Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-994

Geodata solutions contributing to sustainable development

Clara Modenesi, Niels Walrave*, Joek Peuchen
Fugro, Nootdorp/Utrecht, The Netherlands, n.walrave@fugro.com

ABSTRACT: The energy transition and climate change require sustainable investments including the development of major infrastructure. This implies a need for acquisition and availability of geodata for input in asset design including mitigation of geo-risk. This paper focuses on the application of geodata solutions in two real-world infrastructure projects and their contributions to the United Nations Sustainable Development goals (SDGs). The first case covers the conceptual design phase of a large-scale offshore wind farm in the Netherlands. The geodata solution included the application of regional databases and frequentist and Bayesian data analysis, enhancement of small-strain shear modulus (G_{max}) by use of a multi fidelity data fusion statistical framework, and the application of advanced technologies for 'synthetic' or ultra ultra high-resolution seismic (UUHRS)-derived parameters. The selected design approach aims at increased value of geodata with practically no impact on the timeline for first-electricity-to-shore (SDG 7). The geodata solution of the second example focuses on the detailed design phase of a river levee reinforcement in the Netherlands. The design of the ground model included acquisition of targeted and high-density geodata for accurate interpretation of ground conditions. The resulting 3D ground model enabled tailor-made reinforcement design, incorporating efficient use of sheet piles and soil, reducing environmental impact while enhancing constructability and long-term performance (SDGs 9 and 11). In conclusion, it is postulated that the currently available indicators and guidelines for SDG implementation and progress tracking cannot yet provide unique quantifiable metrics for SDG contributions by geodata solutions.

KEYWORDS: Geodata, sustainability, site characterization, value enhancement, data-driven applications.

1 INTRODUCTION

The global efforts towards a low-carbon economy and the escalating impacts of climate change demand sustainable investments towards the development of infrastructure driven by regulatory requirements. These investments are essential for mitigating environmental risks, but also for fostering long-term social and economic resilience. In this context, the United Nations Sustainable Development Goals (SDGs) provide a globally recognized framework for guiding and measuring progress toward a more sustainable future (United Nations, 2015).

The SDGs encompass 17 interconnected goals, each supported by specific targets and indicators that address critical aspects of environmental protection, social equity, and economic development. Achieving these goals requires informed decision-making, often years in advance of infrastructure development. Informed decisions partially depend on the availability and responsible use of high-quality geodata. Often, specific contributions in the domain of geodata are not captured by conventional sustainability indicators.

Nevertheless, geodata plays a pivotal role in the planning, design and management of sustainable infrastructure projects. Figure 1 shows the progression of two real-world infrastructure projects in terms of efforts. The strategic use of geodata solutions reduces geotechnical uncertainty (vertical axis) as the project advances (horizontal axis) while simultaneously increasing the value of geodata (represented by the orange and green lines and outlines). Geodata solutions are adaptive and innovative ways of applying geodata through leveraging combinations of well-stablished technologies, procedures, and domain expertise, in accordance with (inter)national standards (e.g. ISO 19900, ISO 19901-4, ISO 19901-8, ISO 19901-10, NEN9997-1). These solutions can be applied independently or in sequence. They can be continuously tailored to meet the specific needs of a project, such as sustainable development.

Sections 2 and 3 present selected elements of two geodata solutions, illustrating their context and added value in real-world applications. The presented descriptions are not comprehensive yet highlight key components that demonstrate their contribution to sustainable infrastructure development. The first case (orange line and outline in Figure 1) focuses on the development of an integrated ground model for an offshore wind farm, contributing to SDG 7: Affordable and Clean Energy. The second case (green line and outline) describes the detailed design phase of a river levee reinforcement project, contributing to SDG 9: Industry, Innovation, and Infrastructure and SDG 11: Sustainable Cities and Communities.

Section 4 suggests an industry discussion on the impact of geodata solutions to SDGs. Section 5 provides a summary.

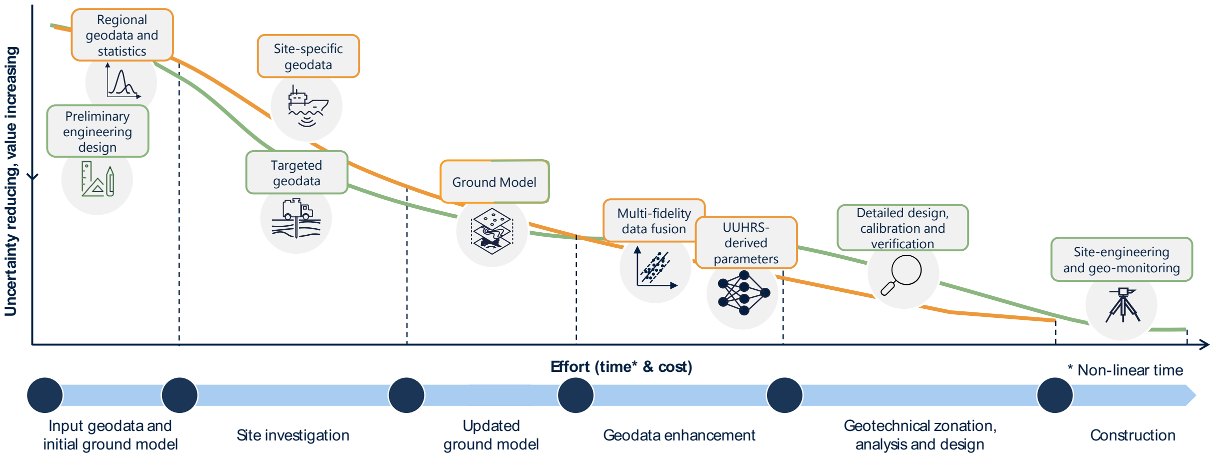

Figure 1. Geodata solutions applied in real-world infrastructure projects: offshore wind farm (in orange) and river levee reinforcement (in green).

2 GEODATA SOLUTION FOR OFFSHORE WIND FARM

2.1 *Nederwiek wind farms, Netherlands*

The Dutch government has designated several areas in the North Sea for the development of offshore wind energy infrastructure (Netherlands Enterprise Agency, n.d.). These areas are known as Dutch 'Wind Farm Zones' (WFZ). The Netherlands Enterprise Agency (RVO) is responsible for supplying potential developers with detailed information about these zones to support their preparations for permit tenders.

The presented geodata solution is for Nederwiek Wind Farm Zone Sites II and III (NWWFZ), located approximately 100 km off the Dutch coast. The planned capacity for wind energy is in the order of 4 GW. Planned infrastructure includes monopiles for wind energy generators and power cables for transport of energy. At the time of submission of this paper (July 2025), site characterization for NWWFZ was ongoing.

2.2 *Regional geodata and statistics*

Site characterisation of NWWFZ benefits from a wealth of pre-existing, high-quality geodata. The database of Dutch North Sea geodata is extensive and is becoming increasingly larger as development projects progress (e.g., Peuchen and Gomez Meyer, 2021). In line with European directives, much of this valuable information is made available through open-access platforms, facilitating informed decision-making for developers and stakeholders.

The geodata solution allows added value by combining Frequentist and Bayesian data analysis approaches. These types of analysis are both covered by international standards (e.g. ISO 19901-4:2025). Bayesian analysis can be regarded as the upper end of industry practice. Particularly, Bayesian analysis for NWWFZ provides straightforward added value by using pre-existing data. This is because of favourable geostatistical similarities between different geotechnical units across nearby wind farm zones (see Murali et al., 2025). In other words, no transfer learning (a type of machine learning) is needed.

Key benefits include:

- Engineering guidance for scoping of marine soil investigation according to ISO (2023);
- Support for developing an initial ground model (e.g., Eady and Steven, 2025);
- Detailed optimization of geodata acquisition strategies with impact on schedules (e.g., reduction of laboratory test quantities, Murali et al., 2025).

2.3 *Site-specific geodata and ground model*

The availability of site-specific geodata for NWWFZ aligns with industry practice (ISO 19901-8 and ISO 19901-4), see Table 1. This allows a robust starting point for site de-risking and data enhancement in support of geotechnical design for windfarm infrastructure.

Table 1 highlights the geodatasets spatial resolution in horizontal (xy in investigation locations per km^2) and vertical (z in geodata values per meter below seafloor BSF) dimensions and volumes of geodata values (xyz is dimensionless). The geodata listed in Table 1 is not exhaustive of the complete scope of the site-specific geodata, and a direct spatial resolution comparison is not applicable. Seismic cone penetration test (SCPT) profiles' vertical resolution can be affected by site and/or operational conditions (e.g., near-field effects, signal-to-ratio; see Parasie et al. 2022). Under similar conditions, a piezo cone penetration test (PCPT) dataset yield approximately 2,500 geodata points over the same depth interval, offering up to 50 times greater geodata volume and significantly higher spatial resolution. Borehole geophysical logging (BGL) key geodatasets can include P and S suspension logging (PSSL), downhole magnetic resonance (DMR) and spectral gamma ray (SGR). The ground model (GM) is according to ISO (2021, 2023, 2025).

2.4 *Multi-fidelity data fusion*

The integration of geodata sets with varying accuracy, spatial resolution and volume into the GM is a complex task. A multi-fidelity data fusion statistical framework (MFDF) facilitates this process (Fugro 2023; Peuchen et al. 2024). An illustrative example of MFDF application involves the verification of limit states in monopile design, which typically requires representative values of the small-strain shear modulus (G_{max}) of soil.

The reference methods (or reference scale) for G_{max} are the in-situ seismic velocity test (SVT) by seismic cone penetration testing and borehole geophysical logging (ISO, 2023). G_{max} values can also be derived from cone penetration test (CPT) correlations with SVT-derived G_{max} values. Global CPT-derived G_{max} values (e.g., Robertson and Cabal, 2015), where stand-alone, represent a higher volume, lower accuracy method compared to SVT-based values. MFDF allows site-specific enhancement by leveraging the higher accuracy SVT-based geodata to the higher volume CPT geodata, using analyses specific to geotechnical soil units captured in the GM. Typically, this results in reduced combined measurement and transformation uncertainties for G_{max} (ISO, 2025).

2.5 *UUHRS-derived parameters*

The geodata solution for NWWFZ includes parameters derived from ultra ultra high-resolution seismic reflection (UUHRS) surveys. The definition of UUHRS is according to the classification of ISO 19901-10 (ISO, 2021). This approach provides about 10^8 to 10^9 UUHRS-derived parameter values for G_{max}, along survey track lines, significantly enhancing spatial coverage of the GM. This high volume supports advanced representations, e.g., by zonation maps (Peuchen et al., 2024) and a 3D ground model visualization using volumetric pixels or 'voxels'. Note that this paper uses 'derived values' at common depth points (CDP). The term 'synthetic values' is also used.

Historic milestones for this approach include:

- 1990's: research project GEOSIS, integration of 2D seismic reflection data and geotechnical data for offshore site investigations, including seismic inversion (e.g. Nauroy et al. 1998);
- 2020: derived values for a single geotechnical parameter for wind farm offshore Netherlands (Peuchen et al., 2022);
- 2021: short method description included in ISO 19901-10 (ISO, 2021).

Table 1. Geodatasets in numbers: spatial resolution and volume.

NWWFZ dimensions	400 km^2	0 m to 60 m BSF	24 km^3
Geodata	xy	z	xyz
Geophysical: 2D UUHRS	$1 \cdot 10^3$	near-continuous to z = 100 m	$1 \cdot 10^6$ x upscale ($\sim 10^{2\text{-}3}$)
Geological:	0.05	≤ 1	200
Geotechnical: PCPT	0.5	50	$0.5 \cdot 10^6$
SCPT	0.1	1	$0.1 \cdot 10^6$
BGL	0.04	5	$5 \cdot 10^3$

3 GEODATA SOLUTION FOR RIVER LEVEE REINFORCEMENT

3.1 *Tiel-Waardenburg levee reinforcement, Netherlands*

The Tiel-Waardenburg (TiWa) levee reinforcement (Figure 2) is for enhancing flood protection infrastructure in the Netherlands. The project is part of the broader Dutch national flood defence program (HWBP).

The presented geodata solution supports design activities for strengthening a 20 km stretch of levee along the river Waal, an important European waterway that flows through densely populated areas. Particularly, the TiWa project aims at minimizing and optimizing the use of sheet pile walls. Sustainable development is a key priority.

At the time of submission of this paper (July 2025), the project was under construction.

3.2 *Preliminary engineering design*

In levee reinforcement projects, sheet pile walls are often efficient and cost effective for enhancing macrostability in areas with weak ground conditions. Obviously, to minimize material usage and optimize sustainable development, it is crucial to place sheet piles only where they are most needed.

The primary value in the preliminary design phase was identification of critical zones along the existing levee alignment that require reinforcement (see light blue coloured body in Figure 2). This phase leveraged pre-existing geodata (e.g., geotechnical parameter values and surface elevations) to define constraints for the initial design and guide the acquisition of targeted geodata.

3.3 *Targeted geodata*

The targeted geodata phase expanded on the pre-existing data. The phase led to a comprehensive database of site investigation data meeting the requirements of Eurocode 7. The database included more than 1,500 CPT profiles and geotechnical logs and laboratory test results for 450 borehole locations. The geodata allowed critical insights into detailed soil stratigraphy and geomechanical properties.

3.4 *Ground model*

The ground model phase included a fully georeferenced 3D ground model. The unified spatial framework enabled comprehensive visualization and analysis of ground conditions, linking soil data to both surface elevation and geometric design of the levee reinforcement (see Figure 2). Additionally, the ground model was designed to generate longitudinal and cross-sectional profiles directly from the integrated data to support automated geotechnical analysis, particularly for slope stability and settlement behaviour. These features enabled simultaneous interpretation of below-ground structures for geotechnical analysis, and above-ground elements for contextual clarity (see Walrave et al. 2025 for more details).

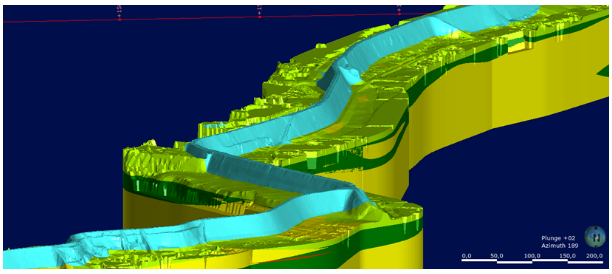

Figure 2. 3D ground model, with existing levee body in light blue.

3.5 *Detailed design, calibration and verification*

The phase of detailed design, calibration and verification included a finite element model with manual integration of the 3D ground model (i.e., in PLAXIS, 2019). This model allowed process streamlining through (1) automated generation of soil stratigraphy and pore water pressure profiles, and (2) automated selection of representative design locations for verification of macrostability limit states of the levee.

The design space included multiple variables, particularly sheet pile length and stiffness, sheet pile anchoring strategies, and installation methods (e.g., vibratory driving versus jacking). Optimal solutions were based on numerical performance and contextual constraints (e.g., proximity to existing structures, site accessibility). This allowed focus on the optimization of the design and iterative simulations of various configurations to enhance design efficiency.

In parallel, automated settlement calculations helped identifying potential settlement hotspots early in the design process. A field test calibrated the model against actual settlement performance. The model calibration allowed increasing use of pre-existing laboratory test data and AI-based estimation of strength parameter values at an early stage (e.g. Stals et al., 2024).

This phase demonstrated a measurable reduction in sheet pile usage, delivering an optimized design compared to the designs considered during earlier phases. These outcomes are consistent with recent findings on carbon footprint reduction through smart geodata utilization (e.g., Hermann et al., 2025).

Geo-monitoring (see Section 3.6) supported verification of design approach for meeting the stringent performance requirements for each levee section.

3.6 *Site-engineering and geo-monitoring*

The phase of site-engineering and geo-monitoring can be regarded as ‘surveillance’ in conformity assessment: confirmation and attestation that the design intent is effectively translated into practice.

The integration of design and construction models enabled direct and controlled application of design optimizations on-site. Real-time geo-monitoring verified the design assumptions and its impacts, through the following measurements:

- Soil settlement;
- Pore water pressure;
- Vibration on adjacent structures.

The acquired geodata enabled control over construction by refining stability assessments and enhancing the understanding of the as-built levee reinforcement. This feedback loop (ongoing, July 2025) supports adaptive construction management, with real-time insights to support strategic decisions for sheet pile installation and soil handling.

4 MEASURABLE SDG CONTRIBUTIONS?

The link between geodata solutions and their supporting role in the sustainable development of infrastructure is evident. But can this role be measured in terms of contributions to the Sustainable Development Goals (SDGs)? The authors are of the opinion that while benchmarking and directional estimates are currently feasible, truly quantifiable measurement is not yet achievable.

Available indicators and guidelines (e.g., ISO/UNDP PAS 53002:2024) offer a broad framework for SDG implementation and progress tracking. However, these frameworks are primarily designed for organizations and supply chains, and do not provide metrics tailored to high-value, data-driven decisions in infrastructure projects.

The authors encourage discussion on the development of clear, transparent, and commonly accepted industry metrics to benchmark the performance of geodata solutions. Such metrics would help communicate their quantifiable value to stakeholders and support informed decision-making in sustainable infrastructure development.

5 SUMMARY

The energy transition and climate change mitigation require the sustainable development of major infrastructure. The UN SDGs provide a framework to guide and track. As demonstrated for the Nederwiek offshore wind farm and the Tiel-Waardenburg levee, geodata solutions contribute to this effort by:

- Applying geodata through adaptive combinations of well-established technologies and procedures, such as seismic inversion, machine learning, and multi-fidelity data fusion;
- Adding value and reducing uncertainty in infrastructure applications, enabling optimized designs, reduced material use, and improved long-term asset performance;
- Aligning with specific project needs and phases from conceptual design to detailed engineering and decommissioning including sustainability objectives.

Although the impact geodata solutions is not directly captured by current SDG indicators, their role in enabling smart, sustainable development of infrastructure decisions is clear. The evolvement of interpretation methods for geodata solutions will continue to support shaping resilient, adaptive, and lower carbon infrastructure.

6 ACKNOWLEDGEMENTS

The authors would like to thank RVO and the Mekante Diek consortium consisting of Ploegam B.V., Dura Vermeer Infra Landelijke Projecten B.V., and Van Oord Nederland B.V. for allowing their projects to be presented in this paper. The authors also thank Fugro for active participation in the United Nations Global Compact (United Nations Global Compact, n.d.). The authors declare no conflict of interest.

7 REFERENCES

Carpentier, S., Peuchen, J., Paap, B., Boullenger, B., Meijninger, B., Vandeweijer, V., Van Kesteren, W. and Van Erp, F., 2021. Generating synthetic CPTs from marine seismic reflection data using a neural network approach. In: Proceedings of the Second EAGE Workshop on Machine Learning, Online, 8–9 March 2021, (1-), pp.1–3. European Association of Geoscientists & Engineers.

Eady, H. and Steven, C., 2025. Best practice approach to ground model optimised geotechnical location selection strategies. In: Proceedings of the 5th International Symposium on Frontiers in Offshore Geotechnics (ISFOG 2025), Nantes, France, 9–13 June 2025, 429-434.

Fugro, 2023. IJmuiden Ver Wind Farm Sites I-IV – Dutch Sector, North Sea, Integrated Ground Model (IGM). Fugro Netherlands Marine. B.V: Nootdorp Fugro Document Number IJV20230127_RVO_IGM_FUG_04.

Hermann, K.M., Walrave, N.S. and Hop, M., 2025. The reuse potential and sustainability of locally reclaimed sand in levees. Proceedings of the DFI-EFFC International Conference on Deep Foundations and Ground Improvement, 1036-1043.

International Organization for Standardization, 2019. Petroleum and natural gas industries — General requirements for offshore structures (ISO 19900:2019). Available at: https://www.iso.org/standard/69761.html

International Organization for Standardization, 2021. Petroleum and natural gas industries – Specific requirements for offshore structures – Part 10: Marine geophysical investigations (ISO 19901-10:2021). Available at: https://www.iso.org/standard/77017.html

International Organization for Standardization, 2023. Oil and gas industries including lower carbon energy — Offshore structures — Part 8: Marine soil investigations (ISO 19901-8:2023). Available at: https://www.iso.org/standard/82890.html

International Organization for Standardization, 2025. Oil and gas industries including lower carbon energy — Specific requirements for offshore structures — Part 4: Geotechnical design considerations (ISO 19901-4:2025). Available at: https://www.iso.org/standard/79594.html

International Organization for Standardization and United Nations Development Programme, 2024. ISO/UNDP PAS 53002:2024: Guidelines for contributing to the United Nations Sustainable Development Goals (SDGs). Available at: https://www.iso.org/standard/87945.html

Murali, M., Peuchen, J., Constant, M., Spinewine, B., Vrolijk, M. and Lebbink, P.P., 2025. Optimising laboratory test quantities using Bayesian statistics. In: Proceedings of the 5th International Symposium on Frontiers in Offshore Geotechnics (ISFOG 2025), Nantes, France, 9–13 June 2025, 434-439.

Nauroy, J.F., Colliat, J.L., Puech, A., Kervadec, J.P. and Meunier, J., 1998. GEOSIS: Integrated approach of geotechnical and seismic data for offshore site investigations. In: P.K. Robertson and P.W. Mayne, eds. Geotechnical Site Characterization: Proceedings of the First International Conference on Site Characterization – ISC'98, Atlanta, Georgia, USA, 19–22 April 1998. Vol. 1, 497-502.

NEN, 2023. NEN9997-1:2023: Eurocode 7 NL – Geotechnisch ontwerp van constructies – Deel 1: Algemene regels.

Netherlands Enterprise Agency. (n.d.). Offshorewind RVO. Available at: https://offshorewind.rvo.nl/

Parasie, N., Franken, T. and Peuchen, J., 2022. Assessment of seismic cone penetration testing for small strain shear modulus. In: Proceedings of Cone Penetration Testing 2022, Bologna, Italy, 8–10 June 2022, 204-209.1

Peuchen, J., van Kesteren, W., Vandeweijer, V., Carpentier, S. and Van Erp, F., 2022. Upscaling 1,500,000 synthetic CPTs to voxel CPT models of offshore sites. In: Proceedings of Cone Penetration Testing 2022, Bologna, Italy, 8–10 June 2022, 641-645.

Peuchen, J. and Gomez Meyer, E., 2021. Geo-intelligence from databases of offshore in situ tests in public domain. In: Proceedings of the 6th International Conference on Geotechnical and Geophysical Site Characterization (ISC'6), Online (originally Budapest, Hungary), 26–29 September 2021, 521-526.

Peuchen, J., Murali, M., Sijbrandij, L., Atkins, S., Carpentier, S., Boullanger, B., Vandeweijer, V. and Vrolijk, M., 2024. Small strain shear modulus derived from offshore seismic reflection data. In: Proceedings of the 7th International Conference on Geotechnical and Geophysical Site Characterization (ISC'7), Barcelona, Spain, 18–21 June 2024, 240-245.

PLAXIS, 2019. PLAXIS 2D Reference Manual. Bentley Systems International Limited.

Stals, M.T., Siderius, K. and Brinkgreve, R.B.J., 2024. Advanced constitutive model parameter determination, optimisation and selection using a database of triaxial tests and machine learning tools. In: Proceedings of the XVIII European Conference on Soil Mechanics and Geotechnical Engineering (ECSMGE 2024), Lisbon, Portugal, 26–30 August 2024, 861-864.

United Nations, 2015. Transforming our world: The 2030 agenda for sustainable development. Available at: https://sdgs.un.org/2030agenda

United Nations Global Compact, n.d. UN Global Compact. Available at: https://www.unglobalcompact.org

Walrave, N.S., Hop, M., van der Kop, J., Hermann, K.M., Haile, A., Unal, E. and Schuringa, J.W.T.A., 2025. 3D ground model Neder-Betuwe levee reinforcement project in The Netherlands. In: Proceedings of the DFI-EFFC International Conference on Deep Foundations and Ground Improvement, Bruges, Belgium, 21–23 May 2025, 192-201.