Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering– Rahman and Jaksa (Eds)

MIDAS: Monopile Improved Design through Advanced cyclic Soil modelling

MIDAS: Amélioration du dimensionnement des monopieux basé sur la modélisation avancée de comportement cyclique du sol

Federico Pisanò, Amin Askarinejad, Huan Wang, Soheib Maghsoodi, Kenneth Gavin & Maxim Segeren
Faculty of Civil Engineering and Geosciences, Delft University of Technology, Netherlands, f.pisano@tudelft.nl

Ahmed Elkadi, Dirk de Lange, Maria Konstadinou
Geo-Engineering Unit, Deltares, Netherlands

ABSTRACT: The renewable energy sector is experiencing a worldwide boom, with offshore wind playing an increasingly prominent role. Larger and more powerful offshore wind turbines (OWTs) are being installed, which is enabled by the technological progress and cost reduction achieved in the last few years. Installations in deeper waters and harsher environments are significantly challenging engineering design, particularly with regard to OWT foundations such as monopiles. Higher capacity OWTs require larger monopiles, depending on soil conditions and environmental (wind/wave) loading. Presently, about 15-24% of the investment for the construction of an offshore wind farm relates to the design, production, and installation of substructures. This fact continues to motivate new threads of geotechnical research. Despite the remarkable advances in the analysis of monopile-soil interaction, significant knowledge gaps are still to be filled, for instance regarding the response of monopiles to cyclic loading of different amplitude, duration, and frequency. This paper summarises the objectives, structure, and methodology of MIDAS, a new Dutch joint industry project led by TU Delft in collaboration with Deltares and offshore industry partners. MIDAS targets fundamental understanding of monopile-soil interaction under lateral cyclic loading, particularly for sandy soils. The research programme combines advanced physical and numerical modelling studies, including centrifuge testing and detailed 3D FE modelling. The outcomes of both experimental and numerical activities will be used to develop new cyclic 1D soil reaction models for monopiles in sand, of the kind most commonly used in engineering practice. Ultimately, MIDAS' results will support more accurate analysis of cyclic monopile behaviour, and therefore design optimisation and cost reduction.

RÉSUMÉ : Le secteur des énergies renouvelables est en pleine croissance dans le monde et le secteur éolien offshore joue un rôle prépondérant. Des éoliennes offshore (EO) de plus en plus larges et puissantes ont été installées, grâce aux progrès technologiques et réductions de coûts réalisées ces dernières années. Leur installation dans des eaux plus profondes et des environnements plus rudes représente un vrai défi, et particulièrement le dimensionnement des fondations telles que les monopieux. Des EO plus imposantes nécessitent de plus gros monopieux, dont la taille dépend des conditions de sol et des charges imposées (vagues/vents). Actuellement, 15-24% de l'investissement pour la construction d'une ferme éolienne offshore sert à dimensionner, produire et installer les fondations, ce qui motive de nouvelles recherches en géotechnique. Malgré les avancées remarquables dans l'analyse des interactions sol-monopieu, il reste de nombreuses lacunes dans leur compréhension, particulièrement sous chargement cyclique d'amplitude, durée et fréquence variables. Cet article résume les objectifs, la structure et la méthodologie de MIDAS, un nouveau projet de recherche néerlandais, mené par TU Delft, en collaboration avec Deltares et d'autres partenaires industriels. MIDAS se concentre sur la compréhension fondamentale des interactions sol-monopieu sous chargement cyclique, particulièrement pour les sols sableux. Le programme de recherche combine des modélisations physique et numérique avancées, comprenant des modèles réduits testés en centrifugeuse et des modélisations éléments finis 3D. Les résultats numériques et expérimentaux seront rassemblés dans un modèle de réaction cyclique 1D pour les monopieux installés dans des sables, similaire aux modèles les plus utilisés en pratique. Finalement, les résultats du projet MIDAS permettront une analyse plus précise du comportement cyclique des monopieux, une optimisation de leur dimensionnement et donc de leur coût.

KEYWORDS: offshore wind, monopiles, cyclic loading, sand, modelling

MOTS-CLÉS: éolien offshore, monopieux, chargement cyclique, sable, modélisation

1 INTRODUCTION

Late 2019, the European Union (EU) initiated the so-called European Green Deal, which aims to make Europe the first CO_2-neutral continent by 2050. Also aligned with the EU agenda is the national strategy of the Netherlands, where a shift of the energy mix towards renewables is decisively being pursued through the joint efforts of political, industrial, and research institutions. In this context, offshore wind energy has attracted significant attention, even though harvesting wind energy from the ocean is still more expensive than from wind power plants on land. Remarkable technological advances in the last few years have enabled a growth in size and power output of offshore wind turbines (OWTs), as well as a gradual reduction of the costs associated with their fabrication and installation.

Presently, 15-24% of the investment for the construction of an offshore wind farm is taken by the design, production and installation of substructures (Stehly and Beiter, 2019). In this respect, large-diameter steel monopiles (MPs) are at present the most common foundations for OWTs and will continue to dominate the market in the foreseeable future, owing to their simplicity and robustness. As larger MPs are used to support bigger OWTs in deeper waters, optimising the engineering design of MPs is key to economic viability (Byrne et al., 2019). In particular, MP geotechnical design must return structural dimensions (length, diameter, wall thickness) suitable to enable "satisfactory" performance under the forces transmitted by the OWT superstructure. The main MP design criteria may be summarised as follows (Bhattacharya, 2019):

1. the first resonance frequency of the OWT-MP-soil system must lie within prescribed limits (*soft-stiff design*);
2. the MP must not fail under prolonged loading during the whole operational life – Fatigue Limit State (FLS);

3. the MP must safely bear the largest design loads – Ultimate Limit State (ULS);
4. the MP must remain usable under service loading, i.e. limited deformations are allowed – Serviceability Limit State (SLS).

The above design criteria must be satisfied in the presence of environmental cyclic loading, i.e. under wind/wave loads applied during the entire operational life of the structure. As is well-known, cyclic loading mobilises aspects of soil behaviour that are still challenging to describe and predict quantitatively, such as variations in stiffness and strength, accumulation of permanent strains, and energy dissipation. For example, cyclic soil deformations may cause excessive MP rotation (or tilt), which is a serviceability issue often remedied through larger MP embedment in the ground. Although less studied so far, the case of OWTs subjected to seismic loading is also relevant in this context (Kaynia, 2019), e.g., regarding more recent offshore wind farming in the Asia-Pacific region.

The geotechnical uncertainties that still underlie MP design have motivated a number of valuable research programmes across Europe, such as PISA and PICASO in the UK (Byrne et al., 2019, 2020), VIBRO in Germany (Achmus et al., 2020), REDWIN and WAS-XL in Norway (Skau et al., 2018; Klinkvort et al., 2020), and DISSTINCT and GDP in the Netherlands (Kementzetzidis et al., 2020; Metrikine et al., 2020). These projects, some of which still in progress, have enhanced the fundamental understanding of monopile-soil interaction, and its implications in the analysis and design of OWTs.

This paper introduces MIDAS, a new Dutch programme for the study of cyclically loaded monopiles. In what follows, MIDAS' objectives, structure, and methodology are presented, including a brief overview of relevant background research carried out in Delft in previous years.

2 MIDAS: A RESEARCH PROGRAMME ON CYCLIC LATERAL BEHAVIOUR OF MONOPILES IN SAND

The MIDAS project officially began in May 2020, with combined funding granted by RVO (*Rijksdienst voor Ondernemend Nederland – Netherlands Enterprise Agency*) and a number of industry partners. Planning and setup of the project was facilitated by GROW, which is a Dutch consortium established to initiate research and accelerate innovation in offshore wind. GROW's strength lies in its ability to run focused R&D activities, with the involvement of about twenty partners that cooperate to carry out joint research (https://grow-offshorewind.nl/).

MIDAS OFFSHORE WIND

Figure 1. MIDAS project logo.

MIDAS' research programme is led by TU Delft in cooperation with Deltares, and benefits from the interaction with six industry partners. The project team covers expertise along the whole offshore wind supply chain and includes wind farm developers, wind turbine manufacturers, marine contractors, and research institutes. Additionally, the Norwegian Geotechnical Institute and DNV GL are the members of an external technical review panel, which will provide feedback on research activities and the Technology Qualification of the project findings (DNV GL, 2019).

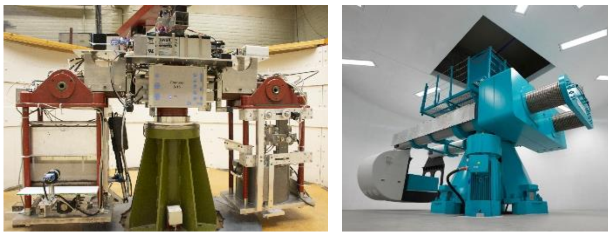
The acronym in the project title, *Monopile Improved Design through Advanced cyclic Soil modelling*, defines MIDAS' main goal, and remarks the need for further understanding of cyclic MP-soil interaction mechanisms – particularly, in sand. As further elaborated in what follows, MIDAS builds on the combination of advanced physical and numerical modelling of MPs in sand and will produce novel engineering models/tools for their design. The project is due to conclude in October 2023.

3 RESEARCH BACKGROUND

MIDAS aims to generate new knowledge for the optimisation of MPs in real offshore wind projects, with due account of cyclic loading effects. The project team is supported in this endeavour by the body of valuable research carried out internationally in the past few years. In this respect, recent Delft developments in the field of physical/numerical modelling of MPs are directly relevant, in that they provide MIDAS' main foundation. Such developments are briefly overviewed hereafter to clarify the links between fundamentals and applications in MIDAS.

3.1 *Physical modelling*

MIDAS' experimental programme will be conducted at TU Delft and Deltares using two different centrifuge facilities (Figure 2), with the aim of (i) investigating the mechanics of monopile-sand interaction, and (ii) producing novel data in support of numerical modelling and, ultimately, monopile design. During centrifuge experiments, a model which is geometrically *N* times smaller than the real prototype is tested under enhanced acceleration – *N* times the Earth's gravity (Taylor, 1995). This allows to re-establish appropriate stress levels and obtain reliable test results, on condition that proper scaling laws and boundary conditions are fulfilled (Askarinejad et al., 2017). Having access to two set-ups with different scales provides the possibility to test the concept of *modelling of models* for the case of MPs subjected to lateral cyclic loading.

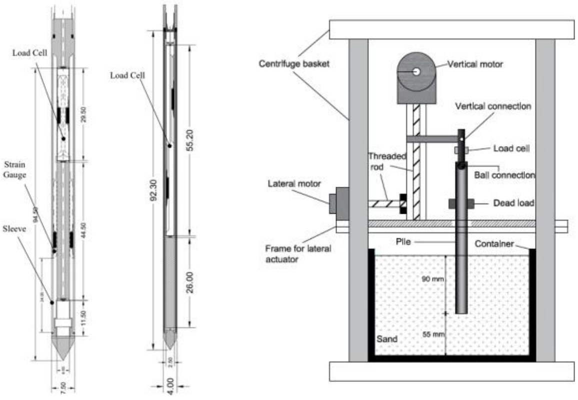


(a) (b)

Figure 2.Centrifuge facilities at (a) TU Delft and (b) Deltares.

The geotechnical centrifuge at TU Delft (Figure 2a) is a beam centrifuge with a nominal radius of 1.22 m and a maximum payload of 30 kg at 300g, which will allow MIDAS tests to be performed under an augmented gravity of up to 100g. The facility is equipped with a miniature CPT device (De Lange et al., 2020) (Figure 3a), novel optical fibre pore pressure transducers (Askarinejad et al., 2020), and miniature pore pressure transducers which can be installed inside a model MP to measure excess pore water pressures at the soil-pile interface during cyclic loading (Askarinejad et al., 2017). Experience has already been gained about instrumenting model MPs with pairs of strain gauges, load cells, and displacement transducers for deriving experimental soil reaction curves (Chortis et al., 2020).

The geotechnical centrifuge at Deltares (Figure 2b) is a newly designed Actidyn C72-31 beam centrifuge, and has been available for use since early 2021. It has a platform radius of 5.0 m and can be operated with a maximum payload of 260 g-ton. A data-acquisition system including 40 channels with a sampling rate up to 100 kHz, a high-speed camera system, and a 4-axis robotic actuation system have been designed. The advanced centrifuge facility at Deltares adds to the experimental programme by enabling the study of scale effects in relation to MP prototypes of different size.



(a) (b)

Figure 3. Design schematics of (a) the miniature CPT and (b) the 2D MP-loading actuator with a frictionless ball connection.

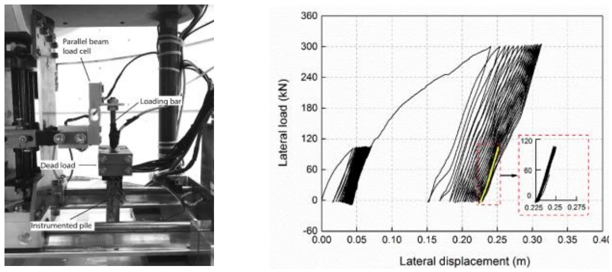
Previous experimental work has already been devoted to the in-depth study of MP behaviour using the TU Delft physical modelling facility. Li et al. (2020a) developed a frictionless load transfer mechanism for a 2D loading actuator, which enables application of lateral cyclic loading with minimal rotational fixity (Figure 3b). In the same study, centrifuge tests have been performed to assess the effect of scour on the performance of piles with low embedment ratio – particularly, with regard to the effects of scour type and depth.

Li et al. (2020b) investigated a less studied aspect of MP-soil interaction, i.e., the influence of combined vertical and lateral loading on the lateral response (Figure 4a). The experimental results indicate that for piles with aspect ratio (*L/D*) equal to 5, increasing vertical loading improves both the pile initial stiffness and lateral capacity. A similar trend was observed for piles with *L/D*=3, when the vertical loading was below 44% of the pile's ultimate vertical capacity. The beneficial effects of a higher vertical load level seem to gradually vanish in a fashion similar to that widely observed for shallow footings.

Li (2020) studied the influence of cyclic loading characteristics (amplitude and degree of asymmetry) on MP lateral behaviour by also including combinations of operational and exceptional (storm-like) loading (Figure 4b). Data analysis focused on the influence of cyclic loading on the evolution of lateral displacement, secant cyclic stiffness, pile bending, and *p-y* reaction curves. Cyclic loading was found to be most damaging in terms of tilt accumulation when featuring load sign reversals (*two-way loading*); nonetheless, a progressive increase in the secant MP cyclic stiffness was observed with increasing number of cycles. The same study provided depth-dependent cyclic trends of lateral soil reaction, as well as a new empirical framework for the prediction of cyclic MP tilt and secant stiffness under drained conditions.

3.2 *Numerical modelling*

The physical modelling of MP-sand interaction is complemented in MIDAS by numerical modelling research, which builds on the efforts spent at TU Delft in recent years (Pisanò, 2019). Such efforts are related to the integrated modelling of OWT-MP-soil systems under cyclic loading, with emphasis on the accurate description of non-linear soil behaviour. The importance of integrating the modelling of structures and foundations is well recognised in the field of offshore engineering, and is also being further confirmed in relation to offshore wind applications.

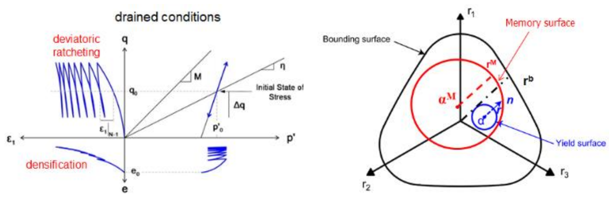


(a) (b)

Figure 4. (a) Vertically load model MP subjected to lateral loading, and (b) MP response in the centrifuge to a combination of operational and exceptional cyclic loading.

While several options are available for describing soil-foundation interaction – e.g., 0D macro-elements, distributed 1D soil reaction models, 2D/3D continuum models (Houlsby, 2016) – fully 3D continuum modelling allows highest flexibility in terms of geometry, loading history, and material behaviour. In this context, the inevitable use of non-linear constitutive models for the soil renders numerical solutions, e.g., via the finite element (FE) method, strictly necessary.

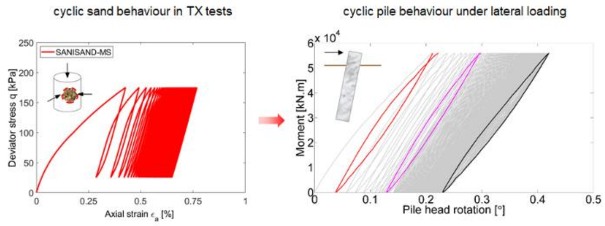
Despite their conceptual/computational difficulties, 3D FE modelling studies can support deeper understanding of MP-soil interaction over a wide range of loading/geotechnical conditions (Corciulo et al., 2017), also in the presence of dynamic and hydro-mechanical effects (Kementzetzidis et al., 2019, 2020). Nonetheless, even when restricting the attention to low-frequency loading and likely drained conditions, serious knowledge gaps emerge in the modelling of cyclic soil behaviour, for instance in terms of cyclic densification and strain accumulation (*ratcheting*, Figure 5a). Such phenomena relate fundamentally to microstructural fabric effects, and have been found to influence the response of MPs to cyclic loading.



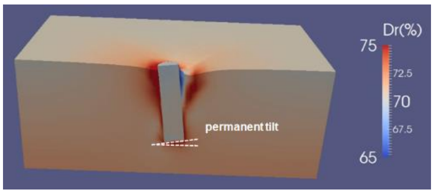
(a) (b)

Figure 5. (a) cyclic ratcheting/densification of sand under non-symmetric cyclic loading – modified after Pasten et al. (2014); (b) yield, bounding, and memory surfaces in the SANISAND-MS model.

Some progress in the constitutive modelling of cyclic sand ratcheting under drained conditions has recently been made, for instance, through the SANISAND-MS model proposed by Liu et al. (2019). This model builds on the existing SANISAND bounding surface framework of Dafalias and Manzari (2004), and is enhanced with an additional "memory surface" (Corti et al., 2016) – hence the name SANISAND-MS (Figure 5b). The memory surface enables phenomenological representation of fabric changes induced by the cyclic loading history, such as variations in stiffness and dilatancy. Details regarding model formulation, calibration, and validation against high-cyclic laboratory test results are provided by Liu et al. (2019). The performance of SANISAND-MS in drained, non-symmetric cyclic triaxial tests is exemplified in Figure 6a(left), and reveals the possibility to obtain a realistic ratcheting response owing to the memory hardening mechanism. The advantages of the memory surface formulation are not limited to the simulation of cyclic drained ratcheting, but have been also extended to the cyclic simulation of pore pressure build-up during undrained loading (Liu et al., 2020).



(a)



(b)

Figure 6. Application of SANISAND-MS to the 3D FE analysis of cyclically loaded MPs: (a) from sand ratcheting to MP tilt; (b) 3D simulation of sand densification around a tilting MP.

As mentioned in Section 1, design criteria for OWTs include the prediction of lateral tilt under cyclic loading, which is in turn related to the (evolving) cyclic stiffness of the soil around the foundation. One of the main challenges in this area is to account for the high number of irregular loading cycles experienced by OWTs during their operational life – up to $10^{7\text{-}8}$ (Houlsby, 2016). Numerical tilt predictions are generally non-trivial for at least two reasons: (a) the high computational burden associated with time-domain, step-by-step analyses (*implicit*, in the terminology of Niemunis et al., 2005), and (b) the dearth of constitutive models that can reliably reproduce soil behaviour under high-cyclic loading. Alternative *explicit* methods have also been proposed, in which cyclic strain accumulation is directly linked to the number of loading cycles – very recent instances of this approach are provided, e.g., by Staubach and Wichtmann (2020) and Klikvort et al. (2020).

The use of SANISAND-MS in MIDAS gives an opportunity to improve the cyclic analysis of MPs through "implicit" 3D FE modelling (Liu et al., 2021). As shown in Figure 6a, the detailed simulation of soil ratcheting can "spontaneously" return the typical tilting response of a monopile, based on a direct link between soil behaviour and MP-soil interaction (Figure 6b). Although high-cyclic 3D FE analyses may not (yet) be feasible in daily engineering practice, they can certainly assist the understanding of soil-foundation interaction mechanisms, and support the conception of simpler 1D engineering models.

4 OBJECTIVES AND METHODOLOGY

As mentioned in Section 2, MIDAS targets further understanding of cyclic MP-soil interaction in sand by combining physical and numerical modelling. The new knowledge obtained from advanced modelling studies will be lumped into a 1D MP-soil interaction model for use in MP design. Ultimately, the project aims to support optimal use of structural steel, and therefore cost reduction in offshore wind developments.

To accomplish such a mission, experimental/numerical research is currently being executed using facilities and expertise available at TU Delft and Deltares. A thorough centrifuge testing programme has been planned to explore the influence of relevant geotechnical/loading factors on the cyclic response of stiff monopiles. To this end, the two centrifuge facilities in Figure 2 will be jointly used to shed light on the quantitative role of scale effects in MP physical modelling. At the same time, centrifuge tests will provide data for the validation of detailed 3D FE models, which will be in turn exploited for extensive parametric studies. The availability of high-fidelity experimental/numerical data will form the knowledge basis for developing new cyclic 1D soil reaction models, which shall include lateral (*p*-*y*), rotational and base fixity reactions. The need for multiple soil reaction components for short MPs has been clearly emphasised by Byrne et al. (2019) in the context of the PISA project (Byrne, 2019).

In the last stage of the programme, industry partners will test the soundness of the research outcomes against in-house design cases and field experience. These activities will enable critical assessment of MIDAS' findings, and facilitate their use in future projects. In this respect, a collaboration with DNV GL has also been established to pursue the Technology Qualification of MIDAS' MP design model.

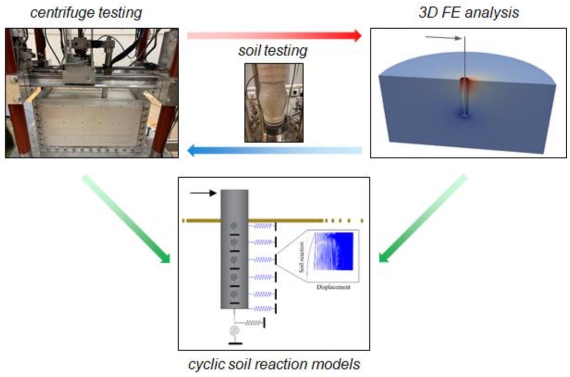


Figure 7. Synopsis of MIDAS' research methodology.

From a methodological standpoint, the research programme builds on the interaction between experimental and numerical work (Figure 7). Cyclic centrifuge tests will be performed on instrumented MPs of different aspect ratio, and will provide novel data regarding the load-displacement response at the MP head, the evolving bending along the MP, and the surrounding soil behaviour (in terms of total soil pressure and, when applicable, pore water pressure development). Alongside small-scale MP testing, the same sand used in centrifuge experiments is being thoroughly characterised (element testing) at Deltares laboratory. The experimental data regarding the cyclic behaviour of the sand and of the MP-sand system will support parameter calibration for the aforementioned SANISAND-MS model and in-depth validation of 3D FE MP-soil models. Extensive 3D FE parametric studies will expand the experimental dataset for soil and loading conditions not considered in the centrifuge testing programme. The interpretation of soil reaction mechanisms as obtained from detailed 3D FE simulations will inspire the conception of 1D cyclic models for each soil reaction component. Such 1D models will be mathematically formulated within the same memory-enhanced bounding surface framework adopted for SANISAND-MS (Figure 7). Such a parallelism in the upscaling from soil behaviour to MP-soil interaction will allow the identification of fundamental links between response features and parameters in 3D and 1D modelling, with emphasis on the evolution of the cyclic stiffness and the accumulation of cyclic deformations (Pisanò, 2019; Liu et al., 2021).

In summary, MIDAS will deliver:

1. high-quality experimental data about the cyclic behaviour of stiff MPs in sand (lateral stiffness and permanent tilt), as well as cyclic characterisation of the sand used in the centrifuge;
2. a wealth of 3D FE results about cyclic MP-sand interaction from numerical parametric studies based on the use of the SANISAND-MS model;
3. a new set of cyclic 1D soil reaction models for MPs in sand, to be implemented into practical design tools and technically assessed through Technology Qualification;
4. dissemination of research findings through publications, webinars, and a conclusive project workshop.

5 STRUCTURE OF THE RESEARCH PROGRAMME

The research programme includes detailed tasks ranging from MP testing and simulation to the implementation of new 1D soil reaction models into practical design tools. Such tasks are associated with four interconnected work packages (WPs) (Figure 8). Along with the contents of the four WPs (and related sub-packages), the interaction between research institutes and industry partners is also visualised in Figure 8.

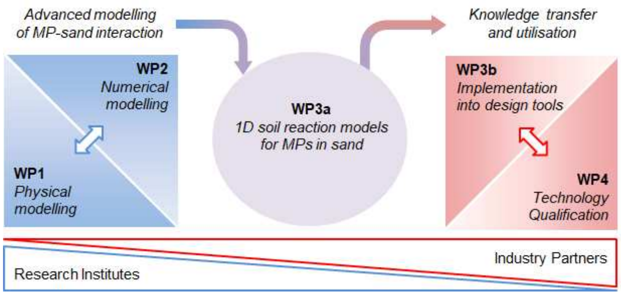


Figure 8. Organisation of project tasks and interaction among WPs.

5.1 *WP1 – "MP-sand physical modelling"*

Previous studies on the lateral response of MPs have been mostly executed on small-scaled models at natural gravity (1g), which cannot reliably reproduce the stress-dependency of soil behaviour and, in turn, MP-soil interaction at real scale.

In WP1, centrifuge tests will be performed to investigate experimentally the influence of the following factors on MP cyclic response, in the presence of more realistic stress levels:

(i) MP diameter and aspect ratio;
(ii) cyclic loading characteristic – e.g., symmetric vs non-symmetric, constant vs variable amplitude;
(iii) drainage condition and pore pressure regime around the MP;

The planned testing programme consists of two phases: in phase 1, about 35 tests will be performed at TU Delft in Geba sand (Zhang and Askarinejad, 2019), with the aim of modelling geometrical/geotechnical/loading conditions relevant to North Sea projects. Changes in soil state (i.e., soil pressures, pore water pressures, and void ratio) associated with the MP cyclic response (lateral tilt and bending) will be measured to shed more light on the evolution of MP deflection, stiffness, damping, and soil reactions. In phase 2, additional tests will be carried out using the new/larger centrifuge at Deltares. The second set of tests will further expand MIDAS' database in the direction discussed in Section 3.1.

WP1 also includes extensive laboratory element testing of Geba sand to support the calibration of constitutive model parameters in WP2.

5.2 *WP2 – "MP-sand numerical modelling"*

Data from centrifuge tests will be complemented by 3D FE studies. High-fidelity 3D FE simulation of soil-foundation interaction is nowadays not only viable, but also warmly recommended by offshore industry standard (DNV GL, 2016 – Sections 7.7.4.2 and F.2.4.1).

WP2 builds on recent Delft research about the 3D FE modelling of OWT-MP-soil systems and the constitutive description of cyclic sand behaviour (Section 3.2), and includes research activities fully aligned with WP1: (i) the laboratory tests performed on the selected Geba sand will enable the calibration of SANISAND-MS model parameters; (ii) 3D FE MP-soil models will be set up for scenarios associated with sand conditions, MP geometry and loading histories relevant to North Sea offshore wind projects; (iii) validation against centrifuge results, followed by extensive numerical parametric studies.

WP2 will inform about (i) global MP cyclic response (lateral stiffness and tilt accumulation), and (ii) local soil response in terms of displacement, stress/strain and, where applicable, pore pressure fields. The effect of irregular cyclic loading history will be numerically explored, so as to produce more challenging benchmarks for the 1D modelling work in WP3. 3D simulation results will finally be processed to obtain relevant soil reaction components around the MP and inspect their cyclic evolution.

5.3 *WP3 – "Engineering MP-sand modelling"*

5.3.1 *WP3a – 1D soil reaction models for MPs in sand*

The results of advance modelling studies can be fully utilised only if translated into more practical design tools. DNV-GL (2016) recommends the dynamic analysis of OWTs to be performed based on "*appropriate stiffness values for the soil support of the foundation structure*", resulting e.g. from "*p-y curves describing the pile-soil interaction*". WP3 will take further previous work on the generation of 1D soil reaction models MPs in sand, accounting for relevant cyclic loading effects. MIDAS' research team will pursue advances in this area based on the results of WP1-2, particularly about description of different MP-soil stiffness components as functions of MP displacement, depth, and sand density conditions (e.g., from loose to dense). As previously mentioned, 1D reaction models will be formulated in the framework of memory-enhanced bounding surface plasticity, which will allow realistic modelling of cycle-by-cycle MP response and, ultimately, to reliably analyse the cyclic performance of OWT-MP-soil systems.

5.3.2 *Implementation into design tools*

The project partners will facilitate the implementation of the new cyclic soil reaction models into their in-house software for OWT/MP analysis. The partners provided with new modelling capabilities will reassess previous MP designs, and quantify the technical/economic benefits enabled by MIDAS' findings.

5.4 *WP3b – WP4 – "Technology Qualification"*

Technology Qualification is the process of providing evidence that a technology/methodology will function within specified operational limits with an acceptable level of confidence and ensuring that applicable standards are fulfilled (DNV GL, 2019). MIDAS' WP4 aims to support the qualification of the final cyclic 1D soil reaction models, so that, when qualified, they can be used in the design and certification of future wind projects.

While the first phase of the process will focus on internal risk assessment (challenges/uncertainties related to the development of a new MP design method), the second phase will produce the actual Qualification Plan. The MIDAS team will then execute such a plan, which will finally lead to the issue of a Technology Certificate.

6 CONCLUSIONS

This paper has overviewed the motivation, objectives, and methodology of MIDAS, a recent Dutch joint industry project on the analysis/design of offshore monopiles under cyclic loading conditions. MIDAS began in May 2020 and consists of a 3.5 years research programme led by TU Delft in collaboration with Deltares and industry partners. Core of such a programme is the combination of recent Delft research in the fields of physical and numerical modelling of offshore foundations – particularly, for the case of monopiles in sandy soil. To this end, the unique use of two distinct centrifuge facilities has been planned to investigate the cyclic behaviour of monopiles at different scales, stress levels, and hydro-mechanical conditions; at the same time, recent advances in the 3D FE modelling of monopile-soil systems are being taken further to enable extensive validation and parametric studies using the SANISAND-MS model.

Experimental and computational activities will altogether produce new detailed information about the cyclic behaviour of monopiles. Such information will be exploited to formulate a new set cyclic 1D soil reaction models, which will be implemented into industry design tools and assessed for Technology Qualification.

MIDAS is expected to positively impact the current state of monopile design practice and, more broadly, the soundness of experimental/numerical approaches for the cyclic analysis of foundations. MIDAS adds to the international momentum around monopile research, which is overall providing solutions to the engineering challenges posed by cost-reduction targets.

7 ACKNOWLEDGEMENTS

MIDAS is an initiative developed in the framework of the GROW joint research programme. Funding from *Topsector Energiesubsidie van het Ministerie van Econsomische Zaken* under RVO grant number TEHE111013 and the following partners (in alphabetical order) is gratefully acknowledged: Delft University of Technology, Eneco Wind B.V., IHC MTI B.V., RWE Offshore Wind Netherlands B.V., Shell Global Solutions International B.V., Siemens Gamesa Renewable Energy B.V., Stichting Deltares, and Van Oord Offshore Wind B.V. The valuable collaboration of NGI and DNV GL is also appreciated.

8 REFERENCES

Achmus M., Schmoor K.A., Herwig V. and Matlock B. 2020. Lateral bearing behaviour of vibro-and impact-driven large-diameter piles in dense sand. *geotechnik*, 43(3), 147-159.

Askarinejad A., Sitanggang A.P.B. and Schenkeveld F. 2017. Effect of pore fluid on the behaviour of laterally loaded offshore piles modelled in centrifuge. *Proceedings of the 19th International Conference on Soil Mechanics and Geotechnical Engineering (ICSMGE 2017)*, Seoul (South Korea).

Askarinejad A., Quinten T.O., Alvarez Grima M., van't Hof C. and Gavin K.G. 2020. Use of optical fibres to measure pore water pressure development during impact pile diving: a geotechnical centrifuge study. *Proceedings of the 4th European Conference on Physical Modelling in Geotechnics (ECPMG 2020)*, Luleå (Sweden).

Bhattacharya S. 2019. *Design of foundations for offshore wind turbines*. Wiley.

Byrne B.W., Burd H.J., Zdravkovic L., Abadie C.N., Houlsby G.T., Jardine R.J., Martin C.M., McAdam R.A., Pacheco Andrade M., Pedro A.M.G., Potts D.M. and Taborda D.M.G. 2019. PISA design methods for offshore wind turbine monopiles. *Proceedings Offshore Technology Conference*, Houston, TX (USA).

Byrne B.W., Aghakouchak A., Buckley RM., Burd H.J., Gengenbach J., Houlsby G.T., McAdam R.A., Martin C.M., Schranz F., Sheil B.B. and Suryasentana S.K. 2020. PICASO: cyclic lateral loading of offshore wind turbine monopiles. *Frontiers in Offshore Geotechnics IV: Proceedings of the 4th International Symposium on Frontiers in Offshore Geotechnics*, Austin, TX (USA).

Chortis G., Askarinejad A., Prendergast L.J., Li Q. and Gavin K.G. 2020. Influence of scour depth and type on p–y curves for monopiles in sand under monotonic lateral loading in a geotechnical centrifuge. *Ocean Engineering*. 106838.

Corciulo S., Zanoli O. and Pisanò F. 2017. Transient response of offshore wind turbines on monopiles in sand: role of cyclic hydro–mechanical soil behaviour. *Computers and Geotechnics*, 83, 221-238.

Corti R., Diambra A., Wood D.M., Escribano D.E. and Nash, D.F. 2016. Memory surface hardening model for granular soils under repeated loading conditions. *Journal of Engineering Mechanics*, 142(12): 04016102.

Dafalias Y.F. and Manzari, M.T. 2004. Simple plasticity sand model accounting for fabric change effects. *Journal of Engineering Mechanics*, 130(6): 622-634.

De Lange D., Honardar S. and Askarinejad A. 2020 Design of a miniature cone penetrometer for the geotechnical centrifuge of Delft University of Technology. *Proceedings of the 4th European Conference on Physical Modelling in Geotechnics (ECPMG 2020)*, Luleå (Sweden).

DNV GL. 2019. *Recommended Practice DNV-RP-A203, Technology Qualification*.

DNV GL. 2016. *Support structures for wind turbines - Standard DNV-GL-ST-0126*.

Houlsby, G.T. 2016. Interactions in offshore foundation design. *Géotechnique*, 66(10): 791-825.

Kaynia A.M. 2019. Seismic considerations in design of offshore wind turbines. *Soil Dynamics and Earthquake Engineering*, 124, 399-407.

Kementzetzidis E., Corciulo S., Versteijlen W.G. and Pisanò, F 2019. Geotechnical aspects of offshore wind turbine dynamics from 3D non-linear soil-structure simulations. *Soil Dynamics and Earthquake Engineering*, 120, 181-199.

Kementzetzidis E., Metrikine A.V., Versteijlen W.G. and Pisanò F. 2020. Frequency effects in the dynamic lateral stiffness of monopiles in sand: insight from field tests and 3D FE modelling. *Géotechnique*, ahead of print, DOI: 10.1680/jgeot.19.TI.024

Klinkvort R.T., Sturm H., Page A.M., Zhang Y. and Jostad H.P. 2020. A consistent, rigorous and super-fast monopile design approach. *Frontiers in Offshore Geotechnics IV: Proceedings of the 4th International Symposium on Frontiers in Offshore Geotechnics*, Austin, TX (USA).

Li Q. 2020. *Response of monopiles subjected to combined vertical and lateral loads, lateral cyclic load, and scour erosion in sand*. PhD thesis, Delft University of Technology.

Li Q., Prendergast L.J., Askarinejad A., Chortis G. and Gavin K.G. 2020a. Centrifuge modeling of the impact of local and global scour erosion on the monotonic lateral response of a monopile in sand. *Geotechnical Testing Journal*, 43(5).

Li Q., Askarinejad A., Gavin K.G. 2020. The impact of scour on the lateral resistance of wind turbine monopiles: an experimental study. *Canadian Geotechnical Journal*, ahead of print, DOI: 10.1139/cgj-2020-0219.

Liu H.Y., Abell, J.A., Diambra A. and Pisanò F. 2019. Modelling the cyclic ratcheting of sands through memory-enhanced bounding surface plasticity. *Géotechnique*, 69(9), 783-800.

Liu H.Y., Diambra A., Abell J.A. and Pisanò F. 2020. Memory-enhanced plasticity modeling of sand behavior under undrained cyclic loading. *Journal of Geotechnical and Geoenvironmental Engineering*, 146(11), 04020122.

Liu H.Y., Kementzetzidis E., Abell J.A. and Pisanò F. 2021. From cyclic sand ratcheting to tilt accumulation of offshore monopiles: 3D FE modelling using SANISAND-MS. *Géotechnique*, ahead of print, DOI: 10.1680/jgeot.20.P.029.

Metrikine A.V., Tsouvalas A., Segeren M.L.A., Elkadi A.S.K., Tehrani F.S., Gómez S., Atkinson. R, Pisano F., Kementzetzidis E., Tsetas A., Molenkamp T., van Beek K. and De Vries P. 2020. GDP: a new technology for Gentle Driving of (mono)Piles. *Frontiers in Offshore Geotechnics IV: Proceedings of the 4th International Symposium on Frontiers in Offshore Geotechnics*, Austin, TX (USA).

Niemunis A., Wichtmann T. and Triantafyllidis T. 2005. A high-cycle accumulation model for sand. *Computers and Geotechnics*, 32(4): 245–263.

Pasten C., Shin H. and Santamarina J.C. 2014. Long-term foundation response to repetitive loading. *Journal of Geotechnical and Geoenvironmental Engineering*, 140(4), 04013036.

Pisanò F. 2019. Input of advanced geotechnical modelling to the design of offshore wind turbine foundations. *Proceedings of the 17th European Conference on Soil Mechanics and Geotechnical Engineering (ECSMGE2019)*, Reykjavik (Iceland).

Skau K.S., Page A.M., Kaynia A.M., Løvholt F., Norén-Cosgriff K., Sturm H., Andersen H.S., Nygaard T.A., Jostad H.P., Eiksund G.R., Havmøller O, Strøm P. and Eichler D. 2018. REDWIN – REDucing cost in offshore WINd by integrated structural and geotechnical design. *IOP Conference Series-Journal of Physics, EERA DeepWind*.

Staubach P. and Wichtmann T., 2020. Long-term deformations of monopile foundations for offshore wind turbines studied with a high-cycle accumulation model. *Computers and Geotechnics*, 124, p.103553.

Stehly T.J. and Beiter P.C. 2019. *2018 cost of wind energy review*. Technical report, National Renewable Energy Laboratory (NREL), Golden, CO (USA).

Taylor R.N. 1995. *Geotechnical centrifuge technology*. Blackie Academic & Professional.

Zhang, W. and Askarinejad, A. 2019. Centrifuge modelling of submarine landslides due to static liquefaction. *Landslides*, 16(10), 1921-1938.