Geo-intelligence from databases of offshore in situ tests in public domain

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ABSTRACT: In situ test data are increasingly available in public domain databases. Key drivers for Europe are the energy transition initiatives and the European INSPIRE directive for spatial information. What is available and how can we use such geodata now and for future geo-intelligence? Can we develop enhanced site-specific parameter values? Can we improve spatial parameter assessment by integrating in situ test data with ultra-high resolution seismic reflection data? Examples are presented for in situ test data available in the public domain for the Dutch sector of the North Sea, particularly for rapidly expanding wind energy assets. In-situ data sets mainly cover piezocone penetration tests (CPT), seismic CPTs and borehole geophysical logging results.

Keywords: in-situ test; offshore; database

1. Introduction

In situ test data are increasingly available in public domain databases. Key drivers for Europe are the energy transition initiatives and the European INSPIRE directive for spatial information [1].

This paper focuses on in-situ test data available in the public domain for the Dutch sector of the North Sea, particularly piezocone penetration tests (CPT), seismic cone penetration tests (SCPT) and borehole geophysical logging (BGL) results. Open-access to these data is of interest, primarily because of a wider context of available geodata, including geological information, UHR (ultra-high resolution) seismic reflection data and advanced laboratory test data.

Can we use such geodata now and for future geo-intelligence? Can we develop enhanced site-specific parameter values? Can we improve spatial parameter assessment by integrating in-situ test data with ultra-high resolution seismic reflection data? Should we envisage disruptive technologies?

The following sections provide an outline of current status, example developments and opinions on prospects.

2. Dutch sector of the North Sea

The Dutch sector of the North Sea covers an area of about 57 000 km^2. Water depths are up to 70 m. Fig. 1 shows a large part of the Dutch sector of the Norh Sea, i.e. the left of a yellow-brown line representing the territorial (formal sea-land) boundary for the North Sea. A geological map [2] is shown as background and blue polygons represent areas of planned offshore wind farm zones for which extensive in situ test data are (or will be) in the public domain.

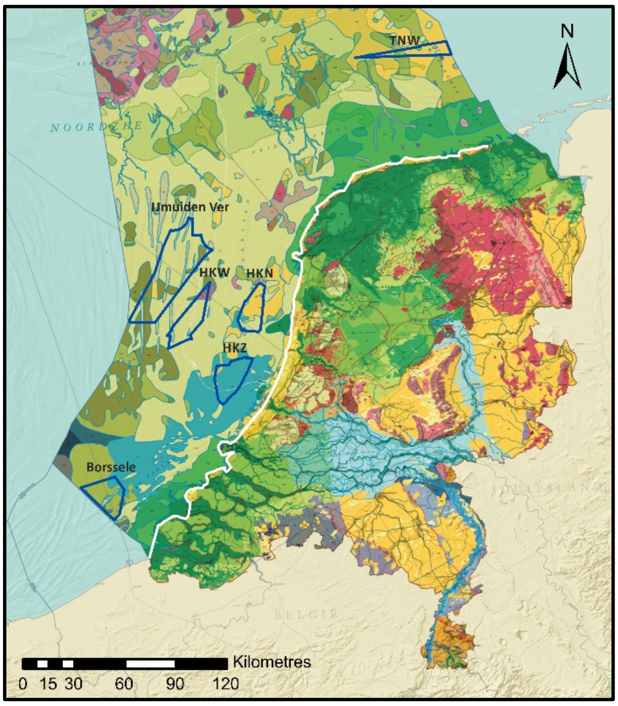

Figure 1. Dutch sector of North Sea, based on [2]

Existing and future assets and resources for the Dutch sector include a marine biological ecosystem, fishing, infrastructure for shipping, climate monitoring systems, wind energy, hydrocarbon fossil energy facilities, energy transportation systems (cables and pipelines), CO_2 and H_2 storage, and aggregates (sands) for coastal defence and maintenance. The development of wind energy facilities is one of the prime drivers for increasing availability of public-domain geodata. Primarily, this is because of a licensing approach in which the Dutch government provides geotechnical and geological data to tenderers for design, installation and operation of wind farms.

The seabed of the Dutch Sector of the North Sea is generally favourable for in situ testing. The seabed predominantly consists of dense sands of Holocene and Pleistocene origin, deposited in marine, coastal, tidal, fluvial, aeolian or glacial environments. Episodic low-energy conditions favoured local fine grained sediments and peat in tidal, deltaic and lagoonal depositional environments.

CPTs conducted in non-drilling mode [3], i.e. single push from seafloor, typically achieve depths of >30 m below seafloor (BSF). The shallower penetrations (say 25 m) are more common for the northern part of the Dutch Sector, which was exposed to glacial ice sheet loading. Fig. 2 shows an offshore CPT system that commonly achieved penetrations up to about 50 m in the southern part of the Dutch sector. Some of these systems incorporate fluid injection above the cone penetrometer for reduction of rod friction [4]. CPT penetrations to below 100 m can typically be achieved in drilling mode [3], i.e. push from the bottom of a borehole, whereby the use of special cone penetrometers can be necessary to allow measurement of cone resistance values in the range of 50 MPa to 120 MPa.

Figure 2. Offshore CPT system with coiled push rod for about 50 m penetration (courtesy Fugro)

3. DATABASES – PUBLIC DOMAIN

Table 1 presents an excerpt of relevant public domain data for the the Dutch Sector of the North Sea. The BRO database [5] is a Subsurface Key Register ("Basis Registratie Ondergrond" or "BRO" in Dutch). It combines, harmonises, unifies and builds on existing databases. The BRO database and planned integration/ enhancements meet the INSPIRE requirements.

The RVO part of the BRO database should have high potential for enhanced site-specific parameter values and improved spatial parameter assessment. RVO is a Dutch government organisation. One of its tasks is to provide (public) geotechnical and geological data to tenderers for contracts for wind farm development and operation. The available geodata are typically of high quality, typically meeting the requirements of ISO 19901-8:2014 [3] for geotechnical data and the requirements of ISO 19901-10:2021 for marine geophysical investigations [6].

Table 1. Overview of BRO database – offshore (based on [7])

BRO Subsurface Key Register		
Databases/repositories	**Data type and description**	**Remarks**
DINOloket - Data and information on the Dutch subsurface www.dinoloket.nl [8]	- Geological borehole data, including borehole log profiles, sample descriptions, soil classifications, sample photographs, results of chemical analyses, particle size distributions and geophysical well logging profiles - Typical depth range to about 12 m below ground surface (seafloor) - Geodata for > 500 000 locations onshore and offshore, acquired from as early as 1605 to present	High data density for onshore; low density offshore
	- Seafloor sediment data, including sample descriptions, results of chemical analyses and particle size distributions - Information for > 4 400 locations acquired from 1934	Only offshore
	- Geotechnical cone penetration test (CPT) data - Typical depth range to about 20 m below ground surface - Geodata for > 175 000 locations onshore and offshore, acquired from 1937	High density for onshore; low density offshore
	- Shallow seismic reflection data	Planned
NLOG - Information about oil, gas, geothermal energy exploration and production in the Netherlands and the Dutch sector of the North Sea, acquired under the Mining Act www.nlog.nl [9]		
	- Borehole data, including borehole log profiles, lithostratigraphy, core and other sample measurements and geophysical well logging profiles	Onshore and offshore
	- Seismic reflection data (2D and 3D)	
	- Hydrocarbon production data and reservoir injection data	
	- Information on field and production licenses of developed fields	
	- Models, maps and spatial datasets	
RVO - Data acquired for (planned) offshore wind developments shown in Fig. 1 www.rvo.nl [10]	- Detailed marine geophysical data for > 1 000 km^2 (to December 2019), bathymetry, sidescan sonar data, 2D UUHR seismic reflection data, 2D (and 3D) UHR seismic reflection data	Planned for future incorporation in BRO
	- Borehole and seafloor sampling data for about 140 location clusters (to December 2019), including geotechnical logs, geological and geotechnical laboratory test data, groundwater information and borehole geophysical logging profiles	
	- Cone penetration test (CPT) data for about 400 location clusters (to December 2019), including pore pressure dissipation tests (PPDT), thermal dissipation tests (T-CPT) and seismic downhole tests (SCPT)	
	- Models, maps and spatial datasets	

4. ENHANCED SITE-SPECIFIC PARAMETER VALUES

This section presents an example of geo-intelligence by combining geodata for site-specific enhancement of shear wave velocity (Figures 3 to 6). Shear wave velocity (v_s) is an important geotechnical parameter for earthquake hazard assessment [11], [12]. It is also commonly used for obtaining input for verification of serviceability limit states, by calculation models requiring G_{max}, shear modulus at small strain and applying a transformation model for v_s and G_{max}. As is the case for most geotechnical parameters, no methods are available for obtaining measured values of (in situ or laboratory) shear wave velocity.

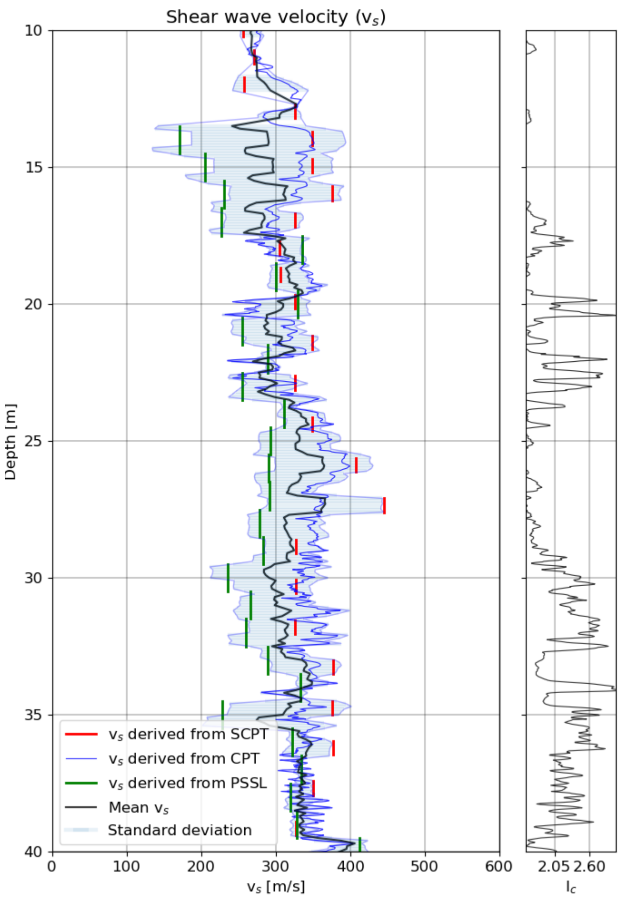

Figure 3. Location HKW025 of the HKW offshore windfarm: comparison of derived values of shear wave velocity v_s from in situ tests

Derived values of v_s can be obtained by a range of in-situ methods, where "derived value" is defined as "value of a geotechnical parameter obtained by theory, correlation or empiricism from test results" [13]. Estimates of true values for in situ v_s can be made. In geotechnical practice, such estimates are inevitably approximate. Comparisons of the results of multiple methods can provide input for estimates of true values. It should be emphasized that statistics for derived values and for comparisons of multiple methods are not necessarily representative of in situ conditions. Aleatory uncertainties are covered to some degree. Epistemic uncertainties are not.

Figure 3 shows a comparision of derived values of shear wave velocity v_s from in situ tests performed at location HKW025 of the planned Hollandse Kust (west) wind farm, shown as "HKW" in Fig. 1 and available in the RVO database presented in Table 1. The data were acquired according to ISO 19901-8:2014 [3]. The selected depth range covers the Yarmouth Roads Formation [14]. This formation was deposited in predominantly fluvial to deltaic environments and soils consists of a) medium dense to very dense, slightly silty to very silty, fine and medium sand, with laminae to medium beds of clay and silt, and b) high strength to very high strength clay or silt, with laminae of sand. Values of CPT soil behaviour type index (I_c, Fig. 3) illustrate vertical variability in soil conditions. For the HKW windfarm, values of $I_c < 2.05$ and $I_c > 2.6$ typically indicate sand and clay respectively. Intermediate I_c values typically indicate transitional soils.

The HKW025 location includes (clustered) data from a SCPT push (non-drilling deployment; [3]) and from a borehole including borehole geophysical logging, particularly P and S suspension logger (PSSL) data. The SCPT push and PSSL borehole are at about 8 m horizontal spacing.

The v_s values derived from CPT-based correlation are according to [15] and presented per 20 mm depth spacing. The data points are connected to a single line. Note that multiple correlations are available in the public domain. The selected correlation provides a good fit for the SCPT data.

The v_s values derived from SCPTs are for 0.5 m depth zones, presented individually. The SCPT data were acquired by means of a dual seismic cone penetrometer with 0.50 m fixed spacing between receivers. Similarly, the v_s values derived from PSSL data are for 1.00 m fixed spacing between receivers. Acoustic source positions differ: source at seafloor for the SCPT and source about 0.6 m below the lower set of receivers for the PSSL.

The "Mean v_s" and "Standard deviation" values of Fig. 3 were calculated by pairing of v_s values derived from CPT data with v_s values derived from PSSL and/or SCPT data. For SCPT and PSSL data points, the v_s value was assigned at the mid-point between the two receivers and data points were paired when the distance between the respective mid-points was less than 0.7 m. CPT-based values of v_s were averaged for the depth range overlapping with the respective PSSL and/or SCPT depth range (distance between receivers).

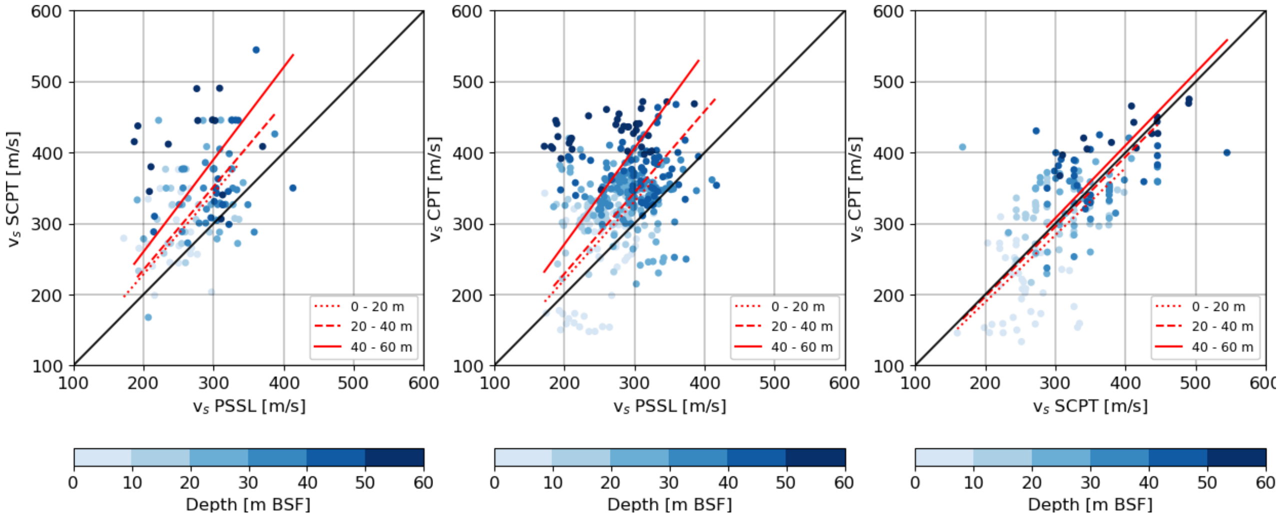

Figure 4. Comparison of derived values of shear wave velocity v_s from in situ tests of five HKW locations including trend lines for soil behaviour type index (I_c)

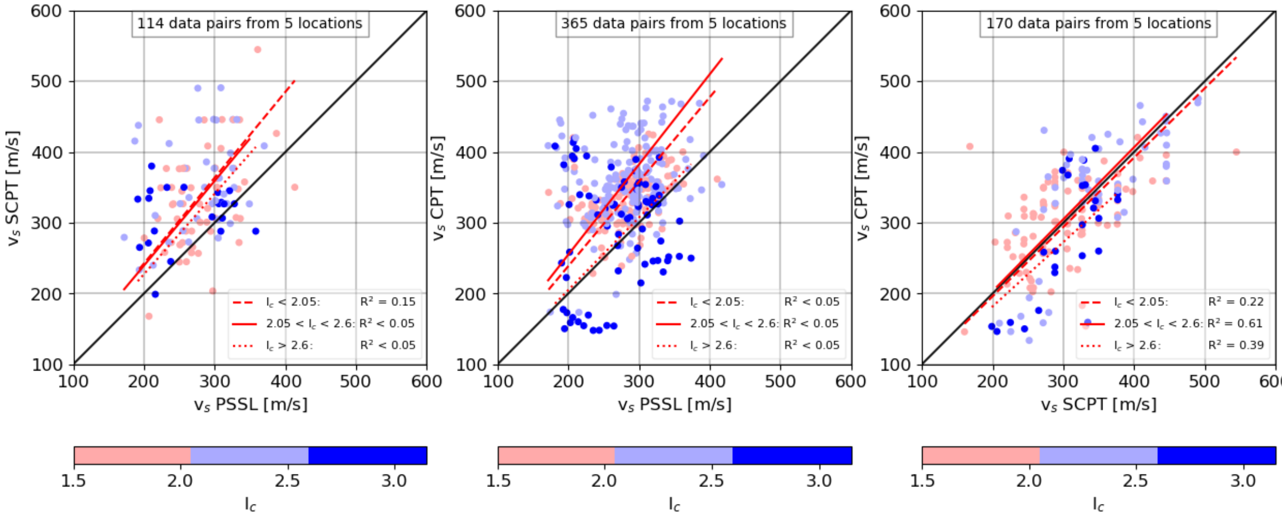

Figure 5. Derived values of shear wave velocity v_s as for Fig. 4, but with trend lines for depth ranges

Fig. 4 and Fig. 5 expand on Fig. 3. Particularly, these figures include (1) an extended depth range for HKW025, (2) four additional HKW locations, and (3) multiple geological formations. The combined depth ranges are: CPT data from seafloor to 60 m depth, SCPT data between 1 m and 55 m, and PSSL data between 6 m and 70 m depth. The coefficient of variation (CoV) for v_s per location ranges from 12% to 19%, with an average of 16 %. This compares with CoV = 13 % for the data of Fig. 3.

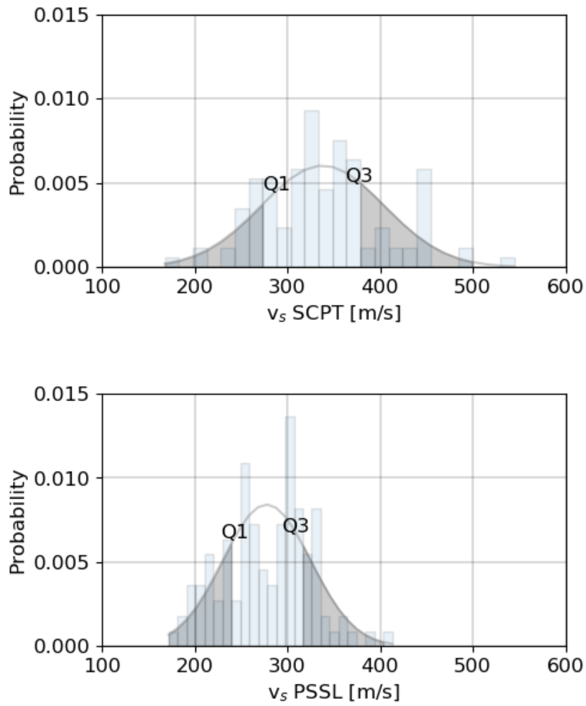

Figure 6. Normal distributions of PSSL and SCPT shear wave velocities

Fig. 4 and Fig. 5 cover 134 sets of CPT, SCPT and PSSL data. The figures include (1) the number of data points available for bivariate pairing, e.g. 114 data points for for SCPT and PSSL correlation and (2) R_0^2 values for linear regression forced through zero-origin. A cut-off value of $R_0^2 = 0.05$ was selected for "no correlation".

It can be observed that v_s values derived from PSSL data are, on average, 20 % (65 m/s) slower than the corresponding SCPT velocities, with CoV between 9% and 14%. A larger variability of v_s derived from SCPT can also be noted, compared with v_s derived from PSSL. The 1st and 3rd quartiles (Q1 and Q3 of Fig. 7) of v_s derived from PSSL are 243 m/s and 309 m/s, respectivily. Q1 and Q3 for the SCPT data are 288 m/s and 377 m/s, respectively. The interquartile range (IQR) for v_s from SCPT is 35% larger than the IQR of v_s from PSSL.

PSSL velocities are 17% (55 m/s) slower than CPT-based v_s values, with CoV between 8% and 18%. The SCPT velocities are, on average, 1 % (2 m/s) faster than CPT-based v_s values, with CoV between 7 % and 19 %.

The extracted data set is clearly limited and falls far short of big data. Nevertheless, some observations allow tentative discussion.

- The data set covers a relatively narrow range of v_s values; between about 200 m/s and 400 m/s for the PSSL data. This compares with, for example, v_s values of up to 750 m/s for soils covered by [12] for seismic design of offshore structures. This narrow range thus limits trend analysis.
- The CPT-based correlation for v_s can serve as proxy for SCPT data. The reason for this is that the correlation is based on a data base of SCPT data, i.e. does not consider PSSL data as reference. Figures 3 to 5 confirm the generally applicability of the CPT-based correlation for SCPT data. However, it can be noted the CPT-based correlation is probably biased to the 5 m to 30 m depth range, for which the more reliable data can be expected to be available in the data base (see comments below). This may possibly explain the weak depth-trend for CPT-PSSL data for HKW site; the ratio between v_s derived from CPT correlation and v_s derived from PSSL increases with depth from 1.1 (0 to 20 m) to 1.35 (40 m to 60 m).
- The uncertainty of v_s values derived from SCPTs is typically high for the upper 5 m below seafloor [3], [16]. Contributing factors include (a) seawater wave interference effects, particularly for interbedded, heterogeneous soil and (b) influence from a seafloor template (seabed frame) required to provide support to the data acquisition activities. In this regard it can be noted that SCPT-derived values for the upper 5 m are approximately 50 m/s faster than CPT-derived values (Fig. 4), compared to a fair 1:1 fit for the general SCPT-CPT data pairing. Appropriate caution is needed in practice, when using in situ test data for this depth range.
- PSSL data are largely unaffected by depth below seafloor, as the source to receiver distance is constant. On the other hand, the importance of seismic trace stacking increases with depth for SCPT data because of reducing signal-to-noise ratios related to increasing distance between acoustic source and receivers. This comparitive PSSL-SCPT setting possibly provides a partial explanation of the apparent depth trend (left diagram of Fig. 5, particularly the 40 m to 60 m depth range).
- A common discussion point for deriving v_s values is actual-versus-assumed travel paths of acoustic waves. The associated uncertainty is typically assessed to be low for homogenous soil, but may be substantial for interbedded, heterogeneous soil such as shown in Fig. 3 by soil behaviour type index I_c.

5. SPATIAL PARAMETER ASSESSMENT - INTEGRATING UHR GEOPHYSICAL DATA

The use of geophysical data for spatial assessment of geotechnical parameters has been attempted for more than a quarter of a century (Fig. 7), for example as documented by [10], [17], [18], [19] and [20], essentially following concepts applied for characterisation of (deep) oil and gas reservoirs. This is because in situ test data typically apply to specific points in space, for example vane shear tests, and for some methods, to 1-dimensional (vertical) profiles, for example cone penetration tests. On the other hand, geophysical data data are typically available for 2-dimensional (vertical) profiles, and increasingly as voxel data (3D).

In-situ test methods have seen little development over the past 25 years, but marine UHR seismic reflection data [6] improved significantly with respect to resolution as well as signal-to-noise ratio.

The following can be noted about *acquisition* of UHR seismic reflection data:

- Improvements in Sparker source signal: a multi-level stacked Sparker fires different amounts of energy over specific tip counts at different depths. As a result, the ghost return and the bubble pulse are significantly suppressed. The resulting acoustic pulse is thus sharper and has a broader, flatter frequency spectrum compared to traditional Sparker sources.
- Improvements in streamer configuration: streamers now typically have a 1 m group interval each with a single hydrophone and they are towed deeper than before. Single hydrophones can record higher frequencies especially at the higher offset channels, with a trade-off for slightly lower signal-to-noise ratio. Deeper tow gives an increase in signal-to-noise ratio but the receiver ghost is more severe.
- Improvements in positioning: acoustic sources and streamers are increasingly equipped with accurate GNSS positioning systems. Better positioning of the survey spread implies improved data stacking for correct spatial position.

The following can be noted about *processing* of UHR seismic reflection data:

- Recent advances in deghosting algorithms have enabled recovery of acoustic energy previously masked by ghost reflections. As a result, streamers can be towed deeper, enhancing signal to noise ratio.
- Improvements in residual static algorithms have allowed for a significant improvement in data bandwidth after stack. These algorithms calculate and remedy static data shifts, related to wave height and streamer control. The shifts vary from trace to trace causing attenuation of higher frequencies when data are stacked. Broadening the bandwidth typically increases data resolution, quality and, ultimately, potential for extraction of attributes of interest for geotechnical characterisation.

Fig. 8 illustrates a selection of CPT attributes (cone resistance q_c, sleeve friction f_s, friction ratio R_f and pore pressure u_2) and UHR seismic reflection attributes (amplitude *AMP*, inverted trace *Itrace* and interval velocity *IntV*).

It cannot be ignored that the incremental improvements in geophysical data and data sciences (machine learning) have potential for a break-through in (offshore) spatial site characterisation and object identification (for example boulders). In this regard, it can be noted that [10], [19] and [20] made use of data planned to be incorporated in the BRO database. Their focus was on extracting added-value from correlation of high-strain CPT data and low-strain geophysical data. Such correlation implies a significant compatibility challenge. Better correlation and compatibility may be expected with low-strain parameters, such as in-situ shear wave velocity (see above). On the other hand, high-strain CPT parameters are more readily available, robust and repeatable (e.g. [21]), compared to benchmarking by in-situ shear wave velocity.

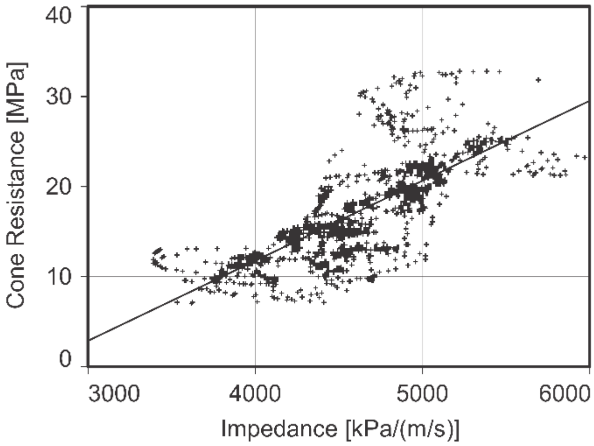

Figure 7. Early attempt at deriving geotechnical properties from UHR seismic reflection attributes, after [17], reproduced with permission

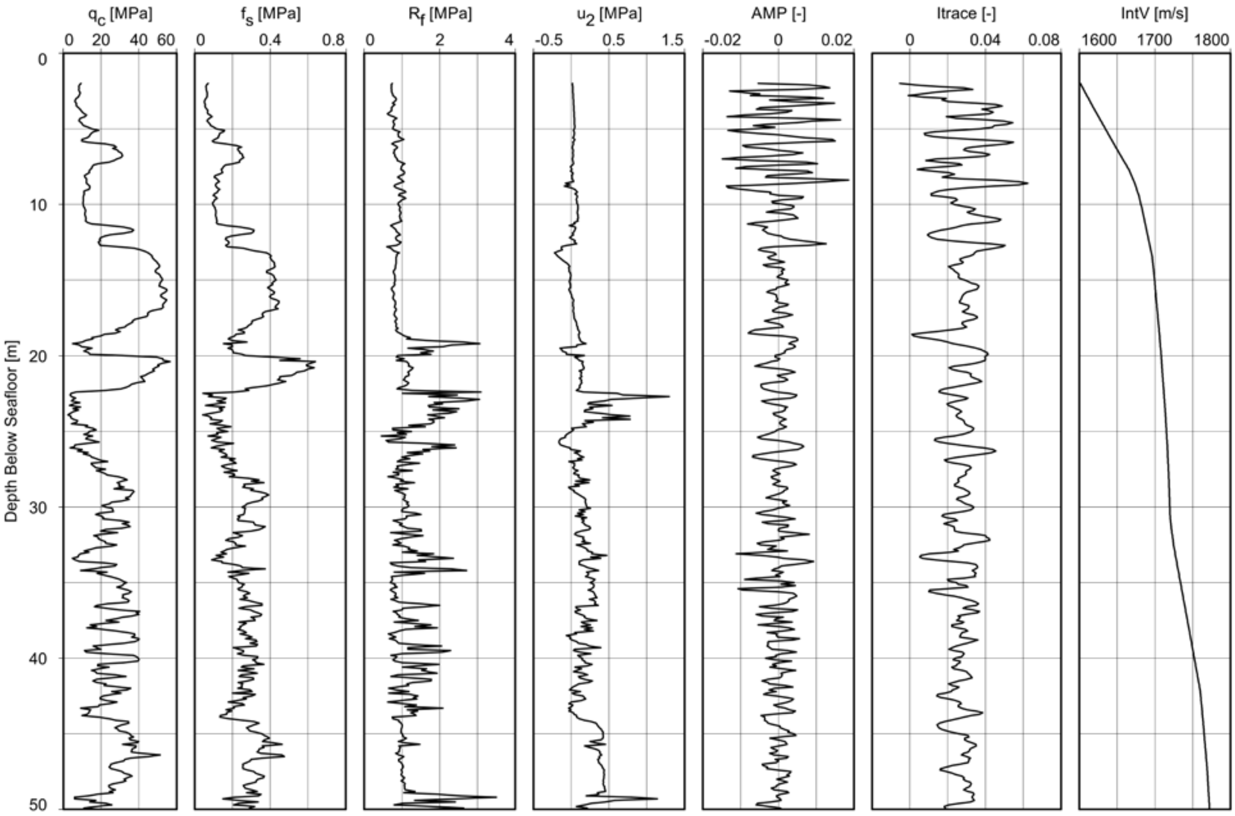

Figure 8. Correlating CPT values with UHR seismic reflection attributes

6. DISCUSSION AND CONCLUSION

A 3D ground model is required for safe and sustainable performance of structures [22]. In-situ test data typically apply to specific points in space, and for some methods, to 1-dimensional (vertical) profiles. For intelligent extraction of value from in-situ test data, we thus require inclusive context, by companion data, comparison with structure performance monitoring, geological models, scientific research of specific features, and, increasingly, data sciences (machine learning) applied to large amounts of data. This inclusive context is enhanced by ongoing expansion of public domain databases on geodata.

Traditionally, geo-intelligence from databases in the public domain will facilitate regional planning for sustainable management of infrastructure and natural resources. The increasing open-and-easy access to high quality data allows us to explore wider and, possibly unprecedented, opportunities, as illustrated here by some examples that include offshore in-situ test data.

Benchmarking is a common discussion point for geo-intelligence, as we typically have to deal with „approximate estimates of true values“ of parameters. Benchmarking of geotechnical in-situ test data is no exception. In practice, we conduct *feasible* measurements, i.e. trade-off in technology, value, ecomomics and schedule. These measurements typically cover time, length (geometry), force, displacement and pressure). Geotechnical parameter values are then derived from the measurements by „transformation“ using empirical and theoretical corrections and models. This setting can be argued to imply limited value of in-situ test databases, except if we can efficiently extract value from large quantity, approximate, data. Such value extraction seems increasingly feasible by computational algorithms and could possibly lead to development of disruptive technologies, as seen elsewhere.

7. REFERENCES

[1] INSPIRE Infrastructure for Spatial Information in Europe, 2018. Available from: https://inspire.ec.europa.eu/.

[2] GDN, 2018. *Geological Overview Map of the Kingdom of the Netherlands 1:600,000 (centennial edition)*, Utrecht: TNO-Geological Survey of the Netherlands, 1 map sheet.

[3] International Organization for Standardization, 2014. *ISO 19901-8:2014 Petroleum and Natural Gas Industries - Specific Requirements for Offshore Structures – Part 8: Marine Soil Investigations*. Geneva: ISO.

[4] Jefferies, M.G. and Funegard, E., 1983. *Cone penetration testing in the Beaufort Sea*. Surrey: Western Geosystems, Surrey, 24 p

[5] BZK Ministerie van Binnenlandse Zaken en Koninkrijk Relaties – Programmabureau BRO, 2018. Ketenontwerp BRO, De Basisregistratie Ondergrond nader verklaard. Available from: https://www.digitaleoverheid.nl/voorzieningen/gegevens/inhoud-basisregistraties/bro/.

[6] International Organization for Standardization, 2021. *ISO 19901-10:2021 Petroleum and Natural Gas Industries - Specific Requirements for Offshore Structures – Part 8: Marine Geophysical Investigations*. Geneva: ISO.

[7] Peuchen, J., Meijninger, B.M.L. and Brouwer, D., 2019. North Sea as geo database, AIMS Geosciences, Vol. 5, No. 2, pp. 66-81.

[8] DINOloket Data and Information of the Dutch Subsurface, 2018. Available from: https://www.dinoloket.nl/.

[9] NLOG information about oil, gas and geothermal energy exploration and production in the Netherlands and the Dutch sector of the North Sea continental shelf, 2018. Available from: https://www.nlog.nl/.

[10] RVO Rijksdienst voor Ondernemend Nederland, 2021. Offshore wind energy. Available from: https://english.rvo.nl/subsidies-programmes/sde/offshore-wind-energy.

[11] European Committee for Standardization, 2004. *EN 1998-1:2004 Eurocode 8: Design of Structures for Earthquake Resistance - Part 1: General Rules, Seismic Actions and Rules for Buildings*. Brussels: CEN. (With Corrigendum EN 1998-1:2004/AC, July 2009).

[12] International Organization for Standardization, 2017. *ISO 19901-2:2017 Petroleum and natural gas industries -- Specific requirements for offshore structures -- Part 2: Seismic design procedures and criteria*. Geneva: ISO.

[13] European Committee for Standardization, 2004. *EN 1997-1:2004 Eurocode 7: Geotechnical Design - Part 1: General Rules*. Brussels: CEN. (With Corrigendum EN 1997-1:2004/AC, February 2009 and Amendment EN 1997-1:2004/A1:2013)

[14] Rijsdijk, K.F., Passchier, S., Weerts, H.J.T., Laban, C., Van Leeuwen, R.J.W., and Ebbing, J.H.J., 2005. Revised Upper Cenozoic Stratigraphy of the Dutch Sector of the North Sea Basin: towards an Integrated Lithostratigraphic, Seismostratigraphic and Allostratigraphic Approach. *Netherlands Journal of Geosciences – Geologie en Mijnbouw*, Vol. 84, No. 2, pp. 129-146.

[15] Robertson, P.K. and Cabal, K.L., 2010. *Guide to Cone Penetration Testing for Geotechnical Engineering*. 4th ed., Signal Hill: Gregg Drilling & Testing.

[16] Gibbs, P., Pedersen, R.B., Krogh, L., Christopher, N., Sampurno, B. and Nielsen, S.W., 2018. In Hicks, Pisanò & Peuchen (Eds). Challenges in marine seismic cone penetration testing. *Proceedings of the 4th International Symposium on Cone Penetration Testing (CPT'18), 21/22 June 2018*, Delft: Delft University of Technology, pp. 303-308.

[17] Meunier, J., Dubois, J., Kuhns, H., Desvallières, T. and Puech, A.A., 1997. Seabed survey by VHR multichannel and borehole seismic: GEOSIS project. In Conference on High Frequency Acoustics in Shallow Water, La Spezia, Italy, July 1997.

[18] Verlinden, V.W.J., 2009. *The Depositional Environments and Shallow Subsurface Architecture of the Northeastern Caspian Sea*. MSc. Thesis, Delft University of Technology. Department of Geotechnology.

[19] Minorenti, V., Brouwer, D.R.H. and Van Kesteren., W., 2017. 3D ground model using geophysical and geotechnical data - a case study from the Netherlands. In Near Surface Geoscience Conference & Exhibition, 3-7 September, Malmö, Sweden, Paper No. We 23 A08.

[20] Sauvin, G., Vanneste, M. and Madshus, C., 2018. High-resolution quantitative ground-model for shallow subsurface. In Near Surface Geoscience Conference & Exhibition, 9-12 September.

[21] Peuchen, J. and Terwindt, J., 2015. Measurement uncertainty of offshore cone penetration tests. In Meyer, V. ed. Frontiers in Offshore Geotechnics III: proceedings of the Third International Symposium on Frontiers in Offshore Geotechnics ISFOG 2015, Oslo, Norway, 10-12 June 2015, Boca Raton: CRC Press, pp. 1209-1214.

[22] International Organization for Standardization, 2015. *ISO 2394:2015 General Principles on Reliability for Structures*. Geneva: ISO.