A novel anvil modelling approach for pile driveability prediction, validated with PDA measurements

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ABSTRACT

The growth of offshore wind turbines pushes the size of monopile foundations and with that the size of anvils that are used to install monopiles. The current simulation programs that are used to predict the pile driveability rely on simple models to represent the anvils. Those models are shown to be inaccurate, especially for anvils > 5.5 m, which reflects directly on the accuracy of the driveability prediction result. Also for pile driving noise emission predictions the force wave that travels through the pile must be estimated accurately, including its high-frequency content, which is not possible with the currently available impact pile driving simulation programs. To overcome this shortcoming, a novel anvil modelling approach is proposed, based on the Mode Displacement Method, which is a Reduced Order Modelling approach. The resulting anvil models are robust and universally applicable since the methodology relies only on a FE model and just a single parameter to defines the model frequency content. A comparison of the simulation results with the novel anvil model to FEA results shows that all relevant behaviour during impact is caught very accurately by the application of the proposed anvil model. Instead the former lumped-mass anvil model results in a large overestimation of the impact force in the impact simulation with an 8 meter anvil, and also relevant high-frequency effects in the force wave are not captured with that model. A validation of the new anvil model based on PDA measurement data from the installation of a wind turbine monopile in the North Sea shows a good match between simulation and reality.

Keywords: impact pile driving, monopiles, pile driveability prediction, reduced order modelling, mode displacement method

1 INTRODUCTION

The installation of offshore monopile foundations by impact pile driving relies on driveability prediction software for the selection of the pile driving equipment. In order to obtain appropriate results in a reasonable time, such software is based on simplified simulation models of the hammer, the anvil, and the pile (Hirsch et al., 1970).

Well-known driveability prediction programs are based on one of the following numerical methods to solve the wave propagation problem: Smith's wave equations (Smith, 1960) or the Method of Characteristics (Middendorp and Verbeek, 2006). In Smith's model the pile driving configuration is simulated as a 1D lumped mass system with also the anvil as a lumped mass model. That modelling approach provided sufficiently accurate results for the small scale piles that were considered when the modelling concept was developed in the '50. In the last few decades however, the size of monopile foundations has increased significantly. The top diameter of XL monopiles that are currently designed for wind turbine foundations reach 8 m. It is clear that this development pushes the size of the sleeves and in particular the size of the anvils.

This development raises questions on the current modelling approaches that are applied for the anvil, since large anvils are much more flexible than small anvils. Therefore the internal dynamics of large anvils contribute more to the impact energy transfer from the ram weight towards the pile. The wave-propagation problem cannot be solved accurately with Smith's 1D lumped-mass model since the force wave propagation through a large anvil relies not only on compression waves but also shear waves play an essential role.

The Methods of Characteristics is also not capable of modelling the behaviour of a large anvil accurately.

The equations of the Methods of Characteristics are derived considering a prismatic beam for which the transverse dimension is small compared to its length (Voitus van Hamme, 1981). Clearly this is not the case for anvils with a diameter > 5.5 m. In case of small discontinuities between components, the Methods of Characteristics still results in realistic behaviour since the shear waves that arise at the transitions dissolve rather quickly to compression waves. However, for large anvils, which are not at all prismatic nor do these have a small D/L ratio, the Method of Characteristics cannot describe the behaviour accurately. This fact was already noted by (Voitus van Hamme, 1981), but apparently no solution was available at that time.

This reveals that the existing wave equation simulation software is not able to model the wave propagation through the anvil accurately, especially for anvils > 5.5 m. It is however essential to be able to predict the force wave in the pile for driveability prediction calculations accurately.

Another current research theme that relies on pile driving impact simulations are noise emission estimations. These analyses rely on an accurate description of the impact force, including the high-frequency contents of the force wave in the pile. Since the 1D wave-equation models are not capable of calculating the force wave propagation through the anvil sufficiently accurate, acoustic simulation models often rely on an externally imposed force wave that is calculated with a dedicated analysis, such as with Finite Element Analysis (FEA) (Tsouvalas, 2020). The calculation load of a FEA impact simulation is however large, so this approach limits the agility of the simulation model to impact energy variations and changes of the pile driving configuration. Furthermore the effect of the reflecting force waves from the soil on the impact behaviour cannot be considered in a model with an externally imposed impact force, though this is becoming particularly relevant for new pile driving technologies that extent the impact duration to suppress noise emission, e.g., the IQIP Pulse system and the BLUE Piling Technology.

Recently a novel anvil modelling approach was developed by (van ‘t Hof and Stathopoulou, 2021). A disadvantage of that model is however the extensive simulation time, which is about three orders slower than real-time on a standard PC. This means that the anvil model is not suitable for application in simulation models that are used for simulation of multiple consecutive blows. Furthermore the input for that anvil model is a simplified schematic of the anvil, so those models are subjected to user input and are therefore not reproducible.

To overcome these issues, there is a desire to develop a novel anvil model that can be applied in wave equation simulation software. The modelling approach must offer the right balance between accurate simulation of the force wave propagation and an acceptable simulation time (i.e., comparable to the existing 1-D pile driveability models). Also it is desirable that the models can be derived with a universally applicable approach, i.e., no manual schematization of the component drawing should be required. To realize this, this paper proposes an anvil modelling approach based on a Reduced Order Model (ROM) technique.

The paper is structured as follows. In Chapter 2 a ROM approach is proposed for modelling an anvil for pile driveability and noise emission simulations. Chapter 3 compares simulation results with the novel anvil model, a lumped-mass anvil model, and FEA results. Also a comparison is done to PDA measurement results from the field. Finally Chapter 4 presents the conclusions from this research.

2 NOVEL ANVIL MODELLING APPROACH

This chapter proposes a ROM-approach for modelling the anvil for impact pile driving simulations. The first paragraph argues which modelling approach is most suitable, after which the application of the proposed ROM-approach is explained.

2.1 Reduced Order Model approaches

A suitable ROM method must be selected for modelling anvils for pile driving simulations. One of the most widely applied ROM-methods is Guyan Reduction (Guyan 1965). This technique condenses the internal DOF on the boundary DOF which can greatly reduce the model size. However, this means that external forces on the internal DOF are neglected, meaning that internal inertia forces are not considered. The internal inertia forces are however essential to describe the behaviour of the anvil during impact, so Guyan Reduction is not a suitable approach for our problem.

Extensions to the Guyan Reduction method, such as the Craig-Bampton method, include free- or fixed internal vibration modes in the model to capture the internal dynamics of the component (van der Valk, 2010). The Craig-Bampton method is particularly suitable for Dynamic Substructuring applications since the boundary DOF can be coupled to other substructures by means of Component Mode Synthesis (CMS). For the behaviour of the anvil during impact pile driving, however, no CMS techniques can be applied since the anvil loses contact with the pile and the ram throughout the course of an impact.

Instead it is desired to apply a ROM method that relies only on the free vibration modes of the anvil, i.e., a ROM approach without predefined boundary DOF. Such an approach is the Mode Displacement Method (Besselink et al., 2013). The next section discusses the equations that represent this ROM approach.

2.2 Theory of the Mode Displacement Method

The starting point for application of the Mode Displacement Method is the general linear equation of motion for a structure:

$$M\ddot{z} + Kz = F \tag{1}$$

where z is the displacement vector, M is the mass matrix, K is the stiffness matrix, and F is the force vector. The mass and stiffness matrix can be obtained from a discretization of the physical component with the finite element method.

From the generalized eigenvalue problem follows the set of normalized mode shapes ϕ_j and corresponding eigenfrequencies ω_j for $j = \{1, \dots, N\}$ for the unforced system, i.e., $F = 0$:

$$\left(K - \omega_j^2 M\right)\phi_j = 0 \tag{2}$$

A set of modal coordinates η_j is defined with which the displacement vector can be described using the expansion concept (Besselink et al., 2013):

$$z = \sum_{j=1}^{N} \phi_j \eta_j \tag{3}$$

where ϕ_j is the j^{th} normalized mode shape of the structure.

With substitution of (3) in (1), premultiplication by $\phi_j^\top$, and application of the orthogonal condition of the mode shapes, this results in:

$$\phi_j^\top M \phi_j \ddot{\eta}_j + \phi_j^\top K \phi_j \eta_j = \phi_j^\top F \tag{4}$$

With the normality condition, the mass term in this equation can be simplified:

$$\phi_j^\top M \phi_j = 1 \tag{5}$$

With (2) the stiffness term is rewritten to:

$$\phi_j^\top K \phi_j = \omega_j^2 \tag{6}$$

The equations of motion can thus be written as:

$$\ddot{\eta}_j + \omega_j^2 \eta_j = \phi_j^\top F \tag{7}$$

A structural damping term, defined by the damping ratio ξ, can be included in (6) by treating the modal coordinates as single DOF systems. This results in the following complete set of equations:

$$\ddot{\eta}_j + 2\xi\omega_j\dot{\eta}_j + \omega_j^2 \eta_j = \phi_j^\top F \tag{8}$$

2.3 Application of the Mode Displacement Method

The anvil model (8) is exact if N is chosen as the total number of mode shapes of (1). Instead, by limiting N, a Reduced Order Model is obtained, which reduces the computation load in simulation, as required. The choice of N must be a balance between numerical accuracy and computation time. To make this modelling approach universally applicable, a proper approach to define N is thus required. A suitable approach is to choose N based on a required frequency content for the models. The frequency content can be determined from the relevant frequencies that exist in the force waves that propagate through the ram and through the pile. For all anvils of comparable size, e.g., all > 5.5 m anvils, this same frequency content can be used. A thorough model validation with more than 10 different anvils has revealed that this approach to choose N is robust.

To perform driveability prediction calculations, the novel anvil model is included in a wave equation simulation program that is based on (Hirsch et al., 1970). In this program the pile is modelled as a multiple lumped-element system where the number of elements is defined by the pile model segment length, which is chosen as 0.5 m. The soil modelling approach lies not within the scope of the analyses that are discussed in this paper since only a 25 ms time window is considered, in which time frame the reflecting impact force waves from the soil-pile interaction have not yet reached the anvil. The definition of the anvil model inputs and outputs is based on the pile top diameter that defines the anvil contact point. Instead in the lumped-mass model the anvil is considered as a rigid body.

3 ANVIL MODEL VALIDATION

This chapter discusses the validation of the novel anvil model that is proposed. First the simulation results are compared to FEA results. Second the simulation results are validated by a comparison to Pile Driving Analysis (PDA) measurement data that is obtained from an offshore pile driving project in the North see.

3.1 Comparison to FEA results

The simulation results with the novel ROM anvil model and the rigid lumped-mass anvil model are compared to FEA results. The pile driving configuration that is used for this analysis is listed in Table 1. The 8 meter anvil that is used in this pile driving configuration is one of the world's largest single-body anvils.

Table 1. Pile driving configuration for FEA comparison.

Hammer/ram	5500 kJ
Anvil	8 m
Pile	8000 mm x 140 mm x 80 m

Fig.1 is a visualization of the pile driving configuration in an axisymmetric FEA model. The figure shows the lower part of the ram weight (blue), the anvil (green), and the top part of the pile (orange).

The FEA results are compared to the simulation results with the novel ROM anvil model and the former lumped-mass anvil model in Fig. 2 and Fig. 3. These figures present the force in the ram due to the contact between the ram and the anvil ('ram impact force'), and the force at the pile top due to the contact between the anvil and the pile ('pile impact force').

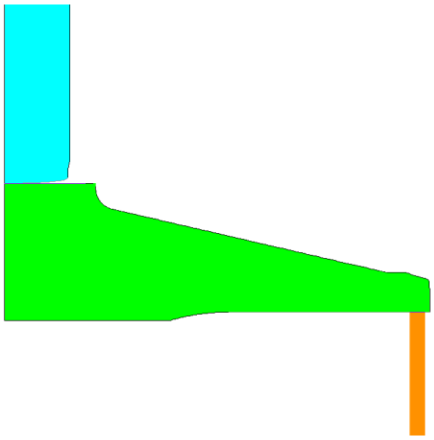

Fig. 1. Visualization of the axisymmetric FEA model.

Fig. 2 and Fig. 3 reveal clear differences in the simulation results with the two different anvil models. Considering the ram impact force, it is clear that the lumped-mass anvil model calculates unrealistic forces in the ram. This makes clear that this 8 m anvil cannot be modelled accurately with a lumped-mass model if the forces in the ram are of interest.

Instead the results with the novel ROM anvil model show a very good correspondence of the ram force between the simulation results and FEA. Also the pile force matches very well: The 4 ms wave propagation time through the anvil is matched exactly in the simulation compared to FEA. The lumped-mass anvil model can of course not account for that wave propagation time. Another relevant effect that is caught accurately in the novel anvil model is the almost stepwise pile force increase at t = 4 ms. This behaviour follows from the anvil's high flexibility: The bending wave in the anvil causes the anvil first to lift and then re-impact on the pile, causing a large force gradient. The lumped-mass model clearly lacks the anvil properties that are responsible for this behaviour. It is important to notice that for a noise estimation analysis this large gradient in the pile force is essential and must thus be captured by the simulation model.

The wave-equation simulation with the novel ROM anvil manages to produce this accurate result while the simulation runs faster than real-time on a laptop, which is a major difference to the FEA calculation which takes more than 10 minutes to calculate one single impact. The achieved simulation speed with the novel ROM anvil is acceptable to run complete driveability simulations, where thus even the effect of the reflecting waves from the soil, which differ each blow, are captured in the model.

Another important conclusion is that the lumped-mass anvil model causes a significant overestimation of the impact force in the pile. For a driveability analysis this may lead to an overestimation of the refusal depth. The novel ROM anvil model on the other hand matches the peak impact force very well.

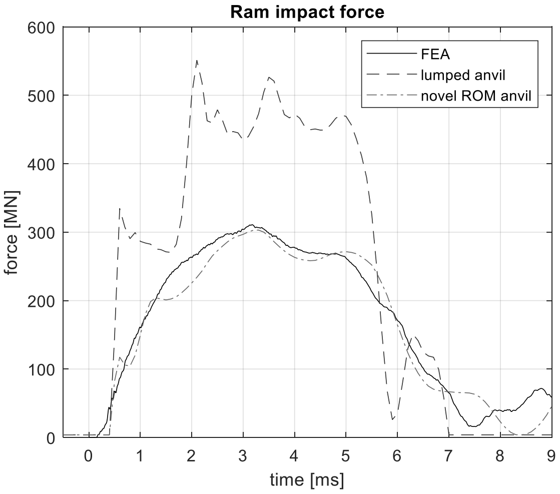

Fig. 2. FEA versus simulation: Impact force in the ram pen.

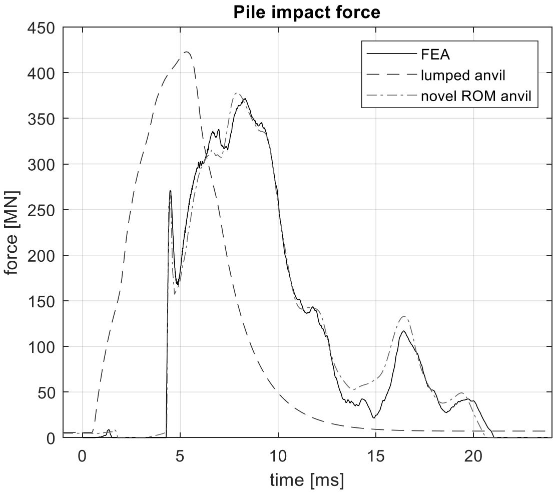

Fig. 3. FEA versus simulation: Impact force in the pile top.

3.2 Comparison to field measurement data

In this section the simulation results with the lumped-mass anvil model and the novel ROM anvil model are compared to field data that is obtained by a Pile Driving Analysis (PDA) measurement from the installation of a monopile foundation in the North Sea that is performed with a 4000 kJ hammer.

In Fig. 4 and Fig. 5 the measurement data (solid line) are compared to simulation results with the lumped-mass anvil (dashed line) and the novel anvil (dashed-dotted line). Notice that the initial force value is zero in the measurement data as a result of calibrating the strain gauges when the hammer was resting on the pile. Instead the simulation results contain the contribution of the gravitational force of the hammer masses that cause the non-zero initial force.

The figures reveal that the novel anvil model captures the actual force wave better than the lumped-mass anvil model, especially during the increase of the force wave to the peak value. In the decreasing slope of the force wave there are more high-frequency contributions in the measurement data than in both simulation results. The origin of this behaviour is not analysed in detail in this report. In the velocity measurement data less high-frequency oscillations are encountered.

Again these results show that the novel anvil model captures the wave propagation time through the anvil accurately while this is not captured in the lumped-mass anvil model. The overall curvature of the two simulated force waves is comparable, therefore it can be expected that both these simulation models result in a comparable driveability prediction result. This means that the novel anvil modelling approach is especially required for the largest XL monopile installation projects, such as the projects that will be done in the near future with the 8 m anvil.

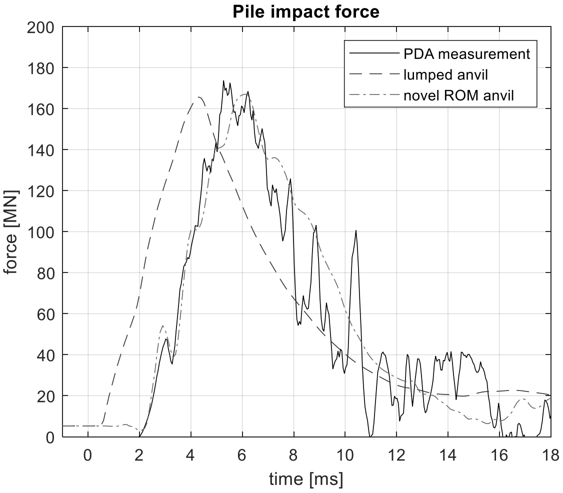

Fig. 4. PDA field data versus simulation: Pile top impact force.

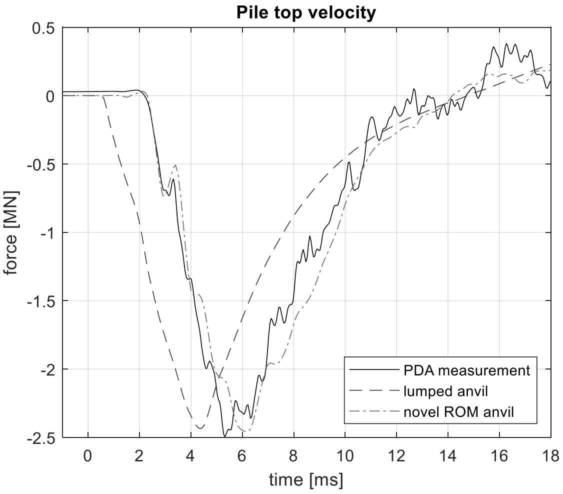

Fig. 5. PDA field data versus simulation: Velocity of the pile top.

4 CONCLUSIONS AND FUTURE WORK

The increasing size of offshore wind turbines pushes the size of monopile foundations, whose installation therefore requires continuously larger anvils.

For driveability prediction simulations and noise emission studies, the industry relies on either Smith's wave equations or the Methods of Characteristics. These simulation models are however not capable of capturing the relevant behaviour of anvils > 5.5 m. To overcome this shortcoming a novel anvil model is proposed based on a Reduced Order Modelling (ROM) approach, called the Mode Displacement Method.

The Mode Displacement Method takes as input the eigenmodes and eigenfrequencies of a component, which can for example be calculated with finite element software. The balance between model accuracy and simulation speed is achieved by selecting a suitable number of considered eigenmodes in the ROM model. The number of eigenmodes is defined based on a required model frequency content. Research has shown that for all anvils of similar size the same frequency content can be chosen, which makes the proposed ROM approach robust and universally applicable, i.e., without requiring user-dependent inputs.

The anvil ROM model is validated in a wave equation simulation program. The simulation results with the novel reduced order model of an 8 meter anvil are compared to FEA results and a simulation based on a lumped-mass anvil model. The results show that the ROM anvil model is capable of capturing all relevant wave-propagation effects, resulting in a highly accurately description of the force waves in the ram and in the pile. This is achieved for multiple consecutive blows while the simulation speed is still faster than real-time. This is a great improvement in terms of analysis duration compared to FEA, where the calculation of one single impact takes already more than 10 minutes. Instead the simulation with the lumped-mass anvil model causes a large overestimation of the peak force in the pile and does not include other relevant behaviour such as the large initial gradient in the pile force. These results clearly reveal the necessity of using the proposed novel anvil modelling approach for these large anvils.

The validation of the simulation results based on PDA measurement data shows a good match between measurement and simulation, which boosts the confidence in the novel anvil modelling approach.

Future work in this research project is to finalize the development of a Reduced Order Model for anvil rings, which is also based on the Mode Displacement Method. Furthermore, the modelling of contact friction between the anvil, the ring anvil, and the sleeve will be incorporated in the simulation model. Finally, a comparison in terms of the pile driveability and the pile driving noise emission between simulation and reality will be executed.

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