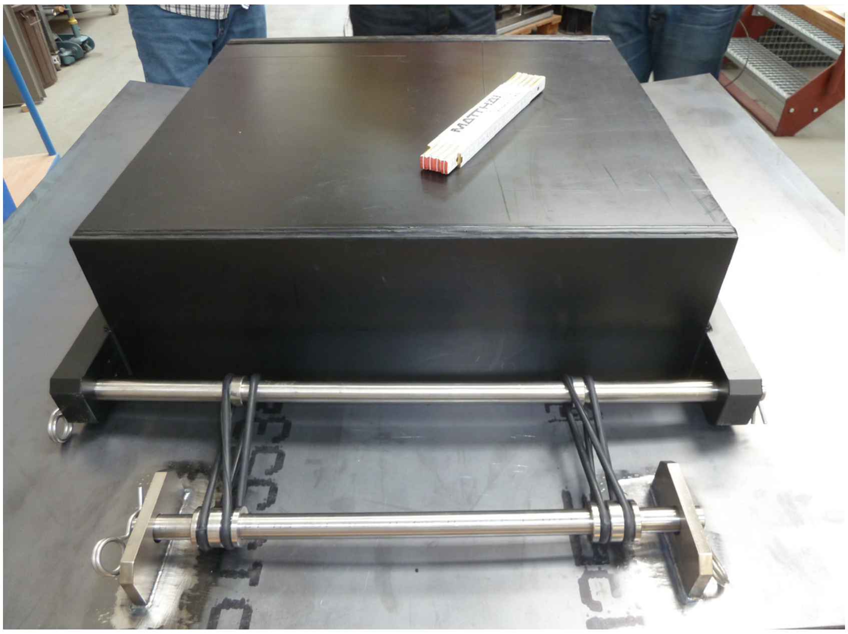

Figure 6 – Elastically suspended box

5. RESULTS OF MEASUREMENTS

5.1 Development of strains

The strain measurement during one blow of pile driving is shown in Figure 7. The axial strain at MS 1 (red dot) shows a compression due to the stress wave travelling from the top of the pile to MS 1 with a maximum compressive strain of 240 µm/m. On its way to the bottom of the pile the amplitude of the compression wave decreases and it is reflected as a tension wave at the bottom with a maximum tensile strain at MS 1 of 140 µm/m. Local peaks in the time series indicating reflections of the wave based on the change of wall thickness.

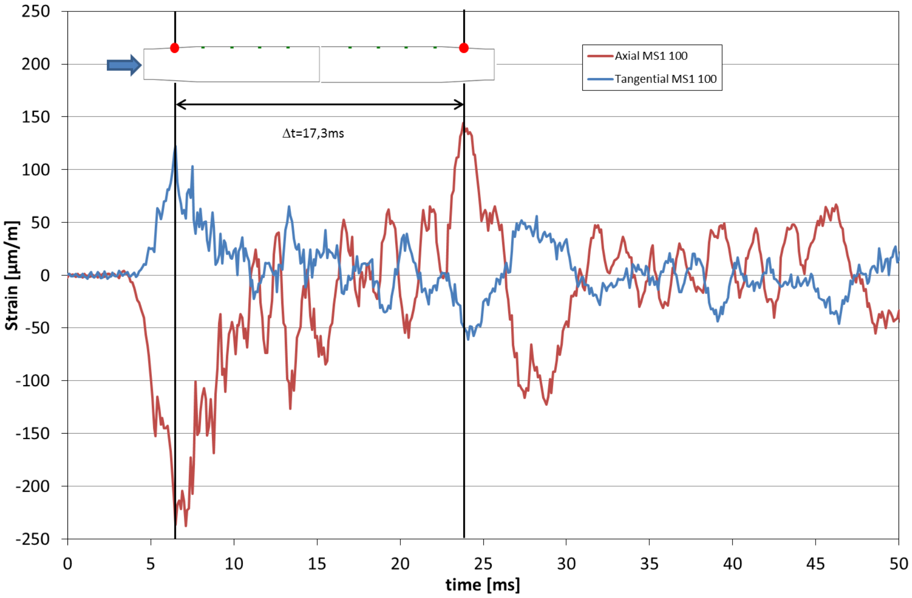

Figure 7 – Axial and tangential strain at MS 1 – blow 100

The runtime of the wave from MS 1 to the bottom and back to MS 1 was measured with 17.3 milliseconds. With this runtime and the theoretical wave speed in steel of 5122 m/s (3) twice the distance between MS 1 and the bottom of the pile can be calculated only with an error of 1.8 %, which is due to a few centimeters of measurement uncertainty after application of the sensors to the corresponding depths.

The blue line shows the tangential strain measurement at MS 1. As can be seen, there is a tension in the tangential strain caused by a radius enlargement (124 µm/m) during the axial compression. The reflected wave causes a reduction of the radius (59 µm/m) at MS 1.

The developing axial strains at MS 1 (yellow), MS 2 (orange) and MS 5 (blue) are shown in Figure 8 while pile driving. The axial strains at all MSs increase during piling – just as the blow number – caused by increasing hammer energy. The runtimes of the waves – from MS x to the bottom and back to the MS x – of blow 10 are shown in table 3. The measurement uncertainty of travel times is between one and three percent.

Table 3 – travel times of blow 10

MS	distance [m]	$\text{time}_{\text{theo}}$ [ms]	$\text{time}_{\text{meas}}$ [ms]	error [%]
1-B-1	90.4	17.65	17.33	1.8
2-B-2	72.7	14.19	13.78	2.9
3-B-3	19.6	3.83	3.78	1.3

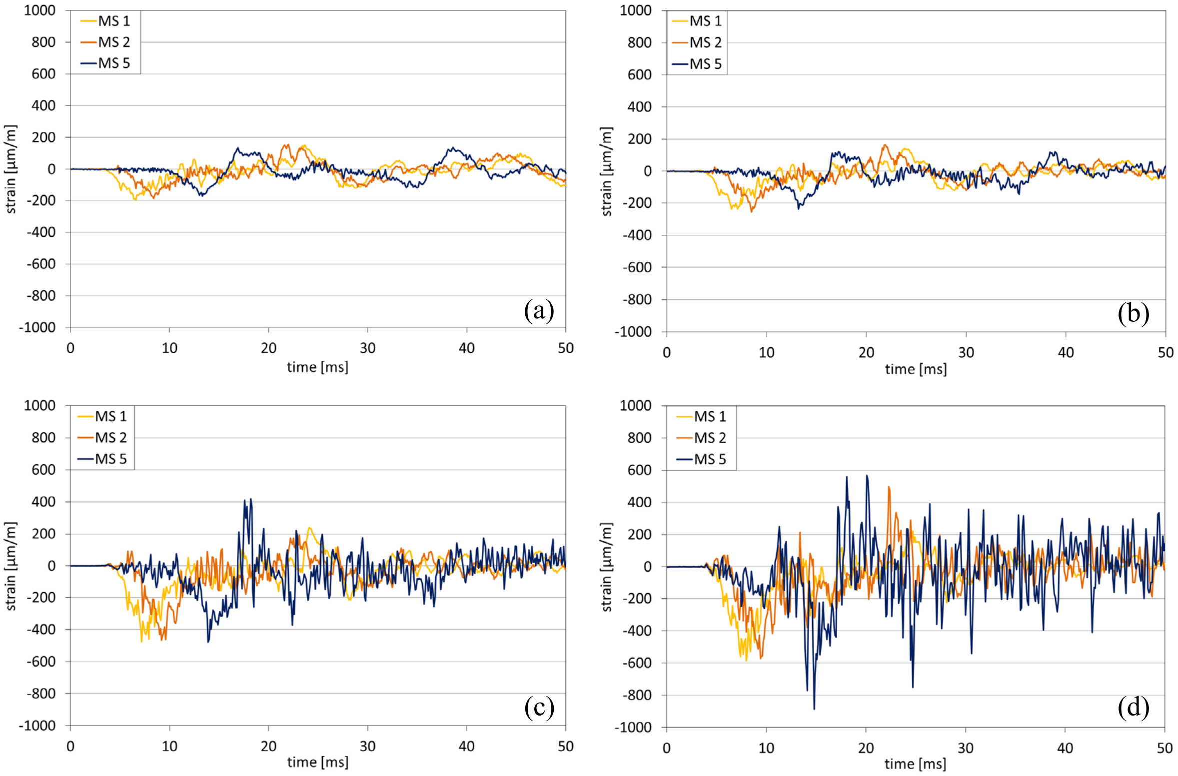

Figure 8 – axial strain of MS 1, MS 2 and MS 5
at blow 10 (a), blow 100 (b), blow 1000 (c) and blow 2000 (d)

The following Figures 9a to 9c show the time series of axial strains at MS 1, MS 2 and MS 5 from different blows.

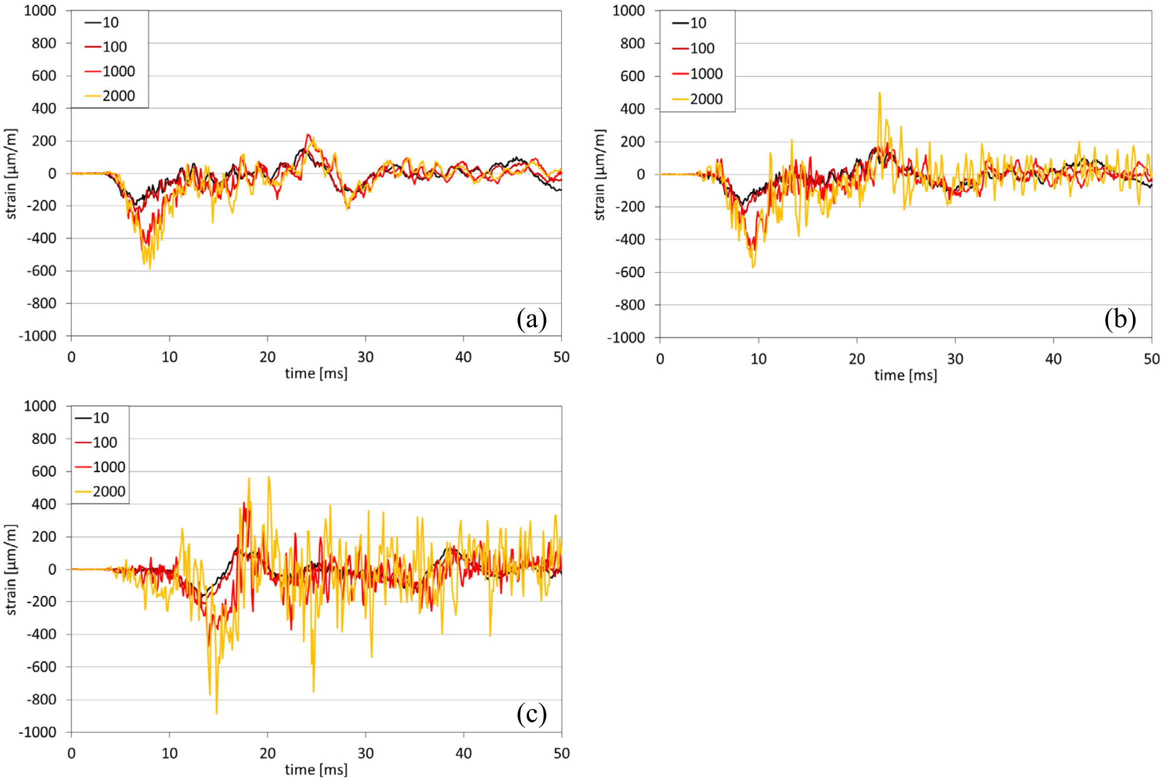

Figure 9 – axial strain of blow 10, 100, 1000 and 2000
at MS 1 (a), MS 2 (b), MS 5 (c)

5.2 Development of radial accelerations

An example of the acceleration measurements is presented in Figure 10. The moving average over 10 samples of the maximum radial accelerations at different MSs is shown vs. the pile penetration. For the first part of the piling to about 15.5 m of penetration an increase of the radial accelerations due to increasing hammer energy can be observed for MS 1 to MS 3.

At the second part of the piling, when the hammer energy remains almost constant until final penetration depth, an influence of the ground can be seen with growing penetration. Within the embedded length, the lateral expansion of the pile is reduced by the surrounding soil, which can be seen in the decrease of the radial accelerations of MS 3 and MS 4 after reaching their point of penetration (pop). The pop of the MSs have been identified from the pile driving protocol. MS 4 reaches its pop at a depth of 18.65 m. MS 3 reaches the pop at a depth of 27.3 m. The radial accelerations of MS 4 and MS 3 amount to 800 g at this point. This means a reduction to 80% of the maximum acceleration of about 1000 g (cf. table 4). Due to the early penetration the results of MS 5 are not representative.

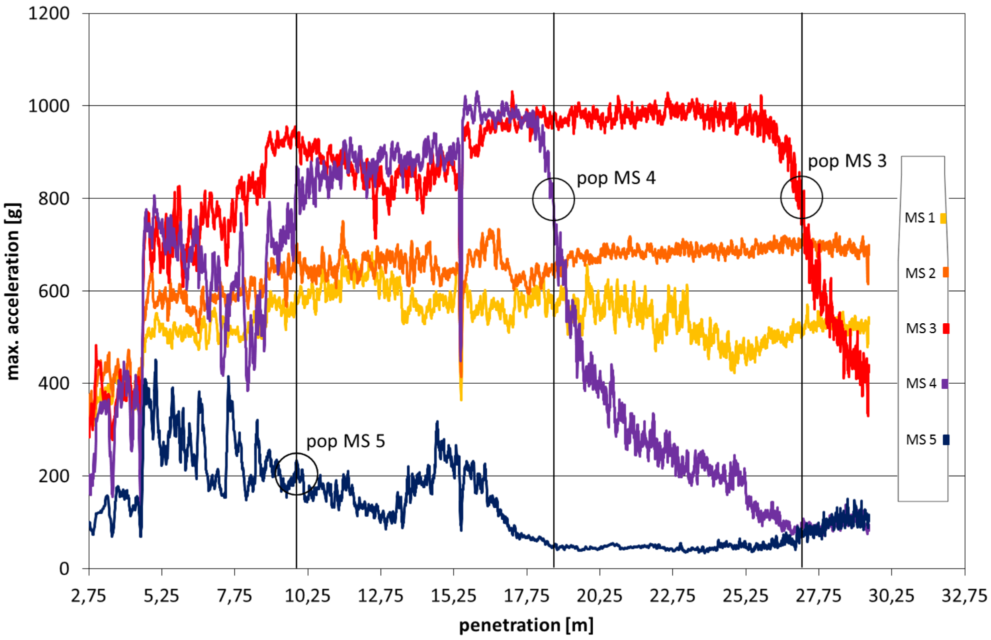

Figure 10 – Maximal radial acceleration

Table 4 – Point of penetration (pop)

MS	point of penetration [m]	max acc$_{rad}$ [g]	acc$_{rad}$ at pop [g]	ratio [-]
5	9.8	451	198	(0.44)
4	18.65	1032	813	0.79
3	27.3	1031	787	0.76

6. SUMMARY

The propagation of waves in tubular steel piles, which lead to the hydrosound and ground vibration phenomena, is investigated as part of the research project 'triad'. A self-governed pile driving monitoring has been installed with acceleration and strain measurement devices within the pile to carry out measurements in several measuring sections. An autarkic, automatically data acquisition system has been attached to the inner shaft of the pile, measuring 32 channels with a sample rate of 10 kHz.

First results of the strain and the acceleration measurements have been presented, showing the influence of the lateral bedding of the soil with increasing penetration. The propagation of waves – axial and tangential deflections – have been measured in accordance to the theory.

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