SOME ISSUES ABOUT THE FOUNDATION DESIGN OF WIND POWER TOWER IN ACTUAL CONDITIONS IN VIETNAM

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Article history: Received 25/2/2023, Revised 20/3/2023, Accepted 21/3/2023
https://doi.org/10.59382/j-ibst.2023.en.vol1-4

Abstract: *The current design of wind power tower foundations in our country is relatively new, the design consultancies in the country do not have much experience and have not fully updated the system of standards and technical documentation in wind power project design. Moreover, a wind power project is a* kind of construction *that is both related to construction engineering and electrical project, and this is a type of construction with high investment costs. Therefore, the requirements are set very complicated for the design works. In this article, the authors would like to refer to "Some issues about the foundation design of wind power tower in actual conditions in Vietnam".*

Keywords: *Wind power tower foundation, Fatigue limit state, the service limit state, Dynamic rotational stiffness*

1. Introduction

The feature of the wind electrical project is a kind of construction that converts wind energy to electricity by rotation of the propeller, which rotates the generator motor. Therefore, the wind power tower foundation serves as very important in transmitting the dynamic load to the foundation, ensuring the stability of construction throughout the project life cycle. Depending on the geological condition of project, some common foundation types are being used such as gravity base (round base), pile foundation or rock anchored... For our country, many areas have stable geological structures such as sand, stiff clay,… very suitable for shallow foundations. However, the design of spread foundation for wind turbines has much more complicated technical requirements than civil works. In this article, we present the design of shallow foundations for wind power towers in some regions of Vietnam.

One of the important issues in the design of wind power towers is the design principle and load case requirements. On that basis, the task of designing the foundation structure of wind power tower will be set.

2. Design principles

The design principle of wind power tower foundation is according to the limit state method including the ultimate limit state (ULS), the fatigue limit state (FLS) and the service limit state (SLS) according to IEC 61400-1:2019 [1]. Ultimate limit states include inspection for failures due to excessive deformations or due to the transfer of the entire structure or its components to a kinematic state or rupture or an unstable condition. Fatigue limit state is the senescence of the material and local structural failure that occurs when the material is affected by repeated loads. Fatigue limit state includes checking failure of structure or its component due to fatigue or other time-depending effects. Service limit states are related to limit states that consider the function of the structure or one of its components under normal service conditions or the appearance of the structure [4]. Structural analysis must be verified with suitable calculation models according to allowable limit states, including design values related to action parameters, material properties, geometric dimensions of the structure and apply partial safety factors for actions, material and strength. The ultimate and fatigue limit states shall be verified for the design situations. Verifications for the fatigue limit state shall be referred to the design lifetime of the structure.

Thereby, it can be seen that the design of the wind power tower foundation has many differences and complexities compared to the conventional foundation design. It requires consideration of fatigue problems due to repeated loading, as well as problems related to the stiffness of the foundation when receiving dynamic loads transferred by the turbine, at once must consider being influenced by complex geological conditions and groundwater. To clarify these issues, the technical aspects related to these are presented below.

3. Loads requirement

The loads used for the design of wind power tower are to comply with IEC 61400-1:2019 [1] standards by applying partial safety factors to actions. According to IEC 61400-1:2019 [1] the load cases shall be determined according to the design situations related to the integrity of the wind turbine structure including the normal design situation N (normal), the abnormal design situations A (abnormal) and design situation related to transportation, installation and maintenance T (transportation). Normal design load cases are expected to occur frequently. The turbine is in a normal state or may have experienced minor faults or abnormalities. This situation occurs throughout the life of the turbine. Abnormal design situations are less likely to occur. They usually correspond to design situations with severe faults. For each design situation, it is necessary to evaluate the structural strength according to the ultimate limit state and the fatigue strength according to the fatigue limit state.

Design load combinations (DLC) according to table 2 of IEC standard 61400-1:2019 [1] , including design situations due to Power production DLC 1.1 to 1.5 , Power production plus occurrence of fault DLC 2.1 to DLC 2.5, Start-up DLC 3.1 to DLC 3.3, normal shutdown DLC 4.1 to DLC 4.2, Emergency stop DLC 5.1, Parked (standstill or idling) DLC 6.1 to DLC 6.4, Parked plus fault conditions DLC 7.1 Transport, assembly, maintenance and repair DLC 8.1 to 8.2.

Therefore, the design situations mentioned in IEC 61400-1:2019 are very diverse, related to the operation of wind turbines in normal state and abnormal state.

The strength verified according to [1], related to assess design action consequences , shall not exceed the corresponding design strength.

$$\gamma_n \gamma_f F_k \le R_k / \gamma_M \tag{1}$$

Where in

γ_n – partial safety factor for consequences of failure, is 0,9 (component class 1); is 1,0 (component class 2); is 1,2 (component class 3);

γ_f, γ_M – is the partial safety factor for loads / material;

F_k, R_k – is the characteristic value for the load/ resistances.

Table 1. *Partial safety factors γ_f for ULS*

Unfavourable loads		Favourable loads
Type of design situation		All design situations
Normal (N)	Abnormal (A)	
1,35	1,1	0,9

When considering the fatigue limit state FLS, the safety factor γf for the load is taken as 1,0 for all normal and abnormal design situations. Normally, fatigue loads are calculated with 10^7 iterations when the design life of the wind turbine is 20 to 25 years.

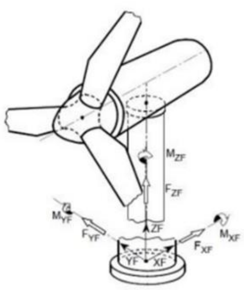


Figure1. *Coordinate system at tower bottom*

The classification of loads acting on the wind turbine foundation includes two main types Markov matrix and fatigue load spectrum. The Markov matrix provides a more accurate and comprehensive way for the analysis of foundations subjected to fatigue loads because of the consideration of the nonlinear behavior of the material.

The fatigue capacity of structure should satisfy the condition that the summed in the fatigue verification D (fatigue damage) calculated by Palmgren–Miner and using the characteristic curve S-N (Wöhler curve) satisfy the condition:

$$D = \sum_{i=1}^{j} \frac{n_i}{N_i} \le 1 \tag{2}$$

Where in:

n_i is the number of load cycles for a given range $\Delta\sigma i$;

N_i is the number of load cycles at failure for the range $\Delta\sigma i$ accounting for mean stress when appropriate and for the partial safety of materials and loads.

Wind turbine towers and foundations differ from most civil engineering structures in a way that they have a very small ratio of static loads to dynamic loads. Therefore, for the design of wind turbine towers and foundations , the SLS load levels S1, S2 and S3 are applied, corresponding to the characteristic load level and two frequent load levels, of different levels of frequency.

SLS characteristic load level S1 for design lifetime actions, which relate to continued correct operation of the wind turbine such as clearance of components, and concrete cracking control.

SLS characteristic load level S2 for frequent actions, which are exceeded for 10^{-4} of the lifetime corresponds to a frequent load occurrence greater than 0,87 hours per year, which relate to fracture toughness, corrosion, concrete cracking control.

SLS characteristic load level S3 for the equivalent to frequent actions, which are exceeded for 10^{-2} of the lifetime corresponds to a frequent load occurrence greater than 87 hours per year, which relate to cracked concrete stiffness checks, concrete cracking control, foundation stiffness, inclination and settlement.

On the basis of the load requirements listed in IEC 61400-1:2019, make a calculation model suitable to the equipment manufacturer's technology to design the foundation to meet the situations. Therefore, in the design stage of the wind turbine foundation, in addition to response to the standards [1], it also depends on the technological properties and requirements of the wind power equipment manufacturer.

4. Design the structureof wind power tower foundation

4.1 Design of reinforced concrete structures

Wind power foundations need to be designed to ensure the conditions of bending, shearing, local bearing between turbine and foundation, fatigue resistance and ensuring long-term durability during use in accordance with current standards.

Although the above requirements are proposed in the standard, in fact design, especially for wind power projects, after considering the technological features and operation of wind turbines, spread concrete foundation selected with the shape of "truncated cone". In which, the typical cross-section (through the center) is in Figure 2, with the center block having a large thickness to respond to the large load transmitted from the upper structure. The two-sided foundation is enlarged and balanced ensures structural strength and increases the stiffness bearing the moment and the load capacity of the foundation.

Based on the foundation structure Figure 2, in design has calculated the efforts and arranged reinforcement for the foundation. In this article, the authors briefly present the steps verified to assurance the foundation structure according to the limit states.

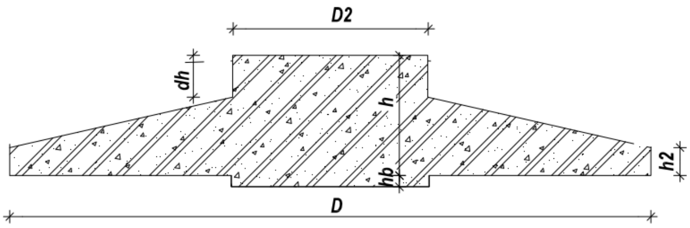


Figure 2. *Typical wind power tower foundation dimensions*

➢ With the ultimate limit state ULS, the verification is done through the main problems:

- Check the bending moment of the radial reinforcement for the upper and lower layers;
- Check the bending moment of the ring reinforcement for the upper and lower layers;
- Check the local compressive strength of mortar and pedestal and arrange reinforcement to ensure

the requirement of compression causing unconfined (horizontal expansion) of concrete;

- Check the shear resistance, punch resistance of the wind power tower foundation;

- Check the tensile strength of the anchor reinforcement layer.

➢ With the fatigue limit state FLS, the verification is done through the main problems:

- Check the fatigue load strength of foundation concrete, radial reinforcement and ring reinforcement for the upper and lower layers;
- Check the fatigue load strength of the reinforcement when subjected to shear;
- Check the fatigue load strength of high grade mortar;
- Check the local compressive strength of the concrete layer under the mortar layer fatigue load;
- Check the fatigue load strength of the reinforcement layer against concrete horizontal expansion;
- Check the tensile strength of the anchor reinforcement layer fatigue load.

➢ With the service limit state SLS, it is necessary to check that the crack width does not exceed the allowable value

4.2 Geotechnical analysis

Similar to the foundation structure, the ground should be designed to ensure bearing capacity and stability under the effect of dynamic loads transmitted by the turbine. According to IEC 61400-1:2019 [1], the geotechnical analysis needs to follow the ultimate limit states (ULS) and the service limit states (SLS).

4.2.1 Ultimate limits state ULS

According to the ULS, it is necessary to consider two cases:

- Equilibrium of the foundation (overturning);
- Soil bearing capacity and sliding.

Because this is a spread, large foundation (gravity foundation), it is very sensitive to buoyancy in the presence of groundwater. The potential effect of buoyancy will be taken into as an additional overturning moment, or by applying the reduced effective weight of the backfill when calculating the stability moment.

Verification of strength involves checking that design effects of actions do not exceed their corresponding design resistances

$$E_d \le R_d \tag{3}$$

For a spread foundation subject to vertical and moment actions, Eurocode 7 requires the design vertical action V_d acting on the foundation to be less than or equal to the design bearing resistance R_d of the ground beneath it.

$$V_d \le R_d \tag{4}$$

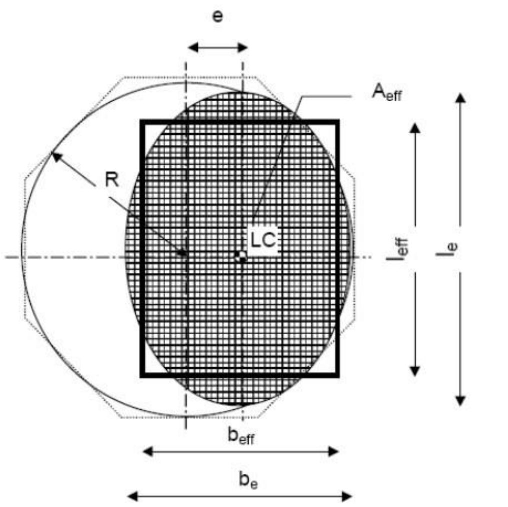


Figure 3. *Effective foundation area*

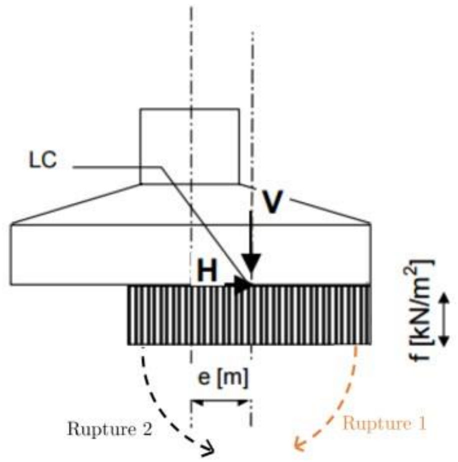


Figure 4. *Define rupture type*

When designing, it is necessary to check the bearing capacity in case of drained and undrained spread foundation, including the effect of the bending moment by the turbine on the foundation

Drained ultimate bearing capacity:

$$q_{ult1} = \frac{1}{2}\gamma b_{eff} N_\gamma s_\gamma i_\gamma + q' N_q s_q i_q + c_d^{'} N_c s_c i_c \quad (5) \quad \text{(Rupture 1)}$$

$$q_{ult2} = \gamma b_{eff} N_\gamma s_\gamma i_\gamma + c_d^{'} N_c s_c i_c (1.05 + tg^3(\varphi_d^{'})) \quad (6) \quad \text{(Rupture 2)}$$

Undrained ultimate bearing capacity:

$$q_{ult} = (\pi + 2)c_u b_c s_c i_c + q \quad (7)$$

Where in: q_{ult} is the ultimate load capacity of the foundation; N_q is the load capacity coefficients, S_q is the shape coefficients, i_c is the coefficient of inclination of the load, φ'_d and C_{ud} is the friction angle and the undrained shear resistance.

Check the bearing capacity of the foundation:

$$q_{Ed} = \frac{F_{zd}}{A'} < q_{Rd} \quad (8)$$

Where in:

q_{Ed} : is the plastic (uniform) ground pressure based on eccentricity calculation;

$A^{'}$: is the effective foundation area around the line of action of the resultant force for F_{zd};

q_{Rd} : is the design values of bearing capacity of soil in ultimate limit state, including appropriate partial safety factor for material (resistance).

In particular, in case large eccentric foundation load (e more than 0.3 times the foundation width), potential alternative failure planes should be taken.

Verification of stability against Sliding (EQU) on the base

$$\tau_{Ed} = \frac{H_d}{A'} < \tau_{Rd} \quad (9)$$

Where in:

τ_{Ed} : is the design values of shear stress acting at the soil/structure interface;

H_d : is the horizontal force acting on the soil formation including unfavorable partial safety factor on load;

A' : is the effective foundation area around the line of action of the resultant force for F_{zd};

τ_{Rd} : is the design values of sliding stress of soil in ultimate limit state, including appropriate partial safety factor on material and/or resistance;

Check safety against overturning in IEC 61400-6

$$\frac{M_{d,stabilizing}}{\gamma_{Rd}} \geq M_{d,overturning} \quad (10)$$

Where in:

$M_{d,stabilizing}$: is the design value of stabilizing moment from gravity load and backfill including favourable partial safety factor on resistance;

$M_{d,overturning}$: is the design value of destabilizing moment from wind load and other loads including the effect of horizontal and torsion loads, and including unfavorable partial safety factors for load;

γ_{Rd} = 1,1: Safety against overturning factor.

The load acting on the foundation shall take account of the wind turbine vertical load, the foundation and soil backfill weight. Effect of buoyancy force in case groundwater level is higher than foundation bottom. The beneficial effects of shear resistance and passive soil pressure around the side of foundation may be included in the calculation when enough reliable data.

4.2.2 Serviceability limit state (SLS)

Verification of the long term geotechnical behavior under SLS shall be performed to ensure that the foundation satisfies the serviceability criteria over the design lifetime of the wind turbine.

Serviceability criteria include:

- Compliance with the dynamic and (if specified) static rotational and lateral stiffness specified by the turbine manufacturer as the basis for the load calculations;

- Control of maximum inclination and settlement of the foundation over the design lifetime of the foundation;

- Prevention of degradation of the soil bearing capacity or stiffness due to repeated or cyclic loading.

a) Foundation stiffness

The foundation stiffness plays a very important role, as a criterion for the design of the foundation to ensure safety, especially under the repeated loads. For each different degree of deformation of the ground, the stiffness will change. However, in order to have the selection and consideration of the foundation stiffness calculation, one comes to a general approach through the soil model.

Soil model

Many models have been researched and developed to relate the non-linear stress-strain characteristics of soil under loading. The stress-strain relationship is presented using normalized parameters, and assumes that ultimate soil capacity is reached at a strain of 1 %(Figure 5). In this diagram, at the beginning of the curve - below the small strain (< 10^{-4}), the soil behavior is elastic.

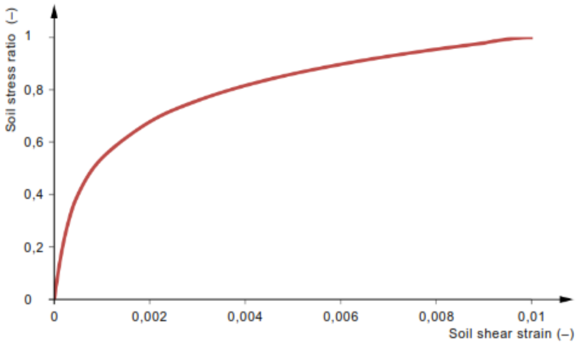


Figure 5. *Stress-strain relationship for soil*

Figure 6 presents the general behavior of soil undergoing loading and unloading cycles. Loading and unloading of the soil during repeated cyclic loading may be idealized by travelling along a line approximately equal to the slope of the stress-strain plot at small strain. The soil stress experienced under serviceability conditions are normally a relatively low proportion of ultimate capacity. The reduction of the slope of the stress/strain plot with increasing strain is indicative of reducing elastic and shear modules.

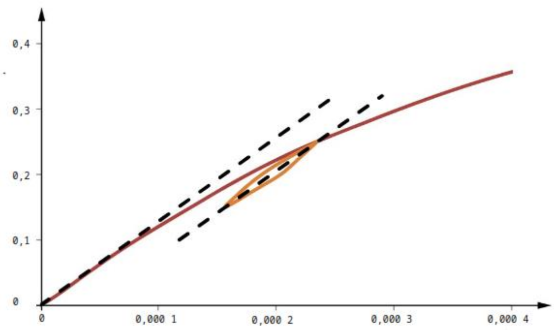


Figure 6. *Loading and unloading behavior of soil*

The reduction of soil shear modulus with strain level may be derived based on the following formula from Yi [1]:

$$\frac{G}{G_0} = \frac{1}{1 + \frac{R_f}{1 - R_f}\left[\frac{\gamma}{\gamma_f}\right]^{\alpha}} \tag{11}$$

Where in:

G : is the secant shear modulus at specific strain level γ;

G_0: is the small-strain shear modulus at γ =0;

R_f = 1- G_f / G_0 với G_f is shear modulus near soil failure;

γ_f is the soil strain near failure.

Figure 7 illustrates this formula in graphical form. The most reliable methods of obtaining site specific small-strain shear modulus (G0) involve the use of geophysical methods to measure shear wave velocity through a representative zone of influence below the foundation. The following relationship allows the small-strain shear modulus to be derived:

$$G_0 = \rho v^2 \tag{12}$$

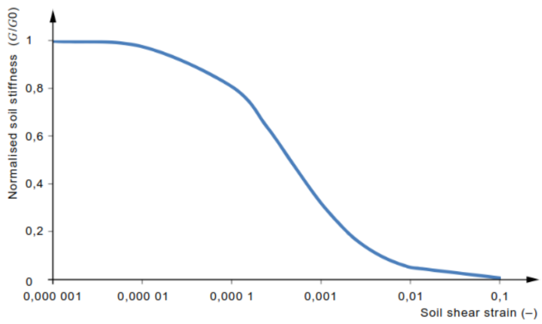


Figure 7. *Variation of shear modulus with soil strain*

Where in:

G_0 : is the small-strain shear modulus;

ρ : is the soil density;

v : is the shear wave velocity.

On the basis of the ground parameters (shear resistance modulus G, ν), foundation dimensions, the foundation stiffness is determined as follows:

- Dynamic rotational stiffness shall be verified based on small-strain shear modulus.

$$K_{R,dyn} = \frac{8 G_0 R^3}{3(1-\nu)} \tag{13}$$

Where in:

$K_{R,dyn}$: is the dynamic rotational stiffness of the foundation subjected to overturning moments;

G_0 : is the small-strain shear modulus of the soi;

ν : is the Poisson’s ratio of the soil;

R : is the effective foundation radius in contact with the subgrade.

The rotational stiffness is proportional to the cube of the radius of the contact area, it is highly sensitive to the contact area. This is a characteristic that can be considered to minimize the effect of cyclic loads on foundation.

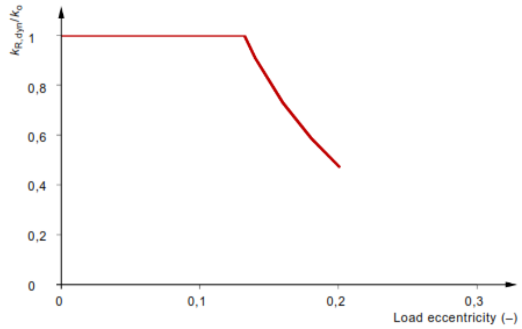


Figure 8. *Reduction in rotational stiffness due to load eccentricity*

- **Static rotational stiffness**

The static foundation rotational stiffness, shall be verified based on a soil modulus which makes allowance for the reduction of small strain shear stiffness as a function of actual soil strain under S1 load case.

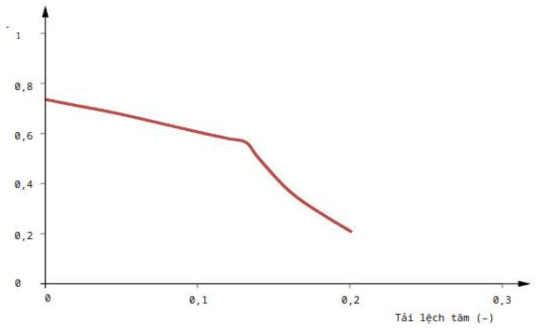


Figure 9. *Static rotational stiffness*

Where in:

$$K_{R,stat} = \frac{8GR^3}{3(1-\nu)} \quad (14)$$

$K_{R,stat}$: is the static rotational stiffness of the foundation subjected to overturning moments;

G : modulus of the soil reduced from G_0 to account for non-zero soil strain;

ν : is the Poisson's ratio of the soil;

R : is the effective foundation radius in contact with the subgrade.

b) Inclination and settlement

Foundation displacement due to long-term settlement should be calculated in order to quantify the maximum inclination (rotation due to differential settlement) and absolute settlement over the design life of the foundation.

The foundation must not exceed the maximum inclination criteria according to which the loads of the wind turbine due to the non-verticality of the mast are calculated. The maximum allowable inclination of the foundation should be specified by the wind turbine manufacturer in addition to any allowable construction tolerances. In the absence of particular criteria specified by the wind turbine manufacturer, a tower base rotation value of 3 mm/m (0.17°) can be assumed due to differential settlement.

The foundation must be limited to a maximum absolute settlement criterion (average over the entire foundation), consistent with the serviceability requirements. Settlement limits may be governed by soil deformation limits, the ductility of electrical conduits where they leave the foundation, or other criteria determined by designers. In the absence of specific criteria imposed by the designers, a value of 25 mm can be assumed for the total allowable settlement.

5. Applying foundation design T26 at Yang Trung, Kong Chro, Gia Lai wind power project

Yang Trung wind power project in Kong Chro district, Gia Lai province, with a design capacity of 145MW and completed in 2020. Using turbine type SG 5.0-145 CIIB HH127.5m manufactured by SIEMENS GAMESA.

5.1 Geological conditions

According to the results of the geological survey, the foundation structure includes:

Layer 1: Sand with gravel, brownish grey, dark gray, medium dense.

Layer 3: Moderately weathered hollow basalt, greenish gray, brownish grey, strongly fracture into lump form, hard rock, with monolithic structure.

Layer 4: Slightly weathered hollow basalt, gray, greenish gray, moderate to little fracture, very hard rock, with monolithic structure.

Layer 5: Sandy clay with lumps, greenish grey, very stiff.

Layer 5a: Sandy clay with lumps, greenish grey, hard.

Layer 6: Strongly weathered granite, strongly fracture into lump form, greenish gray, brownish gray, light gray, very dense.

Layer 7: Moderately weathered granite, greenish gray, gray, moderate to strong fracture, hard rock, with monolithic structure.

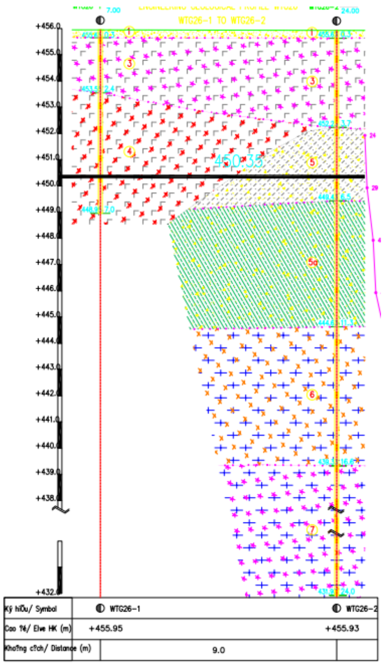


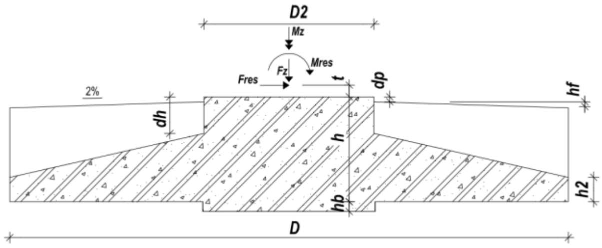
Figure 10. *Geological section T26*

Foundation elevation

- Leveling elevation +454,000;
- Foundation bottom elevation +450,350;
- Design Water level +454,200;
- The buoyancy water level on the foundation is 3,65m.

Foundation dimensions

- Diameter bottom D 27,0m
- Diameter pedestal D_2 6,0m
- Bottom height h_2 0,55m
- Total height foundation h 3,85m
- Stub height dh 1,05m
- Height pedestal above natural ground dp 0,2m
- Slope soil backfill i 2%
- Not refilled height h_f 0,21m
- Bottom height h_b 0,4m
- Height above ground level t 0,17m



- The weight of the foundation W_{Gk} = 22098 (kN)
- Soil weight (dry conditions) W_{soil} = 20440 (kN)
- Soil weight (wet conditions) W_{soil} = 22711 (kN)
- Buoyancy BY = 20375 (kN)

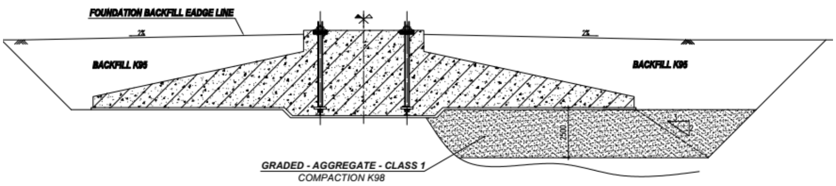


Figure 11. *Replace a part of the base course under the T26 foundation*

The geological structure shown in Figure 10 shows that the ground has a very complex and heterogeneous structure. The soil layers are in the inclination position, overlap and have a strong variation in stiffness in the foundation plan. This is a geological structure that is common in the Central - Highlands area of our country.

In design, the solution of "replacing" a part of the base course (layer 5 - at the bottom of the foundation) and applied calculations according to the principle of limiting the effect of reducing the stiffness of the ground under the effect of cyclic loading. Specifically: control to ensure the condition that the foundation is always in contact with the ground (does not appear in the tensile stress area under the foundation); selection of foundation dimension in combination with partial soil reclamation to ensure the required stiffness. The reasonable dimension of T26 foundation with footing diameter D = 27,0m

5.2 Design Load

- **Ultimate loads with safety factors**

Verification of strength the ground ultimate limit state.

Table 2. *Action provided by manufacturer*

Situations	Loadcase	F_{res}	F_z	M_{res}	M_z	factor
ULS	DLC 6,2	1530,6	7126,66	161717,7	2148,39	1,10

- **Service limit state**

Table 3. *Service limit state*

Situations	Loadcase	F_z		F_{res}	M_{res}	M_z	factor
S1- Characteristic	DLC 1,4	6612,91		994,73	119166	1774,57	1,00
S3- Quasi permanent	DLC 1,4 pf=10^{-2}	6532,07		742,7	94100	2864,32	1,00

- **Fatigue limit state**

Fatigue loads are supplied in two forms, form 1: Markov Matrix supply by the Manufacture and form 2: the equivalent fatigue loads peak to peak for the design, which are derived from Markov Matrix, are included:

Table 4. *Fatigue Load*

m	F_x	F_y	F_z	M_x	M_y	Mz
4	447,95	203,19	-130,31	18974,41	32828,88	6228,31
7	435,71	243,69	-127,81	25213,94	42214,64	6493,85
Mean Load	389,23	1,51	6582,03	3012,7	48956,73	81,67

On the basis of load data, create calculation model and checking the ULS, FLS and SLS for the reinforced concrete structure of the foundation, the results have the reinforced concrete foundation as shown in Figure 12.

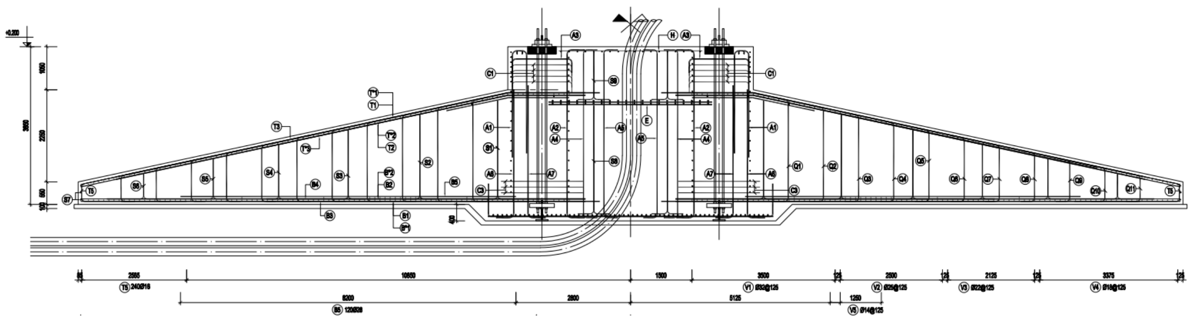


Figure 12. *Reinforce layout section of T26 foundation*

Geotechnical analysis

To ensure safety, for the verifiable strength, two cases of drained and undrained were checked simultaneously. In case of drainage, the calculation results according to the strength are shown in the table below.

Table 5. *Verification of bearing capacity*

Loadcase	qult,1 (kPa)	qult,2 (kPa)	qult (kPa)	qEd (kPa)	qRd (kPa)	Conclus
ULS-DLC6.2	806,2	919,0	806,2	137,4	575,9	**Ok**

In case of no drainage, the test results according to the strength as follows:

Table 6. *Verification of bearing capacity*

Loadcase	qult (kPa)	qEd (kPa)	qRd (kPa)	Conclus
ULS-DLC6.2	766,9	156,5	547,8	**Ok**

In both cases, it see that the design bearing capacity of the ground is much larger foundation pressure.

Verification of stability against sliding, the results are shown in the following table.

Table 7. *Verification of stability against Sliding*

Verification of stability against Sliding (EQU)/ kiểm tra ổn định chống trượt (EQU)						
Loadcase	H'd (kN)	Rd (kN)	Conclus	H'd/Vd	Limit	Conclus
ULS-DLC6.2	1731,0	9237,9	**Ok**	0,044	**0,4**	**Ok**

Verification of stability against overturning according to formula (10) in achieved a high coefficient of stability, the results are as follows:

Table 8. *Verification of stability against overturning*

Loadcase	Md,stb (kNm)	Md,dst (kNm)	Md,stb /Md,dst	γRd	Conclu
ULS-DLC6.2	320576,1	167870,7	1,91	**1,1**	**Ok**

Verification according to deformation: the results show that the settlement of the foundation is very small compared to the limit settlement.

Table 9. *Vertical settlement*

S (mm)	[S] (mm)	**Check**
6,43	50	**OK**

Verification of zero ground gapping: According to IEC 61400-6, combination verification of zero ground gapping is S3. This requirement is very important for the wind power tower foundation, the results as shown in Table 10 meet the requirements.

Table 10. *Verification of zero ground gapping*

Load case /Tổ hợp	**Md**	**Vd**	**e**	**B**	**elimit**	**Check**
	kN.m	kN	m	m	m	
S3	97024	51341				
Buoyancy (BY)	20375					
Gap	97024	30966	3,133	27,0	3,375	**Ok**

Verification of dynamic rotational stiffness: The results in Table 11 and Table 12 show that the dynamic rotational stiffness $K_{R,dyn}$ and the lateral stiffness of $K_{H,dyn}$ sector meet the requirements.

Table 11. *Dynamic rotational stiffness – elastic modules*

Velocity	**Soil density**	**Small-strain shear modulus**	**Gdyn /G0**	**Gdyn**	**Edyn**
Vs (m/s)	γ (kg/m3)	G0 (N/m2)		MPa	MPa
252	1720	109226880	0,32	35	91

Table 12. *Dynamic rotational stiffness KR,dyn*

Gdyn	Edyn	r	v	KR,dyn	Kφ,dyn (required)	Check
MPa	MPa	m		Nm/rad	Nm/rad	
35	91	13,5	0,3	3,3E+11	7,00E+10	**Ok**

Table 13. *Lateral stiffness $K_{H,dyn}$*

Gdyn	Edyn	r	v	KH,dyn	KH,dyn (required)	Check
MPa	MPa	m		N/m	N/m	
35,0	90,9	13,5	0,3	2,6E+09	3,00E+07	**Ok**

6. Conclusion

The design of wind power tower foundation is complicated work, it proposes many different design situations, many different calculation requirements (fatigue analysis, no gapping…). Requires design engineers to have much experience in the field of foundation design.

The system of standards and regulations used to design wind power tower foundations in Vietnam is still incomplete and asynchronous. IEC 61400-

1:2019, IEC 61400-6:2020 are design standards published by the International Electro technical Commission (IEC) and refer to the European standards (Eurocode) and many other specialty standards. Therefore, when applied to Vietnamese conditions, there are many difficulties due to the synchronization with the Vietnam Standards in terms of design and tests, requiring designers to have flexible application in practice.

Assemble data for calculation:

+ In the investigation stage, it is necessary to closely follow the design task to have a suitable investigation plan, to provide all necessary data for the design work, in which it is noted that there are several specialty investigation requirements to provide dynamic parameters for geotechnical design.

Figure 13. *The structure of the foundation reinforces*

Figure 14. *After concreting*

+ In order to have load and action data and accurate technical requirements when designing foundations, it is necessary to analyze thoroughly the requirements of equipment manufacturers to combine data on loads, settlements and special requirements for the turbine base and foundation structure.

For the design of shallow foundation to be economic-technical effective in complicated geological conditions, geotechnical condition assessments need to be a priority. On that basis, consider the plan for soil reclamation (if necessary), combine with the selection of a reasonable foundation dimension to achieve the required stiffness.

Figure 15. *Installing wind-turbin tower*

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