Soil Dynamics and Earthquake Engineering 92 (2017) 126–152

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Design of monopiles for offshore wind turbines in 10 steps

Laszlo Arany[a], S. Bhattacharya[b,*], John Macdonald[a], S.J. Hogan[a]

[a] University of Bristol, United Kingdom
[b] Chair in Geomechanics, University of Surrey, United Kingdom

A R T I C L E I N F O

Keywords:
Monopile
Offshore wind turbines
Eigen frequency
Design

A B S T R A C T

A simplified design procedure for foundations of offshore wind turbines is often useful as it can provide the types and sizes of foundation required to carry out financial viability analysis of a project and can also be used for tender design. This paper presents a simplified way of carrying out the design of monopiles based on necessary data (i.e. the least amount of data), namely site characteristics (wind speed at reference height, wind turbulence intensity, water depth, wave height and wave period), turbine characteristics (rated power, rated wind speed, rotor diameter, cut-in and cut-out speed, mass of the rotor-nacelle-assembly) and ground profile (soil stiffness variation with depth and soil stiffness at one diameter depth). Other data that may be required for final detailed design are also discussed. A flowchart of the design process is also presented for visualisation of the rather complex multi-disciplinary analysis. Where possible, validation of the proposed method is carried out based on field data and references/guidance are also drawn from codes of practice and certification bodies. The calculation procedures that are required can be easily carried out either through a series of spreadsheets or simple hand calculations. An example problem emulating the design of foundations for London Array wind farm is taken to demonstrate the proposed calculation procedure. The data used for the calculations are obtained from publicly available sources and the example shows that the simplified method arrives at a similar foundation to the one actually used in the project.

1. Introduction

Offshore wind turbines are expected to operate for a lifetime of 20–30 years, while foundations are often designed for a longer design life. The selection of foundation type and the design is a complex task, which strongly depends not only on the site characteristics, but also on the maturity and track record of different design concepts. As the offshore wind industry is still in an early stage of large scale development, individual projects take a longer time than the rate at which technology advances. As such, it is not uncommon to change the type of turbine and the size/type of foundations during the development phase of a project. Therefore, development consent is typically obtained for a flexible project that allows for optimised detailed design using the most recent technological advances available at the time of final design. Consequently, it is important to have a simplified design procedure that allows for quick design using only limited site and turbine data, and that can be used in the tender design and early design phases of monopile foundations. Naturally, the procedure described in this paper has to be supplemented and refined with more accurate analyses when more information and data about the site conditions (met ocean data, geotechnical conditions) and chosen turbine becomes available. Accordingly, this paper does not aim to provide a methodology for detailed design and optimisation of monopiles but aims to provide a tool for initial design. Most importantly, the paper aims to show the multidisciplinary complex nature of the task. As such, the procedure defines the monopile through a simple geometry that is described by a pile diameter, wall thickness, pile length, and embedded length. Practical issues related to installation and manufacturing are discussed and it may be noted these aspects are beyond the scope of generalised simplified design procedure. However, it is suggested that manufacturing procedures can be taken into account through S-N curves required for typical welds.

One of the main aims of a foundation is to transfer all the loads from the wind turbine structure to the ground safely and within the allowable deformations. Guided by Limit State Design philosophy, the design considerations are to satisfy the following:

1. Ultimate Limit State (ULS): The first step in design is to estimate the maximum loads on the foundations (predominantly overturning moment, lateral load and the vertical load) due to all possible design load cases and compare with the capacity of the chosen foundation. For monopile type of foundations, this would require computation of

* Corresponding author.
E-mail addresses: S.Bhattacharya@surrey.ac.uk, Subhamoy.Bhattacharya@gmail.com (S. Bhattacharya).

http://dx.doi.org/10.1016/j.soildyn.2016.09.024
Received 6 November 2015; Received in revised form 18 September 2016; Accepted 19 September 2016
0267-7261/

Nomenclature

$b_1,\ b_2$ model parameters for Achmus et al. [4].
e eccentricity of loading ($=M/F$)
f zero shear force point location below mudline
f_0 first natural frequency
$f_{1P,max}$ upper limit of the 1P frequency range
f_{FB} fixed base (cantilever beam) natural frequency of the tower
f_{yk} characteristic yield strength
g gravitational constant
g distance from zero shear force location to pile toe
g_A air gap between the highest expected wave crest level and the platform
k wave number
k_0 equivalent stiffness of first tower mode
k_h horizontal modulus of subgrade reaction
m total structural mass, also strain accumulation exponent
m_0 equivalent mass of first tower mode
m_P mass of the pile
m_{RNA} mass of the rotor-nacelle assembly
m_T mass of the tower
m_{TP} mass of the transition piece
n_h horizontal coefficient of subgrade reaction
n_{h1} coefficient of subgrade reaction at the first load cycle
n_{hN} coefficient of subgrade reaction after N load cycles
s shape parameter of Weibull distribution
s_u undrained shear strength of soil
t, t_a, t_b time, also degradation parameters degradation model
t_G grout thickness
t_P pile wall thickness
t_T tower wall thickness
t_{TP} wall thickness of the transition piece
t_{TP} transition piece wall thickness
u turbulent wind speed component
u_{EOG} extreme gust speed
$u_{EOG,U_{out}}$ Extreme Operating Gust (EOG) wind speed at cut-out wind speed
u_{ETM} turbulent wind speed component for ETM
$w(x,\ z,\ t)$ horizontal water particle velocity
$\dot{w}(x,\ z,\ t)$ horizontal water particle acceleration
x_c characteristics cyclic stress ratio
z_{hub} hub height
A_R Rotor swept area
$C_L,\ C_R$ lateral and rotational foundation flexibility coefficients
C_m inertia coefficient
C_S substructure flexibility coefficient
C_T thrust coefficient
D rotor diameter
D_b bottom diameter of the tower
D_P pile diameter
D_t top diameter of the tower
D_{TP} transition piece diameter
E_{eq} equivalent Young's modulus
E_P pile Young's modulus
$E_S(z)$ vertical distribution of soil's Young's modulus
E_{S0} initial (small deformation) Young's modulus of soil at $1D_P$ depth
E_T Young's modulus of the tower material
EI_η equivalent bending stiffness for horizontal tower top loading
EOG Extreme Operating Gust
ESS Extreme Sea State
ETM Extreme Turbulence Model
EWH Extreme Wave Height
F_d soil density parameter
F_f horizontal load carrying capacity of the foundation
F_i pile installation parameter
F_m maximum horizontal force at the mudline expected in the lifetime of the turbine
F_r cyclic load ratio parameter
F_{wave} total horizontal wave force
$F_{wind,EOG}$ horizontal force due to the Extreme Operating Gust at rated wind speed
$F_{wind,ETM}$ horizontal force due to Extreme Turbulence Model at rated wind speed
F_x fore-aft (along-wind) force on the turbine
F_D drag force due to waves
F_I inertia force due to waves
F_R horizontal load capacity of the foundation (assuming soil failure)
FLS Fatigue Limit State
G^* modified shear modulus
G_S soil's shear modulus
H_m maximum wave height (for a given significant wave height H_S)
$H_{m,50}$ maximum wave height expected in 50 years
H_S significant wave height
$H_{S,50}$ 50-year significant wave height
HWL Highest Water Level with 50 year return period
I reference turbulence intensity
I_P pile's second moment of area
I_T second moment of area of tower
K scale parameter of Weibull distribution
K_L lateral stiffness of the foundation
K_{LR} cross coupling stiffness of the foundation
K_P Rankine coefficient of passive pressure
K_R rotational stiffness of the foundation
L_k horizontal turbulence integral length scale
L_P pile embedded length
L_S platform height (distance from mudline to platform level, that is to the top of the transition piece)
L_T tower length
L_{TP} length of the transition piece
M_{amp} amplitude of the bending moment in a load cycle ($=M_{max}-M_{min}$)
M_f overturning moment capacity of the foundation
M_{ULS} maximum overturning moment at the mudline expected in the lifetime of the turbine
M_{max} maximum bending moment in a load cycle
M_{mean} mean bending moment in a load cycle ($=0.5\bullet(M_{max}+M_{min})$)
M_{min} minimum bending moment in a load cycle
M_y fore-aft (along-wind) overturning moment
M_R overturning moment capacity of the foundation (assuming soil failure)
M_{wave} total overturning moment due to waves
$M_{wave,NWH}$ total overturning moment due to waves for normal wave height (NWH)
$M_{wave,EWH}$ total overturning moment due to waves for extreme wave height (EWH)
$M_{wind,EOG}$ overturning moment due to the Extreme Operating Gust at rated wind speed
$M_{wind,ETM}$ overturning moment due to Extreme Turbulence Model at rated wind speed
N number of load cycles
NSS Normal Sea State
NTM Normal Turbulence Model
NWH Normal Wave Height