

INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING



This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:

<https://www.issmge.org/publications/online-library>

This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.

Foundations analysis in difficult ground conditions for Wind Turbine Generator

Analyse de fondations pour turbines éoliennes en conditions difficiles en terrain

Ramses Huicochea

Geotechnical Consultant, Geotechnics, Mexico, ramsingster@gmail.com

Carlos Belli

ENEL GREEN POWER, Engineering, Civil discipline, Mexico, carlos.belli@enel.com

ABSTRACT: The traditional analysis for Wind Turbine Foundations is, in idealized conditions, enough to develop all the analytical checks such as: overall stability, bearing capacity, settlements, overturning moments, sliding and dynamic actions: rotational stiffness, gap forces, maximum ground pressure all that is generally enough to get an acceptable solution for geotechnical foundation design. Nonetheless, when Engineers have to face some of geotechnical issues such as: soft high compressible soils, rock masses with sinkholes, seepage or very fractured rock with weak layers below, good rock layers and so on, they should perform extra or complementary analysis with other technical tools as soil-structure interaction, dynamic wind analysis, seismic and cyclic vibrations coupled analysis.

RÉSUMÉ : Les analyses traditionnelles pour fondations de turbines éoliennes sont suffisantes en conditions idéales, avec les révisions analytiques suivantes, c'est-à-dire, révision par stabilité globales, capacité de charge, implantations, moments de renversement, glissement et actions dynamiques : rigidité rotatoire, forces de séparation, pression maximale de sol. Ces révisions sont généralement suffisantes pour obtenir une solution acceptable chez l'analyse et dessin de fondations. Cependant, quand les ingénieurs doivent faire face aux problèmes géotechniques, tels que sols moelleux de haute compressibilité, masses rocheuses avec cavernes, filtrages ou roches très abîmées avec des couches fragiles par-dessous et couches de bonne roche par-dessus, etc, ils doivent réaliser des analyses complémentaires avec des outils techniques plus profondes comme l'interaction terrain-structure, des analyses dynamiques de vent, vibrations sismiques et cycliques.

KEYWORDS: WTG (Wind Turbine Generator), ULS (Ultimate limit State), SLS (Serviceability Limit State).

1 BACKGROUND

The traditional analysis for foundation design for WTG is usually performed with basic analytic calculations checks. In general all these checks are enough to accomplish the minimum safety factors within the failure state limit and the service state limit. The context where this situation takes place is where engineers have the need to face with a regular ground, such as: medium to hard granular soils, soft soils with low plasticity with medium to high cohesion values. Talking about rocky ground, engineers face mass rock with RMR values between 40 to 80 without weak joints, also with the absence of underground flows or seepage. Another desirable conditions is the absence of seismic risk for example.

In almost all the projects around the world engineers do not have those ideal conditions mentioned above, so what they normally do are deeper analysis in order to have less uncertainties during the design and construction phase, respectively. This paper involves two examples: one performed in soft soil and saturated ground and the other one is the case of a rocky karstic ground formed from limestone and sedimentary rock with some cavity and karstic conduits.

Complementary analysis and calculations were performed additional to traditional analysis in order to have a better idea of the behavior for WTG foundations in both cases.



Figure 1. WTG general sketch (Courtesy: intechopen.com)

2 GEOTECHNICAL ANALYSIS CRITERIA IN THE WTG FOUNDATION DESIGN

Then is showed the different criteria for analytical calculations for stability checks, it is presented normal criteria and complementary criteria for geotechnical analysis for WTG foundations .

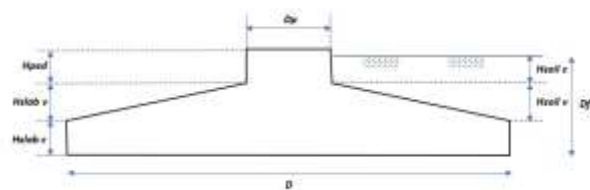


Figure 2. Main geometrical issues for WTG Foundations.

where:

H_{ped} :	Pedestal height
$H_{slab v}$:	Slab variable height
$H_{slab c}$:	Slab constant height
$H_{soil c}$:	Soil constant height
$H_{variable c}$:	Soil variable height
D_f :	Foundation depth
D_p :	Pedestal diameter
D :	Foundation diameter

2.1 Ultimate Limit state (ULS)

This limit state is concerning the safety of human people and the safety of the structure itself. In some cases even the safety of the content in the structure can be seen as ULS.

This statement is valid for the succeeding combination loads: normal, abnormal and extreme events.

The following checking criteria are related for geotechnical calculations:

- a) Bearing capacity
- b) Stability against sliding
- c) Stability against overturning
- d) Rotational stiffness
- e) Translational stiffness

2.2 Serviceability Limit state (SLS)

The succeeding statements have to be checked for geotechnical calculations, in general load factors are set to unit: This state

- a) Differential settlements
- b) Consolidation settlements
- c) Degradation of soil strength in cyclic loading
- d) Gapping foundation

2.3 Dynamic Geotechnical Analysis vibratory

It is known in the machinery foundation design that the vibratory cyclic loads for operation on the foundations produces fatigue effect additional to dead loads. Having mentioned that, engineers have to face three different kind of machinery, as listed below:

- a) Rotatory machinery

The vibration for rotatory load machine can be irregular, due to operate desynchronized two machines

The load is a sinusoidal function with constant amplitude which is independent of operational frequency.

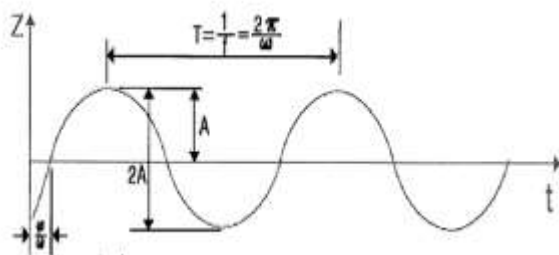


Figure 3. Sinusoidal function about dynamic system (Hernández 2005).

- T: Period
- f: Frequency
- A: amplitude
- φ: Phase angle
- ω: Circular frequency

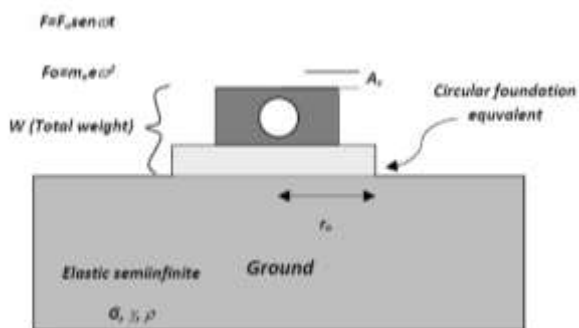


Figure 4. General sketch about dynamic effects from machines acting on the ground-foundation system (Hernández 2005).

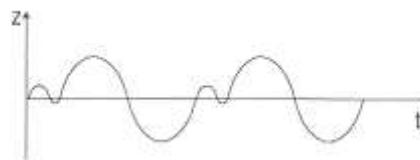


Figure 5. Graphical behavior of displacement vs time in a rotatory machine on the foundation system.

- b) Impact machines

The vibration related to an impact load is generally a transient effect, and in a contrary way for the case mentioned previously, the load is a sinusoidal function with constant amplitude which depends upon operational frequency.



Figure 6. Graphical behavior of displacement vs time in an impact machine on the foundation system.

The analysis method is performed as a modeling system between the ground properties and a freedom grades system as 6 modes vibration machinery

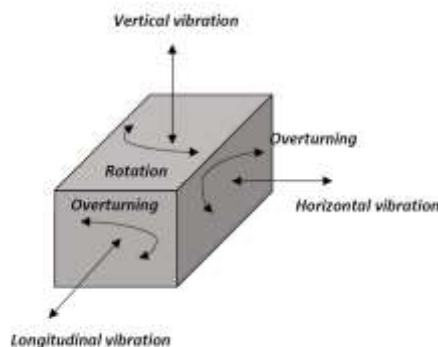


Figure 7. General sketch about dynamic effects from machines acting on the ground-foundation system (Huicochea & Belli, 2016).

The methodology establish the next guidelines:

- a) To calculate the stiffness and damping constants for each vibration modes.
- b) Specify the type of excitation load.
- c) Evaluate dynamic parameters related with the type of load:

Table 1. Formulas for Horizontal and Vertical vibration modes

	Horizontal	Vertical
Equivalent radius	$r_o = \sqrt{B \frac{L}{\pi}}$	$r_o = \sqrt{B \frac{L}{\pi}}$
Mass ratio	$B_x = \frac{7 - 8\nu}{32(1 - \nu)} \frac{m}{\rho(r_o)^3}$	$B_z = \frac{1 - \nu}{4} \frac{m}{\rho(r_o)^3}$
Damping coefficient	$C_x = \frac{4.6}{2 - \nu} \sqrt{\rho G}$	$C_z = \frac{3.4(r_o)^2}{1 - \nu} \sqrt{\rho G}$
Damping ratio	$D_x = \frac{0.288}{\sqrt{B_x}}$	$D_z = \frac{0.425}{\sqrt{B_z}}$
Stiffness	$K_x = \frac{32(1 - \nu)G r_o}{7 - 8\nu}$	$K_z = \frac{4G r_o}{1 - \nu}$

Table 2. Formulas for Overturning and Torsional vibration modes

	<i>Overturning</i>	<i>Torsion</i>
<i>Equivalent radius</i>	$r_o = \left(\frac{B L^3}{3\pi} \right)^{1/2}$	$r_o = \left(\frac{B L^2 + L^3}{6\pi} \right)^{1/2}$
<i>Mass ratio</i>	$B_\psi = \frac{3(1-\nu)}{4} \frac{I_\psi}{\rho(r_o)^5}$	$B_\theta = \frac{I_\theta}{\rho(r_o)^5}$
<i>Damping coefficient</i>	$C_\psi = \frac{0.8(r_o)^4}{(1-\nu)(1+B_\psi)} \sqrt{\rho G}$	$C_\theta = \frac{4\sqrt{B_\theta}}{(1-2B_\theta)} \sqrt{\rho G}$
<i>Damping ratio</i>	$D_\psi = \frac{0.15}{(1+B_\psi)\sqrt{B_\psi}}$	$D_\theta = \frac{0.5}{1+2B_\theta}$
<i>Stiffness</i>	$K_z = \frac{8G(r_o)^3}{3(1-\nu)}$	$K_\theta = \frac{16G(r_o)^3}{3}$

As mentioned above all the formulas apply as complementary calculation in subtopics 2.1 and 2.2, respectively.

3 PRACTICAL CASE A: WTG FOUNDATION IN SOFT SOIL HIGH COMPRESIBILITY

Below the stratigraphy for the first analysis is shown. In this case this terrain consist of highly compressible soft soil with a superficial water table:

Table 3. Geotechnical properties, case A (soft compressible soil)

Estrata	Thickness (m)	length (m)	γ (kN/m ³)	SUCS
A	0.0-1.2	1.2	14	CH
B	1.2-2.4	1.2	14.2	CH
C	2.4-9.9	7.5	14.5	CL
D	9.9-18.30	8.4	14.5	CH
E	18.30-20.70	2.4	15.8	SM
F	20.70-21.90	1.2	15.0	CH
G	21.90-31.30	9.4	15.0	CH
H	31.30-34.30	3	15.5	CL

Table 4. Geotechnical properties, case A (soft compressible soil), following

Estrata	γ (kN/m ³)	ϕ (°)	c (kN/m ²)	E (kN/m ²)	ν
A	14	11	20	7500	0.45
B	14.2	11	20	4500	0.45
C	14.5	11	20	6500	0.4
D	14.5	13	50	42620	0.45
E	15.8	40	50	70000	0.35
F	15.0	26	180	60000	0.45
G	15.0	26	180	61330	0.45
H	15.5	30	200	65000	0.45

3.1 Conventional analysis results, case A

General characteristics for the WTG and the dimensions for WTG foundation analyzed and designed are shown:

Table 5. General characteristics for WTG, case A

Project	Power turbine (MW)	Height tower (m)	Tower type	Rotor diameter (m)
a	2	78	steel	97

Table 6. General dimensions for WTG foundation, case A

D (m)	Df (m)	Dp (m)	H _{ped} (m)	Hslab v (m)	Hslab c (m)
18	2.5	6	0.7	1.3	0.5

The succeeding results in the tables showed troubles to deal with a soft and saturated soil due to low bearing capacity SF, low rotational stiffness value and consolidation settlements much higher than the values required for WTG manufacturer specification.

Table 7. Geotechnical checks results, case A (part 1)

B. Capacity FS	Overturning FS	Sliding FS	Rotational stiffness (kNm)
1.559	1.73	-	4.6x10 ⁸

Table 8. Geotechnical checks results, case A (part 2)

Differential settlements (m)	Consolidation settlements (m)	Foundation gapping (%)
0.003	0.1978	100

Table 9. Values required for geotechnical parameters, case A (ULS)

B. Capacity FS	Overturning FS	Sliding FS	Rotational stiffness (kNm/rad)
3	1.2	1.1	8.0x10 ¹⁰

Table 10. Values required for geotechnical parameters, case A (SLS)

Differential settlements (m)	Consolidation settlements (m)	Foundation gapping (%)
0.003	0	100

As the results shown that shallow foundation was no possible and in this case was needed to perform a deeper foundation as well as soil improvement to reach an acceptable design for WTG foundation.

3.2 Vibratory analysis results. Case A

As mentioned previously vibratory analysis was performed to complement traditional analysis. Results are summarized in the following table:

Table 11. Deformations results for the different vibration modes. Case A

Mode	Amplitude (mm)
Horizontal	0.30
Vertical	0.35
Overturning	0.00
Torsion	0.00

Clearly, WTG foundation system has a good-coupled behavior; nonetheless, the ground foundation has no favorable conditions as mentioned in the deformations analysis.

4 PRACTICAL CASE A: WTG FOUNDATION IN KARSTIC ROCK MASS

The stratigraphy for the first analysis case consist of a terrain with residual soil, and sedimentary rock. Basically limestone and breccia with absence of water table:

Table 12. Geotechnical properties, case B (soft and medium hardness rock)

Estrata	Thickness (m)	length (m)	γ (kN/m ³)	SUCS
A	0.0-2.5	2.5	17	SM
B	2.5-7.5	5.0	23	Breccia
C	7.5-15.0	7.5	23	Limestone

Table 13. Geotechnical properties, case B (soft compressible soil), following

Estrata	γ (kN/m ³)	ϕ (°)	c (kN/m ²)	E (kN/m ²)	ν
A	17	31	0	38000	0.3
B	23	39	26	425000	0.25
C	23	54.7	62	176600	0.2

4.1 Conventional analysis results case B

Similar characteristics for the WTG and the dimensions for WTG foundation analyzed and designed for this kind of ground are presented below:

Table 14. General characteristics for WTG, case B

Project	Power turbine (MW)	Height tower (m)	Tower type	Rotor diameter (m)
b	2	80	steel	114

Table 15 General dimensions for WTG foundation, case B

D (m)	Df (m)	Dp (m)	H _{ped} (m)	Hslab v(m)	Hslab c (m)
16.5	2.4	6	0.7	1.3	0.5

The following results from the previous analysis, shown that shear resistance of rocky ground are enough to support the foundation owing to the fact that all the checks are higher values than the ones required in the Table 18 and 19:

Table 16. Geotechnical checks results, case B (part 1)

B. Capacity FS	Overturning FS	Sliding FS	Rotational stiffness (kNm)
60.9	1.57	13.03	4.79x10 ¹⁰

Table 17. Geotechnical checks results, case B (part 2)

Differential settlements (m)	Consolidation settlements (m)	Traslational sitffness	Foundation gapping (%)
0	0	-	100

Table 18. Values required for geotechnical parameters, case B (ULS).

B. Capacity FS	Overturning FS	Sliding FS	Rotational stiffness (kNm/rad)
3	1.2	1.1	6.6x10 ⁹

Table 19. Values required for geotechnical parameters case b (SLS)

Differential settlements (m)	Consolidation settlements (m)	Foundation gapping (%)
0	0	100

At first impression the results are good enough to develop shallow foundation design, nevertheless in this project during construction phase, some karstic conduits were detected, this situation leads to change the design for a deeper foundation (see below the shallow foundation with micropiles).

4.2 Vibratory analysis results. Case b

Table 20. Deformations results for the different vibration modes. Case B

Mode	Amplitude (mm)
Horizontal	0.05
Vertical	0.07
Overturning	0.00
Torsion	0.00

The deformations produced by the different vibration modes shown that they are insignificant as well as the values are too much lower than the admisible ones given by the WTG manufacturer. The main problem were the karstic holes that were not detected in the geotechnical survey.

5 CONCLUSIONS

It is confirmed that the WTG manufacturers and providers have performed the funtion and the mechanism for WTG up to the point that the WTG foundation system works in a good cupled way that avoids greater resonance effects. This was demonstrated with both type of analysis: normal analysis and the vibratory analysis since the deformations among the WTG and foundations as a system was no significant.

On the other hand when engineers face difficult ground conditions, they have to apply deeper analytical solutions, complemented with 2D and 3D Finite Element Analysis and Structure-Soil interaction, in the soft soil cases.

Regarding to the geotechnical investigations is necessary to do enough geological, geophysical and geotechnical surveys with the strict detail in order to prevent any geotechnical issue during the design and construction phase.

6 ACKNOWLEDGEMENTS

Special thanks to the structural civil engineer Carlos Belli who worked directly in this work. Special thanks to the Enel Green Power Company and all the colleagues who I worked in the past for several Wind Farm projects. Special thanks for my local association SMIG and for the ICSMGE too, for the opportunity to present and share this interesting work with others geotechnical engineers around the world.

7 REFERENCES

Hernández R. Notas de cimentación de maquinaria. 2006. Universidad Nacional Autónoma de México, 11 pp.
 Riso National Laboratory,2002. Guidelines for design of Wind Turbines IEC61400. 2005.Wind Turbines. Part 1: Design Requirements
 US Army Corps of engineers, 1992. Bearing Capacity of soils
 Zeevaert L. 1973. Foundation Engineering for Difficult Subsoil Conditions. Van Nostrand Reinholds.
 Kramer, Steven L. 1996. Geotechnical Earthquake Engineering. Prentice Hall, 653 pp