TECHNICAL ARTICLE WIND ENERGY · SHALLOW FOUNDATION · GROUND STIFFNESS

Rotational stiffness of WTG shallow foundations

What type certification requires – and what the ground beneath the foundation contributes

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ABSTRACT

Type certification of a wind turbine presupposes a minimum rotational stiffness of the foundation, separately for static and dynamic loading. The article explains the half-space approach and the choice of shear modulus from cone penetration tests, and uses a site in Saxony-Anhalt to show how large the margin is – and where it is lost.

KEYWORDS · Wind turbine · Shallow foundation · Rotational stiffness · Shear modulus · Cone penetration test

1 Background

Tower design assumes a given fixity at the foundation. If the ground is softer, the natural frequency of tower and foundation drops and approaches the rotor excitation. The manufacturer's type-tested foundation document therefore specifies two minimum values: $k_{\varphi,dyn}$ for operation and $k_{\varphi,stat}$ for rotation under sustained load; the DIBt guideline [1], [4] governs the verification format. Both must be verified for the site.

2 Half-space approach

For a rigid circular plate on an elastic isotropic half-space with the base fully in contact [2], [3]:

$$k_\varphi = 8 \cdot G \cdot R^3 / (3 \cdot (1 - \nu)) = G \cdot D^3 / (3 \cdot (1 - \nu)) \quad (1)$$

G shear modulus · R, D radius, diameter of the foundation · ν Poisson's ratio (here 0.30)

D enters to the third power, G linearly. The ground down to about 0.5 · D below the base governs; G is averaged over this window. Embedment is not taken into account and remains a reserve. With base gapping, k_φ drops markedly.

3 Which shear modulus?

Statically, G follows from the oedometer modulus; we adopt $E_s = 0.5 \cdot M$ from the CPT [5] as a cautious empirical value. Dynamically, G follows from the shear wave velocity, reduced to the strain level in operation [7]:

$$G_{stat} = E_s \cdot (1 - 2\nu) / (2 \cdot (1 - \nu)) \qquad G_{dyn} = f_G \cdot \rho \cdot v_s^2 \quad (2)$$

ρ density · v_s shear wave velocity · f_G reduction to operational strain (here assumed 0.80; more precisely from the strain in the load case [1], [7])

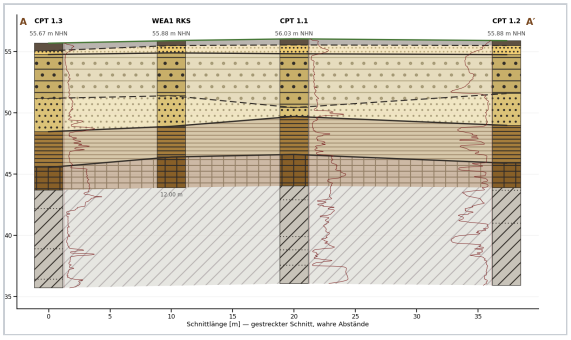


Figure 1. Geotechnical cross-section of a wind turbine site in Saxony-Anhalt from a key borehole and three CPTs (anonymised). Silty sands over ground-moraine till. (Drawing labels in German.)

SITE OVERVIEW

Foundation	circular, D = 29.1 m
Embedment	2.9 m
Averaging window	0.5 · D ≈ 14.6 m
Poisson's ratio ν	0.30
$k_{\varphi,stat}$ required	52 000 MNm/rad
$k_{\varphi,dyn}$ required	260 000 MNm/rad
Bearing stratum	very silty sand

4 Example: Saxony-Anhalt

The box beside Figure 1 gives the site and the requirements. Solved for G, Eq. (1) shows what the ground must provide:

$$G_{req} = 3 \cdot (1 - \nu) \cdot k_{\varphi,req} / D^3 \quad \rightarrow \quad 4.4 \text{ and } 22 \text{ MN/m}^2 \quad (3)$$

Dynamically, 22 MN/m² is G_{dyn}, i.e. $G_0 \approx 28$ MN/m². Statically, the requirement equals an oedometer modulus of only approx. 15 MN/m²; at this site, with silty sand over glacial till, rotational stiffness thus does not govern (Table 1). It becomes critical with gyttja, peat or loose sand in the 0.5 · D window and with smaller foundations.

Table 1. Rotational stiffness per CPT, mean over 0.5 · D; $G_{dyn} = 0.8 \cdot G_0$

CPT	G_{stat} [MN/m²]	k_{stat} [MNm/rad]	G_0 [MN/m²]	G_{dyn} [MN/m²]	k_{dyn} [MNm/rad]
CPT 1	22.0	257 869	190	152	1 782 111
CPT 2	20.2	236 524	197	158	1 846 310
CPT 3	16.2	190 602	165	132	1 553 510
required	4.4	52 000	≈ 28	22	260 000
Margin		3.7-fold			6.0-fold

5 Recommendations

- At least three CPTs per foundation, distributed around the perimeter, to 0.5 · D below the base, or justify extrapolation.
- Verify static and dynamic cases separately, using the least favourable single value, not the site mean.
- Adopt E_s cautiously, disregard embedment; identify soft layers within the window early.

STANDARDS AND REFERENCES

[1] **DIBt (2015)** Richtlinie für Windenergieanlagen, Turm und Gründung. Version Oct. 2012, corr. March 2015

[2] **DNV/Risø (2002)** Guidelines for Design of Wind Turbines. 2nd ed., Copenhagen/Roskilde

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[4] **Quast, A. (2015)** Ansatz der Baugrundsteifigkeit bei der gesamtdynamischen Berechnung von WEA. Aktuelle Forschung in der Bodenmechanik, Springer

[5] **Robertson, P. K. (2009)** Interpretation of cone penetration tests – a unified approach. Can. Geotech. J. 46, 1337–1355

[6] **DIN EN 1997-1** with **DIN 1054** · **DIN 4019** · **DIN EN ISO 22476-1**

[7] **DGGT (2018)** Empfehlungen des Arbeitskreises 'Baugrunddynamik'. 2nd ed., Ernst & Sohn