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A non-collocated method to quantify plastic deformation caused by impact pile driving

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ABSTRACT

The use of bolted connections between the tower and a support structure of an offshore wind turbine has created the need for a method to detect whether a monopile foundation plastically deforms during the installation procedure. Small permanent deformations are undesirable, not only because they can accelerate fatigue of the structure; but also because they can lead to misalignment between the tower and the foundation. Since direct measurements at the pile head are difficult to perform, a method based on non-collocated strain measurements is highly desirable. This paper proposes such a method. First, a physically non-linear one-dimensional model is proposed, which accounts for wave dispersion, effects that are relevant for large-diameter piles currently used by the industry. The proposed model, combined with an energy balance principle, gives an upper bound for the amount of plastic deformation caused by an impact load based on simple strain measurements. This is verified by a lab-scale experiment with a uni-axial stress state. Second, measurement data collected during pile driving of a large-diameter pile show that the proposed one-dimensional model, while able to predict the peak stresses, fails to accurately predict the full time history of the measured stress state. In contrast, an advanced model based on shell membrane theory is able to do that, showing that a bi-axial stress state is needed for these type of structures. This requires an extension of the theory for plasticity quantification presented in this paper.

1. Introduction

Steel monopiles are widely used in the offshore industry as a foundation structure for wind turbines. As a result of the rapid growth of the offshore wind market over the past decades, monopiles now range up to eight meters in diameter in order to support the latest generation of wind turbines [1]. Currently, hydraulic impact hammers are the preferred choice to drive these thin-walled cylindrical structures into the seabed. Each hammer blow generates a compressive stress wave, which propagates down the pile; the latter helps the pile to progress into the seabed. To overcome the increasing soil resistance at greater penetration depths, the input energy of the hammer is increased accordingly. For high energy impacts, the amplitude of the induced stress waves can cause stresses close to the yield limit of the material, increasing the risk of plastic deformations at the pile head.

Until recently, these permanent deformations were of little concern, since the pile head did not contribute to the bearing capacity of the pile due to the use of a grouted connection between the monopile and the superstructure. However, to reduce the cost of offshore wind energy, bolted connections have become more popular in recent years, since they require less steel [1]. This type of connection asks for a perfect alignment between the pile head and the superstructure; and any plastic deformation of the pile head can potentially disturb this delicate alignment. Furthermore, plastic deformation is unfavourable for the remaining service life of the whole structure, since it fatigues the material. A method to infer whether plastic deformation has occurred is therefore needed.

The high stresses generated by a hammer blow can cause damage not only to the pile itself, but also to the sensors, making strain or acceleration measurements directly at the pile head unfeasible during the pile process. A workable method should thus rely on non-collocated measurements, i.e. measurements at another location than where the plastic deformation occurs. Fortunately, it is current practice to monitor the stress levels in the pile during installation. From these measurements, which are taken a few meters below the pile head, and with a wave propagation model similar to the one proposed by Smith [2], the pile driving process is monitored [3]. Smith's model is based on the classical one-dimensional wave equation, which is non-dispersive. Due to its low computational cost, it is widely used in industry, even though more advanced models have been developed over the years; each model addresses different aspects of pile driving, e.g. sound radiation [4,5], and soil modelling [6].

To quantify plastic deformation at the pile head from non-collocated measurements, this paper augments the one-dimensional model of the

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pile installation process with two features: wave dispersion caused by the geometry of the structure and non-linear material behaviour. The former is needed to correctly model the stress wave propagation in the pile, since dispersion cannot be neglected for large-diameter monopiles [7]. The latter is included to account for the physical non-linearity that is necessary to quantify plasticity.

The propagation of elasto-plastic stress waves in solid metal cylinders has been studied already from the 1940s onwards; validated against high velocity impact experiments, rate-independent theories based on the classical wave equation were developed [8,9]. More advanced models included lateral inertia of the cross-section [10] and rate-dependency of the material [11]. Using these models, the dynamic properties of metals can be determined from experimental data [12]. More recently, an energy-based approach to study these impact tests was reported [13].

Similar axial impact tests have been performed on hollow cylindrical shells [14,15]. These thin-walled structures are used in the automotive industry as energy absorption devices, since the dynamic buckling of the cylinders remove energy from the system. Lepik [16] and Karagiozova et al. [17,18] showed that the type of dynamic buckling and thus the deformed state of the cylinder after impact depends on the axial stress wave propagation. Moreover, Karagiozova et al. [19] reported that for low-velocity (drop hammer) impacts, which resemble impact pile driving, most of the permanent deformation is concentrated in a small region at the impacted end of the cylinder. However, the use of non-collocated strain sensors mounted on the structure itself to quantify the amount of plastic deformation during the pile driving process, as proposed in this paper, has not been found in literature so far.

By eliminating terms from a shell theory based on justified assumptions, Section 2 derives the governing equations for elasto-plastic waves propagating in a monopile, resulting in a more accurate description of the behaviour of these waves, which is also valid for the large-diameter monopiles currently used by the offshore wind industry. Subsequently, Section 3 proposes a method to quantify plastic deformation based on non-collocated strain measurements and an energy balance. The proposed method is then validated against two experiments: Section 4 presents a lab-scale experiment of a copper bullet hitting a solid rod [12], and Section 5 discusses a full-scale experiment of a foundation pile installed for offshore wind. The former experiment allows one to validate the concept of the energy balance in a well controlled environment. The latter experiment allows one to validate the wave propagation model including wave dispersion effects in a more realistic setting. Finally, conclusions are drawn in Section 6. The authors believe that these two amendments to the classical model of Smith [2] set the basis for the next generation models to be included in studies of the drivability of piles and detection of plastic deformation for offshore wind applications.

2. Governing equations

A schematic representation of the pile-hammer-soil system is shown in Fig. 1, together with the chosen cylindrical coordinate system that is used throughout this paper; the axial, tangential, and radial direction are denoted by x, θ and r, respectively. The monopile has outer radius R, wall thickness h, and length L. In the next section, strain levels for the detection method will be considered at the cross-section located at $x = a$. First, different models describing the propagation of elastic waves are compared to correctly capture the effect of wave dispersion. Second, material non-linearity is included in order to quantify plasticity.

2.1. Governing equations for axially symmetric deformations of a cylindrically symmetric shell

The natural starting point for deriving the governing equations is a thin cylindrical shell theory, which is justified by the assumption that the pile's radius and length, and the exited wavelengths in the structure due to impact piling are large compared to the wall thickness.

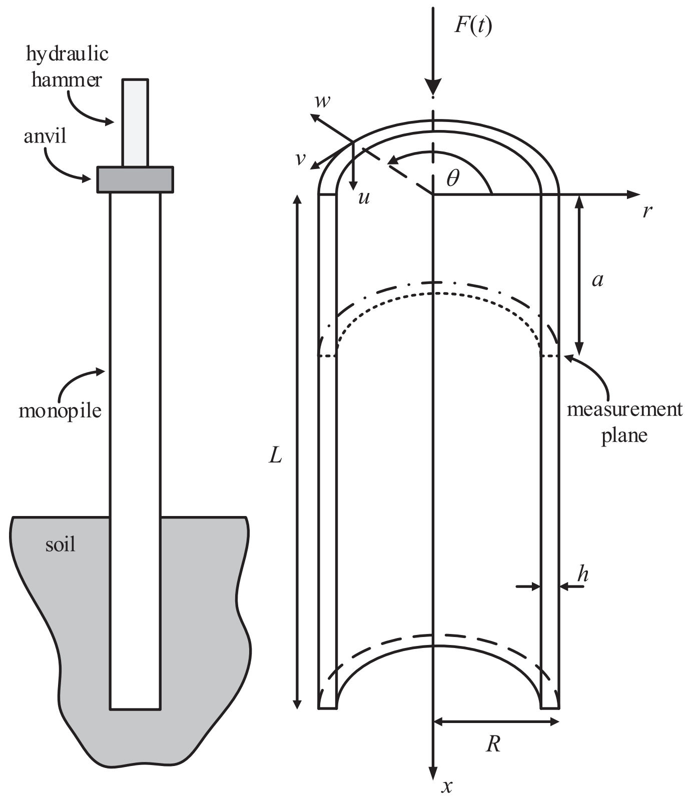

Fig. 1. Left, schematic of the pile-hammer-soil system; right, overview of the thin-walled cylindrical shell structure used to derive the governing equations.

By comparing exact theory and approximate thin shell theory, Greenspon showed that the latter is adequate for predicting the dynamical characteristics of a cylindrical shell structure with a diameter to wall thickness ratio comparable to that of a monopile [20]. Although there are many thin shell theories—each with their own complexity and range of applicability—they can be written in the operator form presented by Leissa [21]:

$$(\mathcal{L}_{\mathrm{D-M}} + \beta\mathcal{L}_{\mathrm{mod}})\bar{\mathbf{u}} = \mathbf{0}. \tag{1}$$

In this expression, $\bar{\mathbf{u}}$ is a vector containing the three displacement components $\bar{u}, \bar{v}, \bar{w}$: the axial, tangential, and radial displacements, respectively, which are all functions of x, θ, and t. To make them dimensionless, each component is divided by the radius, e.g. $\bar{u} = u/R$; bars indicate a non-dimensional quantity. The Donnell-Mushtari operator, $\mathcal{L}_{\text{D-M}}$, is the basis for all theories; other theories emerge by adding the modification operator $\mathcal{L}_{\mathrm{mod}}$. The thickness over radius ratio $\beta \equiv h^2/12R^2$ determines the influence of this additional operator on the resulting theory. For a monopile, this ratio is much smaller than one, and the frequencies of interest are relatively low. Thus, the modification term can be discarded at this point.

The nine components of the Donnel-Mushtari operator can be found in [21]. Since the wave propagation caused by the hammer forcing is assumed to be purely symmetric, the operator can be further simplified. By setting all tangential derivatives to zero, i.e. $\frac{\partial(\cdot)}{\partial\theta} = 0$, the components of the axi-symmetric operator $\mathcal{L}_{\mathrm{axi}}$ yield

$$\mathcal{L}_{\mathrm{axi}}^{11} = \frac{\partial^2}{\partial s^2} - \frac{\partial^2}{\partial \tau^2}, \tag{2a}$$

$$\mathcal{L}_{\mathrm{axi}}^{12} = \mathcal{L}_{\mathrm{axi}}^{21} = 0, \tag{2b}$$

$$\mathcal{L}_{\mathrm{axi}}^{13} = \mathcal{L}_{\mathrm{axi}}^{31} = \nu\frac{\partial}{\partial s}, \tag{2c}$$