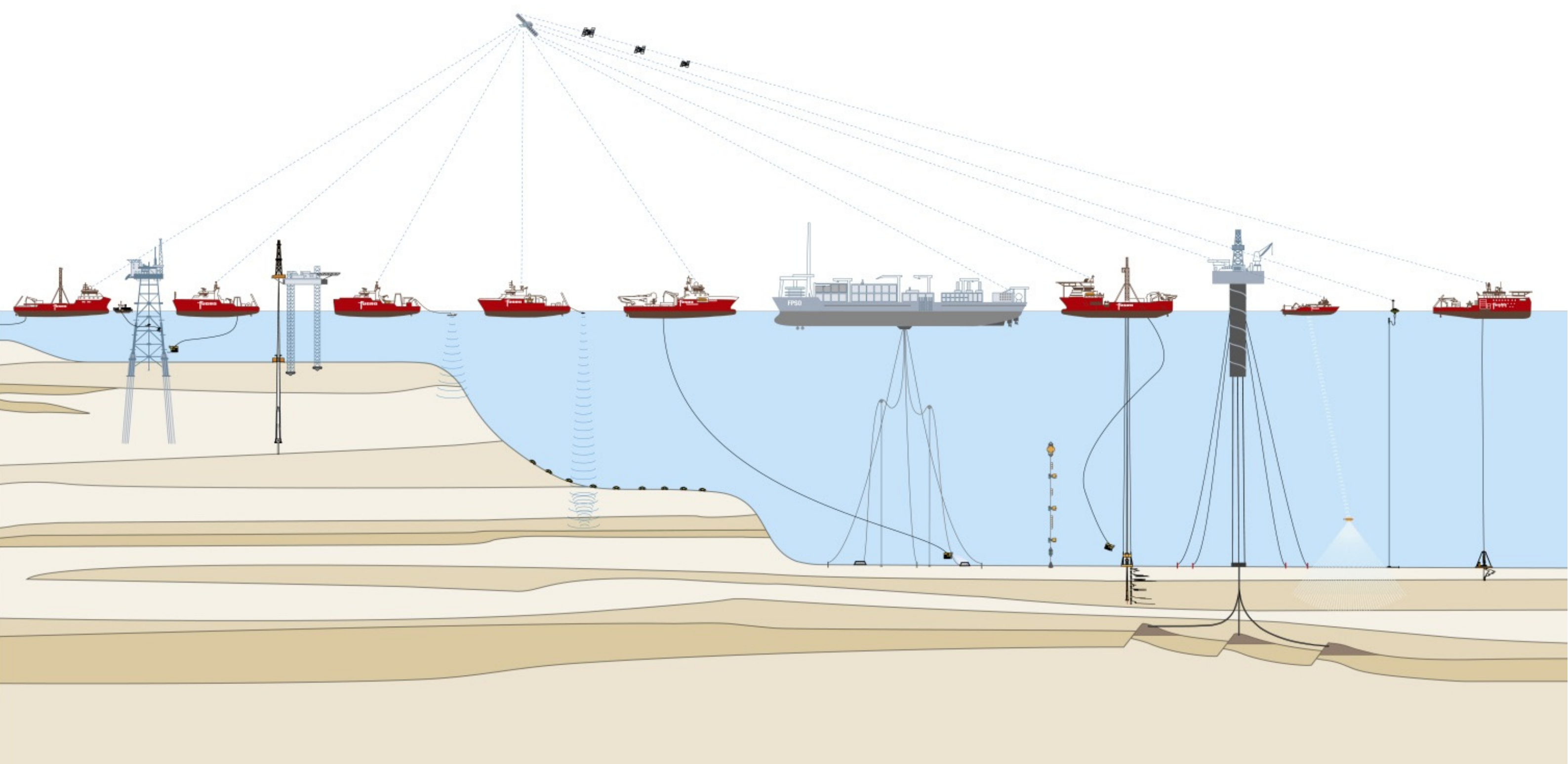
Technical Note
Geotechnical Guidance for Cyclic Resistance of Sandy Soils
Borssele Wind Farm Area
Dutch Sector, North Sea

Client Reference WOZ1500010
Fugro Reference N6083/TN-CYC

Rijksdienst voor Ondernemend Nederland

Rijksdienst voor Ondernemend Nederland (RVO)



Technical Note Geotechnical Guidance for Cyclic Resistance of Sandy Soils Borssele Wind Farm Area Dutch Sector, North Sea	
Ultimate Client	Rijksdienst voor Ondernemend Nederland (RVO)
Client Contact	Mr R. de Bruijne
Client Reference No.	WOZ1500010
Fugro Contact	M. Klein / ☎ +31 70 31 11 316 / ✉ m.klein@fugro.com
Date	4 April 2016

1. PURPOSE AND SCOPE

This technical note provides geotechnical guidance for design verification of monopile foundations at the Borssele Windfarm Area. Specifically, cyclic resistance of sandy soils is addressed, taking the Tongeren Formation as an example.

This technical note is supplementary to and must be read in conjunction with the (cyclic) Laboratory Test Data reports (Fugro 2015e and 2016) and the Geological Ground Model reports, particularly Section 5 (Fugro 2015a to 2015d).

2. DESIGN LIMIT STATES – CYCLIC LOADING

Design situations for monopiles will require assessment of cyclic resistance (stiffness and strength) of soils, for example as addressed by DNV (2014). The relatively large diameter of a monopile implies that design verification will require consideration of pore pressure build-up and development of cyclic shear strain in soil during cyclic loading. Pore pressure build-up can apply to large diameter monopiles where it would not for small diameter piles such as considered by an API based PY-type approach (API 2011, 2014) or similar. For sandy soils, this implies specific consideration of drained, partially drained or undrained soil behaviour, as indicated by the following example.

For example, consider a monopile with a diameter of 7 m installed by impact driving into Tongeren sands. For this case, indicative values for time required for 10% dissipation of pore pressure t_{10} and for 90% dissipation of pore pressure t_{90} can be in the order of 20 s and 12000 s respectively. These values represent approximate averages for the soil zone of interest around a monopile subject to lateral loading (e.g. Osman and Randolph, 2015). This indicative example considers a coefficient of permeability k of 10^{-6} m/s and a Young's modulus E of 100 MPa. Values for t_{10} and t_{90} can be compared to a typical cyclic lateral loading (rise) phase of, say, 5 s.

Further guidance is given below.

3. ASSESSMENT OF CYCLIC SOIL RESISTANCE – TONGEREN FORMATION

3.1 Principal Considerations

Assessment of cyclic soil resistance in sandy soils typically considers:

- pile installation practice
- geological setting
- coefficient of consolidation;
- relationships between cyclic stress ratio and pore pressure build-up for undrained soil behaviour;
- model for dissipation of excess pore pressures around a monopile.

3.2 Pile Installation

Soil around a monopile will have been modified by pile installation. This is generally insignificant for analysis of lateral response of a monopile installed by impact driving. Geotechnical parameter values for in situ sandy soil conditions may require adjustment where a monopile is installed by other methods such as vibratory pile driving.

3.3 Geological Setting

The Tongeren sands include a fines fraction, typically in the range 5 % to 25% by weight, and, locally glauconitic zones.

The Tongeren sands are expected to show "ageing" characteristics, particularly because they are of Tertiary age. A cautious approach should be considered when interpreting in situ measurements, notably (seismic) cone penetration test results if such interpretation includes comparison with relatively young sands. No ageing effects were captured by the laboratory tests performed on Tongeren sands. The laboratory tests were conducted on disturbed and/or reconstituted soil specimens.

3.4 Coefficient of Consolidation

Horizontal (radial) dissipation of pore pressure around a monopile is expected to be dominant.

The coefficient of consolidation (c_v or c_h) is dominated by coefficient of permeability k and soil Young's modulus E.

Design values for k can be assessed from integrated assessment of pile installation practice, geological setting, (CPT) soil behaviour type index I_c and particle size distribution.

I_c values for the Tongeren Formation typically range between 1.5 and 2.0. I_c values locally range between 2 and 3, in zones up to several metres thick. The higher values indicate potential for partially drained soil behaviour during penetration of a cone penetrometer. Scale effects imply that a monopile will probably induce partially drained or undrained soil behaviour during cyclic loading.

Conventional correlations between soil permeability and particle size distribution should be cautiously adjusted for glauconitic zones of the Tongeren Formation. Particle size distribution derived from a laboratory test considers a disturbed sample. The test takes no account of the original macro fabric of the soil.

Values for E will depend on general soil conditions and on stress/strain levels within the zone of interest for pore pressure dissipation. Estimates for E can be derived from correlation with cone resistance from CPT and in situ shear wave velocity available from seismic downhole tests (seismic cone penetration tests). Normalisation of E for stress-strain levels may be considered. Use of a modulus degradation curve can be efficient for optimised design.

3.5 Pore Pressure build-up for Undrained Soil Behaviour

The available geotechnical data for the Tongeren Formation include site-specific measurement results for assessment of pore pressure build-up during cyclic loading of sands according to common practice (ISO 2014, 2015). Particularly, such site-specific assessment can be based on cyclic laboratory test results and referenced to in situ test results, particularly CPT results and shear wave velocity measurements obtained from seismic cone penetration tests.

The cyclic laboratory test programme for the Tongeren sands covers undrained triaxial and direct simple shear tests. A safe and economical approach to foundation design may require factoring of the results of these tests (Andersen, 2015). Considerations should include the following.

- The cyclic test results apply to reconstituted soil specimens. The Tongeren laboratory test specimens were prepared from batch samples. The particle size distributions of the batch samples approximate average conditions. Particularly, in situ glauconitic zones may have percentage fines above average.
- Cyclic resistance of sands strongly correlates with shear wave velocity, which in turn correlates strongly with both soil unit weight and soil fabric induced by geological setting. Estimated uncertainty of the available in situ measurements of shear wave velocity for Tongeren sands is possibly in the order of +/- 15 %, for example 300 m/s +/- 45 m/s. Estimated uncertainty of the available laboratory measurements of shear wave velocity for Tongeren sands is possibly in the order of +/- 10 %. Note that the authors of this document are not aware of any published metrological estimates of uncertainty of shear wave velocity measurement.
- The unit weights of the reconstituted soil specimens are believed to approximate in situ unit weights. It should be noted that common geotechnical practice implies considerable uncertainty for determination of in situ unit weight of sands, probably in the order of +/- 1 kN/m^3. It can be expected that shear wave velocity of reconstituted laboratory specimens will be significantly lower than that of in situ sand of the same unit weight, other conditions being equal. The limited test data appear to support this expectation.
- The shear wave velocity versus unit weight issue inevitably implies considerations for interpretation of the available cyclic laboratory test results. Ideally, laboratory sand specimens will have both soil unit weight and shear wave velocity equal to those of in situ sand. This is difficult to achieve in practice. For the case of equal (laboratory and in situ) unit weight only, then the laboratory test results will significantly underestimate cyclic soil resistance for in situ conditions. This situation applies particularly to “first loading”. If cyclic loading incurs significant soil “damage” (soil fatigue, brittleness) then the difference between in situ conditions and laboratory conditions can be expected to be less for subsequent equivalent design conditions. In other words, it can be expected that soil damage will not be (fully) recovered with time. In situ shear wave velocity will reduce after first loading at practically no change in soil unit weight. This achieves a closer match

of soil behaviour in laboratory test specimens with that for in situ soil, for second and subsequent loading.

- Results from the cyclic laboratory test programmes performed for Borssele (Fugro 2015e and 2016) are for selected initial stress conditions applied to the soil specimens. Use of the test results for other, in situ, stress conditions should consider K_0, coefficient of earth pressure at rest. K_0 values for the Tongeren sands are probably in the range 0.7 to 1.
- The cyclic laboratory test results are for stress-controlled cycles, with a majority of tests performed with zero average stress. This setting is generally conservative. Cyclic soil resistance will be higher for conditions under positive average stress conditions.

3.6 Dissipation Model

Assessment of cyclic soil resistance will usually require consideration of both rapid and slow dissipation of excess pore pressures around a pile. This is because partially drained soil resistance may be lower than fully drained and/or lower than fully undrained soil resistance.

A radial model for dissipation of excess pore pressures around a pile can be considered for providing a high estimate of pore pressure dissipation time, i.e. relatively slow dissipation. Low estimates should consider 3D pore pressure dissipation.

A simplified cycle-by-cycle model can be considered for pore pressure build-up and dissipation, as outlined by Andersen (2015).

4. REFERENCES

Andersen, K.H. 2015. Cyclic Soil Parameters for Offshore Foundation Design. 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.

Det Norske Veritas, 2014. *DNV-OS-J101 Design of offshore wind turbine structures.* Oslo: DNV

Fugro Engineers B.V. 2015a. *Geological Ground Model - Wind Farm Site I Borssele Wind Farm Zone - Dutch Sector, North Sea, Geotechnical report No.: N6016/05, issue 3*. Nootdorp: Fugro Engineers B.V.

Fugro Engineers B.V. 2015b. *Geological Ground Model - Wind Farm Site II Borssele Wind Farm Zone - Dutch Sector, North Sea, Geotechnical report No.: N6016/06, issue 3*. Nootdorp: Fugro Engineers B.V.

Fugro Engineers B.V. 2015c. *Geological Ground Model - Wind Farm Site III Borssele Wind Farm Zone - Dutch Sector, North Sea, Geotechnical report No.: N6083/05, issue 3.* Nootdorp: Fugro Engineers B.V.

Fugro Engineers B.V. 2015d. *Geological Ground Model - Wind Farm Site IV Borssele Wind Farm Zone - Dutch Sector, North Sea, Geotechnical report No.: N6083/06, issue 3*. Nootdorp: Fugro Engineers B.V.

Fugro Engineers B.V. 2015e. *Geotechnical Report – Laboratory Test Data – Wind Farm Site I&II – Borssele Wind Farm Zone – Dutch Sector, North Sea, Geotechnical report No.: N6016/07, issue 3*. Nootdorp: Fugro Engineers B.V.

Fugro Engineers B.V. 2016. *Geotechnical Report – Laboratory Test Data – Wind Farm Site III&IV – Borssele Wind Farm Zone – Dutch Sector, North Sea, Geotechnical report No: N6083/07, Issue 2.* Nootdorp Fugro Engineers B.V.

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.

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

Osman, A.S. and Randolph, M.F. 2015. *On the calculation of cumulative strain around full-flow penetrometers in steady-state conditions*. International Journal for Numerical and Analytical Methods in Geomechanics, Vol. 39, No. 4, pp. 368-387.

5. USE OF THIS TECHNICAL NOTE

Fugro Engineers B.V. prepared this Technical Note according to a project specification determined by the Client.

Fugro understands that the presented information will be used for the purpose described above. That purpose was a significant factor in determining the scope and level of the services. If the purpose for which the presented information is used or the Client's proposed development or activity changes, this Technical Note may no longer be valid.

Document distribution is restricted to project participants approved by the Client.

This document has 7 pages, the definitive versions of which are held in Fugro's information system.

Document Check:	P. Peralta – Senior Geotechnical Engineer
Document Review:	C. Erbrich – Technical Director
Document Approval:	J. Peuchen – Principal Geotechnical Engineer

Project Lead: signed

M. Klein

Principal Geotechnical Engineer

APPENDIX 1

VERIFICATION COMMENT SHEET

Project Title: **Borssele – Offshore Wind Farm**	DNV Project No.: PP118609	VCS Reference: 644235-VCS-14-Rev00	
Reviewed Documents Title / No. / Rev.: /1/- Technical Note *Geotechnical Guidance for Cyclic Resistance of Sandy Soils Borssele Wind Farm Area Dutch Sector, North Sea* Client Reference WOZ1500010 Fugro Reference N6083/TN-CYC dated 2016-04-04	Prepared by: LIHA	Date: 2016-04-05	Sign: Livdlamse
Referenced Documents:	Verified by: DLPRA	Date: 2016-04-05	Sign:

General:
This verification comment sheet (VCS) covers the verification of the documentation listed above as 'Reviewed Documents'.
The documentation listed above as 'Referenced Documents' is used as background documentation; this means that this documentation is not part of the verification covered by this VCS unless it is clearly stated.

VERIFICATION COMMENTS:

No.	Description:	Category [1]	Status [2]
	[1] NC = Non-Conformance; TQ = Technical Query; A = Advice (reply not needed) [2] O = Open; C = Closed; CN = Closed with Note		
1.	General The technical note /1/ has been reviewed, and found to form a reasonable basis for assessment of cyclic degradation of sandy soils, e.g. the Tongren formation found at the Borssele OWF site. The methodology described is in compliance with normal practice and fulfills the requirements in DNV OS J101.	**A**	-