Monopiles in offshore wind: Preliminary estimate of main dimensions

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A R T I C L E   I N F O

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A B S T R A C T

Offshore wind industry is having a great development. It requires progress in many aspects to achieve the sustainable progress of this technology. One of those aspects is the design of foundation, sub-structures and support structures. The most used at present, with more than 80%, is the monopile. Typical piles used in quays in maritime engineering have a maximum diameter about 2 or 3 m. In offshore wind, the diameter can be more than double. There is a risk associated with the difference in scale. Some formulas used for the design of typical piles with diameter less than 2 m can be unsuitable for larger diameter piles. This paper is focused on giving a first estimate of length and weight of piles for knowing its diameter. There are formulas for that for piles with diameters up to 2 m, but there are doubts about whether they can be used for piles with larger diameters. To achieve it, a database gathering offshore wind farms in operation with monopiles is prepared in order to obtain simple formulas relating those parameters. Furthermore, the results of that formula are compared with traditional formula used in maritime engineering for piles with diameters less than 2 m.

1. Introduction

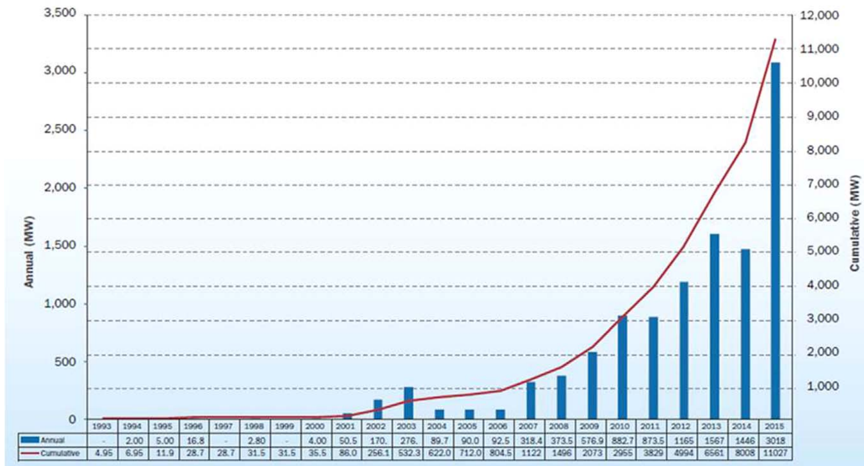
Offshore wind power is currently the most developed renewable energy source that can be taken advantage at sea (Colmenar-Santos et al., 2016; Esteban et al., 2009, 2011a; Myhr et al., 2014; Sun et al., 2012). At the end of 2015, there were 11,027.3 MW (MW) of offshore wind in operation, with a total of 3230 wind turbines. This is specified in energy production of approximately 40.6 Terawatt hours (TWh) in a normal wind year, enough electricity to cover 1.5% of the total electricity consumption in the European Union (EU), considering this as 2770 TWh. UK is the country with the largest installed capacity in the EU, with 5060.5 MW, representing 45.9% of the total in Europe. It is followed by Germany, with 3294.6 MW and 29.9%, and by Denmark, with 1271.3 MW and 11.5% (Fig. 1) (EWEA, 2015).

Noting the evolution of cumulative MWs of offshore wind in operation (Schweizer et al., 2016; Wu, 2014) since the early 90 s of last century in Europe, it is clear the increase in installed annual capacity since 2007. Since 2012, more than 1000 MW have been installed per year, having reached the figure of 3018 MW installed in 2015, which was unthinkable in the early days of this technology (Fig. 1) (EWEA, 2015). Given this boom in offshore wind technology, it is necessary to take care of many aspects to achieve its development in a sustainable manner.

Although part of the technology used in offshore wind comes from onshore wind farms, the marine environment make offshore wind facilities more complex in the design, construction, commissioning, operation, and decommissioning or repowering (Dalgic et al., 2015). This requires the need for progress in numerous areas such as wind resource estimation, foundations and support structures, electrical connection, logistic, etc. (Esteban et al., 2015b; Smit et al., 2007).

The design of foundations, sub-structures and support structures is very complex (Chew et al., 2016; Maria Jose and Mathai, 2016). Fig. 2 clarifies the meaning of foundation, sub-structure and support structure (International Electrotechnical Commission, 2005). There are different types of foundations, the most common being the piles, gravity foundations and suction caissons. The most known sub-structures types at the end of 2015 were the monopiles (80.1%), gravity foundations (9.1%), jackets (5.4%), tripods (3.6%), and others (1.8%). In case of large water depths, the option of either semi-submersible, TLP (Tension Leg Platform) or SPAR floating supports are being considered (Breton and Moe, 2009; Dvorak et al., 2010; Esteban et al., 2011b, 2011c, 2015a, 2015b; Houlsby et al., 2006; Lozano-Minguez et al., 2011; Zaaijer, 2006; Zhao et al., 2012). There is a lot of research studies focused on different types of foundations (Benassai et al., 2014; Chang and Jeng, 2014; Collu et al., 2014; Dunbar et al., 2015; Ha and Cheong, 2016; Perez-Collazo et al., 2015; Rogan et al., 2016; Schafhirt et al., 2016; Zhang et al., 2015, 2016).

So far, the type of foundation and/or sub-structure most commonly



Country	BE	DE	DK	ES	FI	IE	NL	NO	PT	SE	UK	Total
No. of farms	5	18	13	1	2	1	6	1	1	5	27	**80**
No. of turbines	182	792	513	1	9	7	184	1	1	86	1,454	**3,230**
Capacity installed (MW)	712	3,295	1,271	5	26	25	427	2	2	202	5,061	**11,027**

Fig. 1. Global annual mean power distribution (EWEA, 2015).

used in the offshore wind industry is the monopile. Monopiles used in the offshore wind industry are typically hollow, steel cylinder with diameter larger than 3 m. At the beginning of 2016, the monopile had been used as the foundation of 2653 wind turbines, which represents about 80% (EWEA, 2015).

Due to the quick development of offshore wind technology, some improvements are necessary in different aspects, being one of them the design of the foundation and the sub-structure. Some uncertainties in that design have been identified, related for example to the lifetime and return period, loads combination, scour phenomenon and its protection, Morison – Froude Krilov and diffraction regimes, wave theory (Airy, cnoidal, Stokes, stream function), different scale (length and diameter), and liquefaction (Esteban et al., 2015a; Matutano et al., 2013a, 2013b, 2014; Negro et al., 2014; Prendergast et al., 2015).

For instance, the uncertainty related to the different scale (Jung et al., 2015; Li et al., 2011) can be explained as follows. Typical piles used in maritime engineering have a maximum diameter about 2 m, but in offshore wind farms the diameter can be more than double or even larger figures. The difference in scale is clear to be taken into account (Negro et al., 2014). In fact, some formulas used for monopile design have been demonstrated for piles of diameter less than 2 m; for instance, finite element models have shown that the API *p-y* method overestimates soil-pile resistance (Carswell, 2012). This is clearly a risk associated with the difference in scale.

For piles with diameters up to 2 m, there is a formula that allows giving a first estimate of the total length of the pile knowing its diameter (Jiménez-Salas, 1976). However, that formula cannot be suitable for larger diameter piles where the mentioned formulas are off

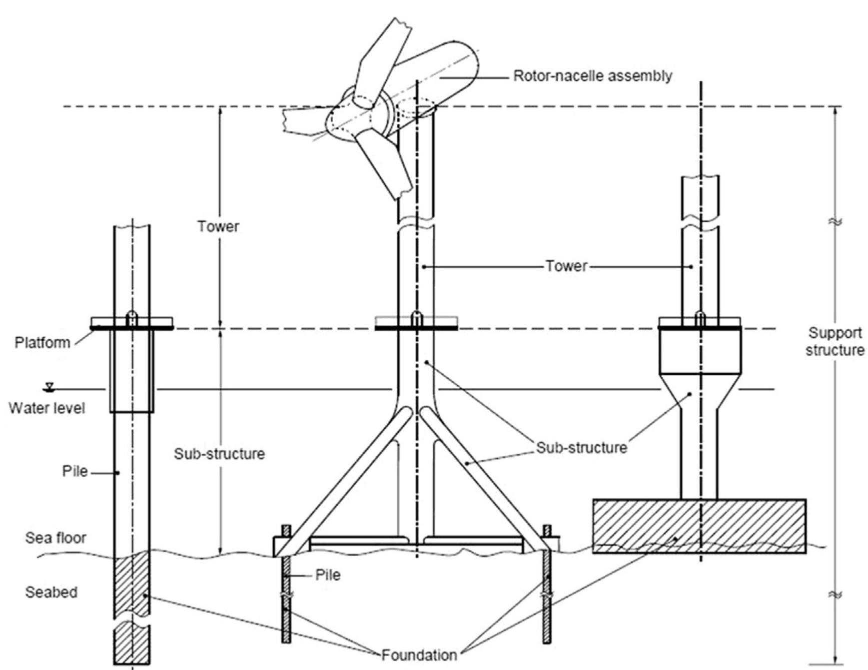


Fig. 2. Offshore wind turbine structure components (International Electrotechnical Commission, 2005).

the scale. This paper presents the results of a research whose main objective is to obtain simple formulas to give a first estimate of the length of the pile based on the diameter figure. Furthermore, a relationship between the length and the weight of the pile is achieved.

2. Methodology

The main objective of the research exposed in this paper is to obtain a simple equation to estimate the length and weight of hollow large steel monopiles used in offshore wind, knowing its diameter. That equation aims to give a first estimation to be verified and optimized with geotechnical and structural detailed design.

To achieve that objective, a research methodology was developed:

- To identify those offshore wind farms with hollow large steel monopile as foundation.
- To gather all the relevant information for the analysis: diameter, length and weight of the monopile, water depth and distance from the coast of the location.
- To create a database with all the information previously collected.
- To make the statistical analysis between the diameter and the total and driving length of the monopile according to the database, trying to find a relationship between the two parameters.
- To repeat the same statistical study between the total length and the weight of the monopile.
- To compare and discuss the results of the statistical analysis with other geotechnical formulas used for a first estimation.

3. Monopiles database: main characteristics and input data for the statistical analysis

The research is focused on the typical hollow, steel cylinder with large diameter monopiles used as foundation and sub-structure for offshore wind turbines. This type is the most common in offshore wind, having been used as the foundation of 2653 wind turbines, which represents about 80% (Fig. 3) (EWEA, 2015).

About five years ago, monopile type was recommended only for water depths less than 20–30 m (Esteban et al., 2011b). Nowadays, it is common to hear about XXL monopiles as viable alternatives to jacket sub-structures. For that, it has been necessary the increase of the

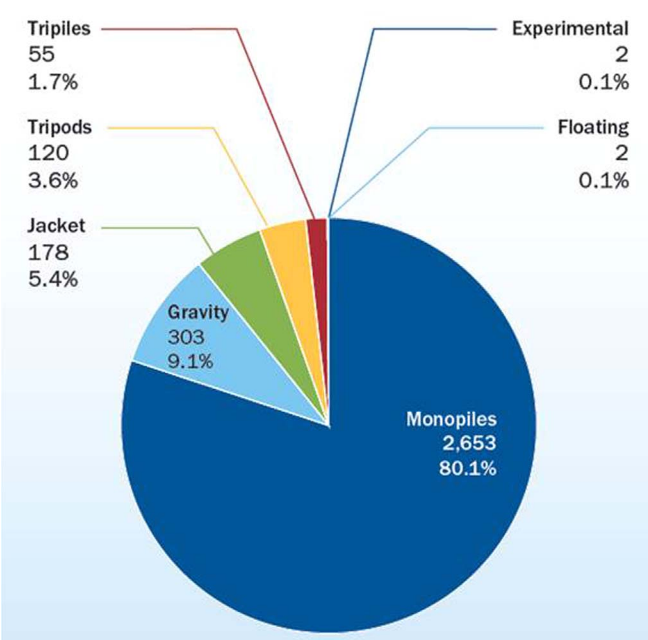


Fig. 3. Share of substructures types for online wind turbines end 2015 (EWEA, 2015).

Fig. 4. Monopile of 7.8 m of diameter and 1302.5 t rolled out of the factory in Rostock, used in Veja Mate offshore wind facility (www.offshorewind.biz/2016/03/14/first-veja-mate-monopiles-reach-eemshaven/).

diameter of the pile. Fig. 4 shows a monopile of 7.8 m of diameter and 1302.5 t rolled out of the factory in Rostock, used in Veja Mate offshore wind facility, located in the German North Sea. They are the world's heaviest monopiles ever built (www.offshorewind.biz/2016/03/14/first-veja-mate-monopiles-reach-eemshaven/).

To achieve the objective of this research, a database has been developed including the offshore wind facilities with monopile and with enough information to carry out the analysis, that is to say, at least the water depth, the diameter, the length and the weight. Furthermore, other relevant information about the facilities has been collected (Table 1) from the following Websites: www.lorc.dk and www.4coffshore.com.

Table 1 includes information about 30 offshore wind farms, located in 6 different countries (Belgium, Denmark, Germany, Netherlands, Sweden and UK), all of them with steel monopiles foundations. Those facilities are located in water depths exceeding 30 m in some cases. The average of the maximum water depths of the farms included in the Table is about 18 m. The minimum diameter of pile is 2.1 m, the maximum is 7 m and the average is 4.8 m. The minimum length of the pile is 21 m, the maximum is 85 m and the average is 51.4 m. The minimum weight of the pile is 43 t (t), the maximum is 805 t, and the average is 421.4 t.

On the other hand, the length parameter included in Table 1 corresponds to the total length of the pile, not only the driving length. For that, the driving length has been calculated considering the maximum water depth in each case with the objective to be conservative. The parameters to be analyzed in detail are included in Table 2.

4. Formulas development based on statistical analysis

This section focuses on the development of simple formulas for estimating the total length, the driving length and the weight of the steel monopiles of large diameter, once known its diameter, considered in this research as an independent known variable. Furthermore, the relationship between the water depth and the driving length has been analyzed. According to the input data, this study is limited to the following conditions: water depths between 5 and 30 m, pile diameter between 3 and 7 m, pile total length between 30 and 80 m, and pile weight between 200 and 800 t.

First, the relationship between the diameter and the length of the pile is analyzed. For that, the dispersion graph has been created (Fig. 5), and after deleting the residuals, the linear equation relating diameter and length of the pile has been created. The regression value has been studied: R^2 is 0.9148, very close to 1, demonstrating the goodness of fit of the linear equation (Fig. 6). So, the equation is shown in [Eq. (1)], where L_T is the total length and D is the diameter, both in meters.

Table 1
Database of offshore wind farms in Europe with monopile sub-structure.

Wind Farm	Country	Project (MW)	Turbine (MW)	Water depth (m)	Distance shore (km)	Diameter (m)	Length (m)	Weight (t)
Belwind	Belgium	165	3	15 to 24	46	5	72	550
Horns Rev 2	Denmark	209.3	2.3	9 to 17	30	3.9	40	280
Horns Rev 1	Denmark	160	2	6 to 14	14 to 20	4	42	230
Samsø	Denmark	23	2.3	10 to 13	3.5	4.5	45	300
Anholt	Denmark	399.6	3.6	15 to 19	15 to 20	5	54	630
EnBW Baltic 1	Germany	48.3	2.3	16 to 19	16	4.3	37	215
Borkum Riffgrund 1	Germany	312	4	23 to 29	54	5.9	66	700
Amrumbank West	Germany	302	3.775	20 to 25	35	6	70	800
DanTysk	Germany	288	3.6	21 to 31	69	6	65	730
Riffgat	Germany	108	3.6	18 to 23	15 to 30	6	70	720
Lely	Netherlands	2	0.5	5 to 10	0.8	3.7	30	89
Prinses Amalia	Netherlands	120	2	19 to 24	23	4	54	320
Egmond aan Zee	Netherlands	108	3	18	10 to 18	4.6	60	250
Bockstigen	Sweden	2.75	0.55	6	4	2.1	21	43
Utgrunden 1	Sweden	10.5	1.5	7 to 10	8 to 12.5	3.65	33.7	165
North Hoyle	UK	60	2	7 to 11	7 to 8	4	25	250
Kentish Flats	UK	90	3	5	8.5 to 13	4	38	247
Scroby Sands	UK	60	2	5 to 10	2.3	4.2	42	200
Robin Rigg	UK	174	3	4 to 13	11	4.3	35	310
Rhyl Flats	UK	90	3.6	6 to 12	8	4.7	40	235
Barrow	UK	90	3	15 to 20	7.5	4.75	60	530
Gunfleet Sands	UK	172.8	3.6	0 to 15	7	5	50	423
Teesside	UK	62.1	2.3	8 to 16.5	1.5	5	48	160
Burbo Bank	UK	90	3.6	2 to 8	6	5	52	400
Sheringham Shoal	UK	316.8	3.6	17 to 22	17 to 23	5.2	61	530
Lincs	UK	270	3.6	8.5 to 16.3	6 to 8	5.2	48	480
Gwynt Môr	UK	576	3.6	12 to 28	13 to 18	6	70	700
Greater Gabbard	UK	504	3.6	20 to 32	26	6	60	700
Walney Phase 2	UK	183.6	3.6	24 to 30	14 to 18	6	68	805
London Array	UK	630	3.6	0 to 25	20	7	85	650

$$L_T = 14D - 17 \quad (1)$$

Second, the relationship between the diameter and the driving length of the pile is analyzed. As in the previous step, the dispersion graph has been created (Fig. 7), and after deleting the residuals, the linear equation relating diameter and length of the pile has been created. The regression value has been studied: R^2 is 0.8391, very close to 1, demonstrating the goodness of fit of the linear equation (Fig. 8). So, the equation is shown in [Eq. (2)], where L_D is the driving length and D is the diameter, both in meters.

Table 2
Information necessary for the further analysis extracted from the previous created database of offshore wind farms in Europe with monopile substructure.

Wind Farm	Water depth (m)	Max water depth (m)	Diameter (m)	Length (m)	Driving length (m)	Weight (t)
Belwind	15 to 24	24	5	72	48	550
Horns Rev 2	9 to 17	17	3.9	40	23	280
Horns Rev 1	6 to 14	14	4	42	28	230
Samsø	10 to 13	13	4.5	45	32	300
Anholt	15 to 19	19	5	54	35	630
EnBW Baltic 1	16 to 19	19	4.3	37	18	215
Borkum Riffgrund 1	23 to 29	29	5.9	66	37	700
Amrumbank West	20 to 25	25	6	70	45	800
DanTysk	21 to 31	31	6	65	34	730
Riffgat	18 to 23	23	6	70	47	720
Lely	5 to 10	10	3.7	30	20	89
Prinses Amalia	19 to 24	24	4	54	30	320
Egmond aan Zee	18	18	4.6	60	42	250
Bockstigen	6	6	2.1	21	15	43
Utgrunden 1	7 to 10	10	3.65	33.7	23.7	165
North Hoyle	7 to 11	11	4	25	14	250
Kentish Flats	5	5	4	38	33	247
Scroby Sands	5 to 10	10	4.2	42	32	200
Robin Rigg	4 to 13	13	4.3	35	22	310
Rhyl Flats	6 to 12	12	4.7	40	28	235
Barrow	15 to 20	20	4.75	60	40	530
Gunfleet Sands	0 to 15	15	5	50	35	423
Teesside	8 to 16.5	16.5	5	48	31.5	160
Burbo Bank	2 to 8	8	5	52	44	400
Sheringham Shoal	17 to 22	22	5.2	61	39	530
Lincs	8.5 to 16.3	16.3	5.2	48	31.7	480
Gwynt Môr	12 to 28	28	6	70	42	700
Greater Gabbard	20 to 32	32	6	60	28	700
Walney Phase 2	24 to 30	30	6	68	38	805
London Array	0 to 25	25	7	85	60	650

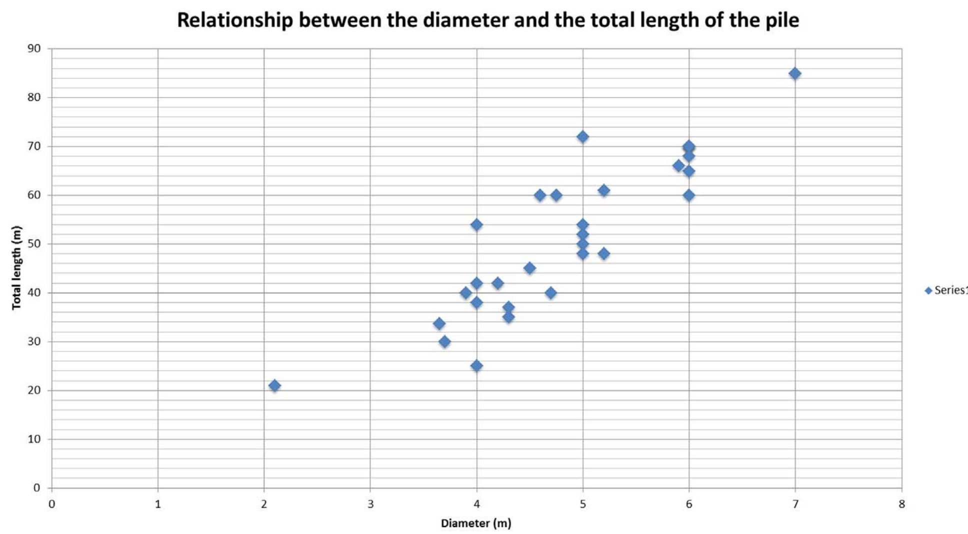


Fig. 5. Dispersion graph: diameter and total length of the pile.

$$L_D = 8D - 5 \quad (2)$$

Third, the relationship between the length and the weight of the pile is analyzed. As in the previous step, the dispersion graph has been created (Fig. 9), and after deleting the residuals, the linear equation relating diameter and length of the pile has been created. The regression value has been studied: R^2 is 0.9418, very close to 1, demonstrating the goodness of fit of the linear equation (Fig. 10). So, the equation is shown in [Eq. (3)], where W is the weight, in tons, and L_T is the total length, in meters.

$$W = 16.5L_T - 392 \quad (3)$$

5. Discussion

Considering a simplified approach, the embedded length of a pile can be estimated as a function of the pile diameter and relative pile-soil stiffness ratio. There are different criteria proposed for the embedded length (DNV, 2014; GermanischerLloyd, 2005; Kuo et al., 2012): zero toe-kick criterion (displacement of the pile toe zero or negative), vertical tangent criterion (deflection curve with vertical tangent at the pile toe), and critical pile length criterion (a further increase in pile length has no or has very limited effect on the rotation and deflection at pile head) (Arany et al., 2017). Based on previous analysis of the mentioned criteria, it is recommended to use critical pile length criterion (Achmus et al., 2009; Arany et al., 2017; Kuo et al., 2012).

Different approaches can be considered for the estimation of embedded pile length such as (Carter and Kulhawy, 1992; Poulos and Davis, 1980; Randolph, 1981; Arany et al., 2017).

In this research, the formula created in 1965 by Davisson and Robinson (Davisson, 1970; Davisson and Salley, 1970) is considered. It allows giving a first estimate of the total length of the pile knowing its diameter (Jiménez-Salas, 1976) and it is demonstrated for pile up to 2 m of diameter. That formula considers the elastic length as the fifth root of the ratio between the modulus of elasticity of the material of the pile multiplied by the inertia of the section of the pile and divided by the horizontal reaction coefficient of the terrain. Once calculated the elastic length, the embedment length can be determined multiplying the elastic length by 1.8. The driving length can be determined multiplying the elastic length by 3. That formula is valid for medium sandy soils.

The results of applying Davisson and Robinson formula to concrete and steel piles with different exterior and interior diameter are shown in Table 3 and Table 4, both of them considering 10 cm of thickness. In fact, for concrete piles with diameter of 1 m, the figure to have the first estimation for the driving length is around ten times the diameter.

An initial value for the thickness (t) of the monopile can be

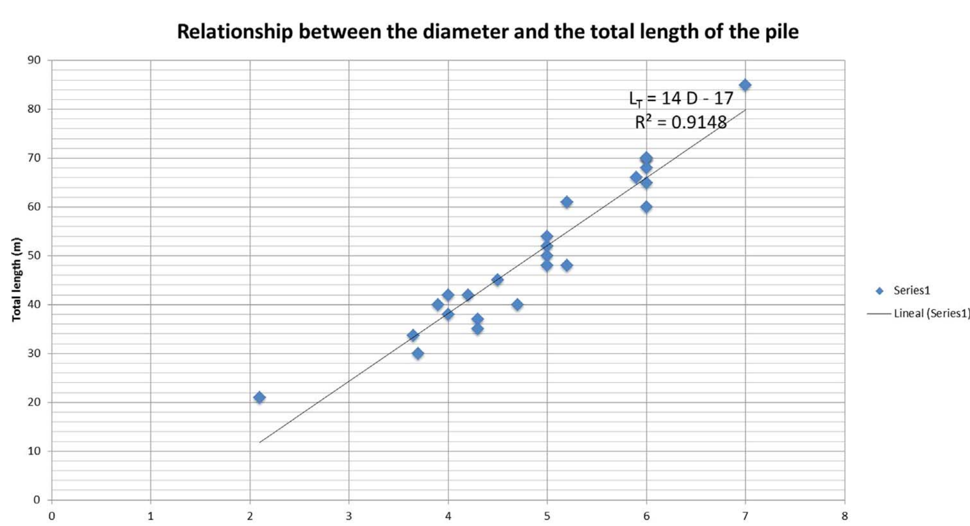


Fig. 6. Regression analysis for the linear equation: diameter and total length of the pile.

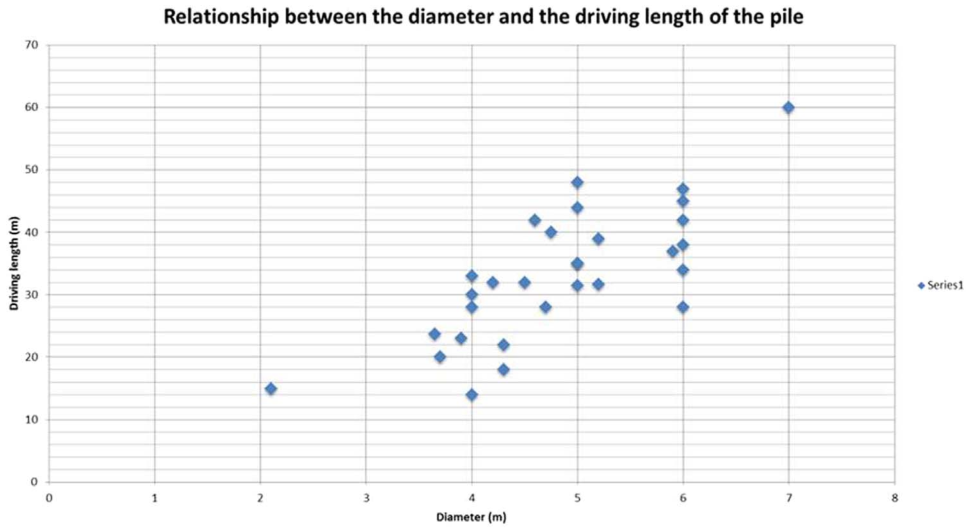


Fig. 7. Dispersion graph: diameter and driving length of the pile.

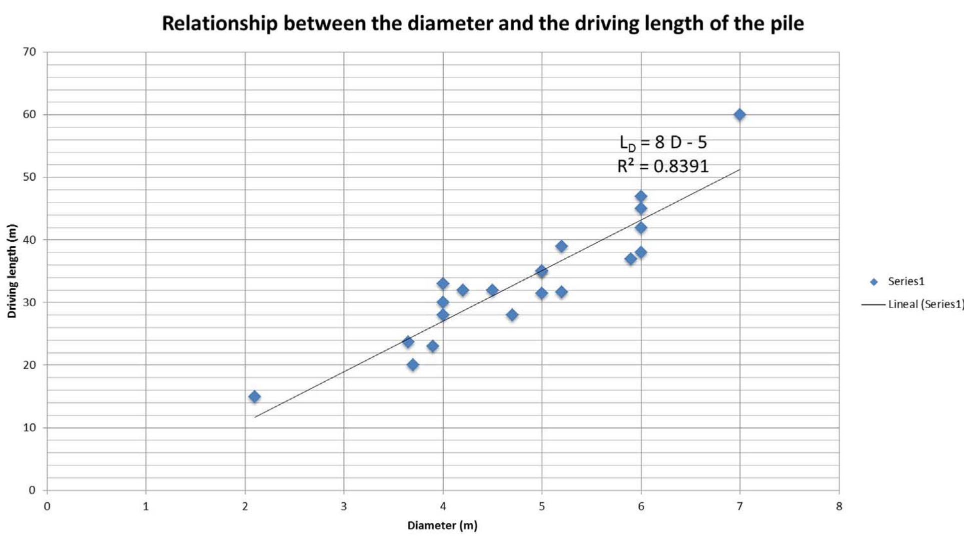


Fig. 8. Regression analysis for the linear equation: diameter and driving length of the pile.

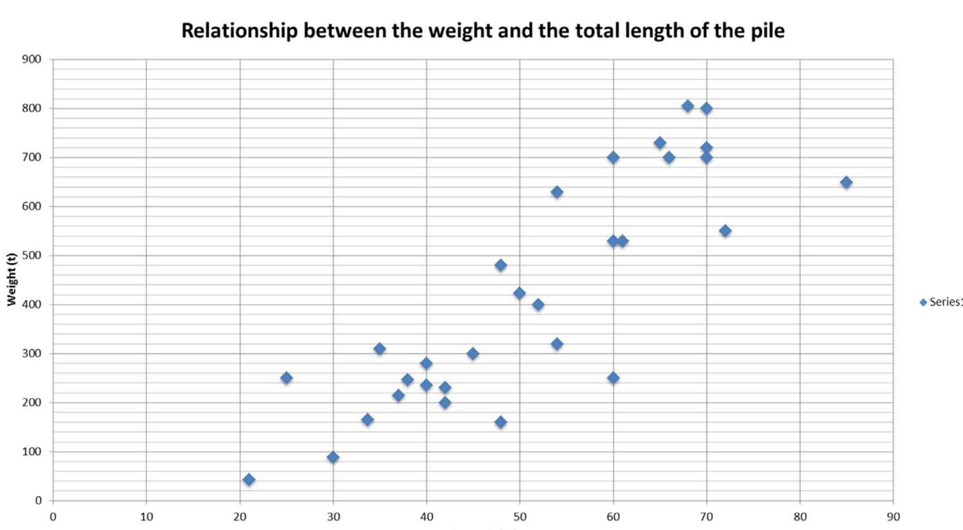


Fig. 9. Dispersion graph: total length and weight of the pile.

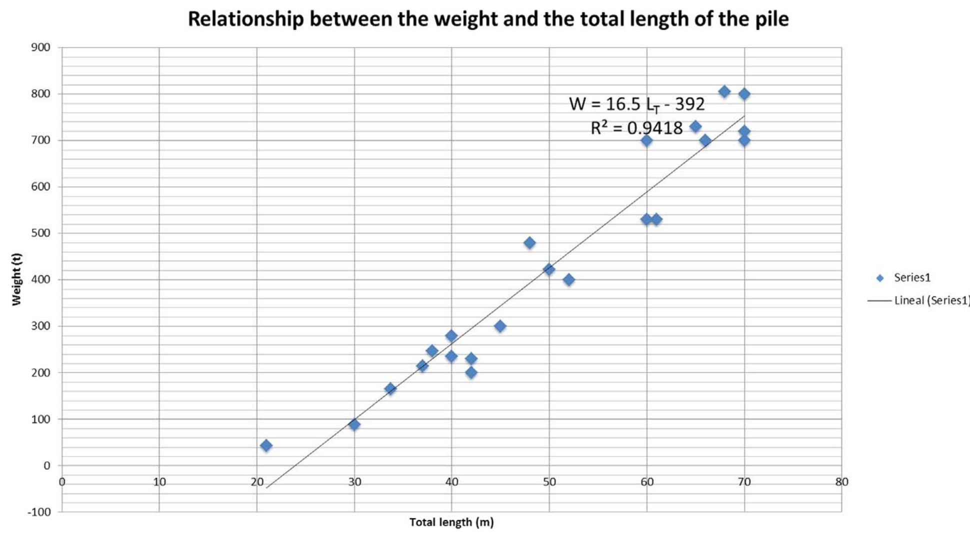


Fig. 10. Regression analysis for the linear equation: total length and weight of the pile.

Table 3
Results of applying Davisson and Robinson formula for concrete piles with different exterior diameter in sandy soils figures in 20 m of water depth.

Concrete pile, water depth 20 m								
Outer diameter (m)	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00
Inner diameter (m)	0.80	1.80	2.80	3.80	4.80	5.80	6.80	7.80
Elastic length (m)	2.87	4.48	5.77	6.89	7.90	8.83	9.70	10.52
Embedment length (m)	5.16	8.06	10.39	12.40	14.22	15.90	17.47	18.94
Driving length (m)	8.60	13.43	17.31	20.67	23.71	26.50	29.11	31.57
Total length (m)	28.60	33.43	37.31	40.67	43.71	46.50	49.11	51.57

Table 4
Results of applying Davisson and Robinson formula for steel piles with different exterior diameter, considering wall thickness of 10 cm, in sandy soils figures in 20 m of water depth.

Steel pile, water depth 20 m								
Outer diameter (m)	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00
Inner diameter (m)	0.80	1.80	2.80	3.80	4.80	5.80	6.80	7.80
Elastic length (m)	4.59	7.17	9.23	11.03	12.65	14.14	15.53	16.84
Embedment length (m)	8.25	12.90	16.62	19.85	22.76	25.45	27.95	30.32
Driving length (m)	13.76	21.50	27.70	33.09	37.94	42.41	46.59	50.53
Total length (m)	33.76	41.50	47.70	53.09	57.94	62.41	66.59	70.53

estimated depending on the pile diameter according to API (API, 2005) as shown in [Eq. (4)] (Arany et al., 2017).

$$t = 6.35 + \frac{D}{100}\ [mm] \tag{4}$$

Table 5 shows the results of applying Davisson and Robinson for steel pile of external diameters between 1 and 8 m, considering the thickness, obtained from API formula and conservatively rounded.

Results from Davisson and Robinson formula has been compared to the linear equation $L_D = 8\ D - 5$ [Eq. (2)] obtained in this research from the statistical analysis, where L_D is the driving length and D is the diameter, both in meters. The results of that comparison are shown in Table 6 in case of wall thickness of 10 cm in all the cases, and in Table 7 in case of thickness calculated with API formula.

Table 5
Results of applying Davisson and Robinson formula for steel piles with different exterior diameter, considering wall thickness calculated with API formula in sandy soils, in 20 m of water depth.

Steel pile, water depth 20 m								
Outer diameter (m)	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00
Inner diameter (m)	0.96	1.94	2.92	3.90	4.88	5.86	6.84	7.82
Elastic length (m)	3.49	5.75	7.78	9.67	11.47	13.20	14.88	16.50
Embedment length (m)	6.28	10.36	14.01	17.41	20.65	23.77	26.78	29.71
Driving length (m)	10.47	17.26	23.34	29.02	34.42	39.61	44.63	49.51
Total length (m)	30.47	37.26	43.34	49.02	54.42	59.61	64.63	69.51

Table 6
Results of the comparison of the results of Davisson and Robinson formula and the formula obtained in this research analysis, considering wall thickness of 10 cm for all the cases. These figures are for steel piles with diameters between 4 and 6 m.

Comparison between driving length values for steel piles					
Outer diameter (m)	4.00	4.50	5.00	5.50	6.00
Inner diameter (m)	3.80	4.30	4.80	5.30	5.80
Driving length (Davisson & Robison formula) (m)	33.09	35.57	37.94	40.22	42.41
Driving length (statistical analysis) (m)	27.00	31.00	35.00	39.00	43.00
Difference between driving length figures (m)	6.09	4.57	2.94	1.22	−0.59
Difference between driving length figures (%)	22.54	14.74	8.40	3.12	−1.37

Table 7
Results of the comparison of the results of Davisson and Robinson formula and the formula obtained in this research analysis, considering wall thickness calculated with API formula. These figures are for steel piles with diameters between 4 and 6 m.

Comparison between driving length values for steel piles					
Outer diameter (m)	4.00	4.50	5.00	5.50	6.00
Inner diameter (m)	3.90	4.38	4.88	5.36	5.86
Driving length (Davisson & Robison formula) (m)	29.02	32.29	34.42	37.57	39.61
Driving length (statistical analysis) (m)	27.00	31.00	35.00	39.00	43.00
Difference between driving length figures (m)	2.02	1.29	−0.58	−1.43	−3.39
Difference between driving length figures (%)	7.49	4.15	−1.65	−3.66	−7.88

Table 8
Comparison between the total length and the weight for steel piles.

Comparison between total length and weight for steel piles						
Total length (m)	30.00	40.00	50.00	60.00	70.00	80.00
Weight (t)	103.00	268.00	433.00	598.00	763.00	928.00
Weight/length (t/m)	3.43	6.70	8.66	9.97	10.90	11.60
Weight/(Length • Specific weight) (m^2)	0.44	0.85	1.10	1.27	1.39	1.48

Table 6 shows the comparison of the results of Davisson and Robinson formula and the formula obtained in this research analysis, considering wall thickness of 10 cm for all the cases, being these figures for steel piles with diameters between 4 and 6 m. Different figures of driving values are obtained using the formula sanctioned by practice and the one obtained in this research from the statistical analysis, to have a rough estimate before using a specific calculation method, such as the methodology "Design of monopiles for offshore wind turbines in 10 steps" included in (Arany et al., 2017). Anyway, the difference in meters is not very large taking into account the objective of both formulas, which is to give a first estimate that must be verified in detail geotechnical and structural calculations, for instance, to avoid resonance issues (Cui and Bhattacharya, 2016; Nikitas et al., 2016). The difference is smaller in case of piles with diameter between 5 and 6 m, the most used up to now in monopiles for offshore wind turbines. In those cases, the difference in percentage is less than 10%.

Table 7 shows the comparison of the results of Davisson and Robinson formula and the formula obtained in this research analysis, considering wall thickness calculated with API formula, in case of steel piles with diameters between 4 and 6 m. Similarly to Table 6, different driving values are obtained using both formulas, being the differences smaller than 10% in all cases.

With the objective to have a simple formula for rough estimate, the following relationship can be used: in case of monopiles with 4 m of diameter, the driving length is about 9 times the diameter; in case of monopiles with 5 m of diameter, the driving length is about 8 times the diameter; and in case of monopiles with 6 m of diameter, the driving length is about 7 times the diameter. In all these cases, the result of the sum of the diameter and the factor of the multiplication is 13.

On the other hand, Table 8 shows the relationship between the total length and the weight for steel piles according the linear equation obtained in this research. It is clear than the weight per meter of length increase because the steel section of the pile has generally to grow with its length.

6. Conclusions

Offshore wind energy is experiencing a tremendous growth in recent years, and it is expected to continue that trend. Therefore, it is essential to achieve a right evolution of the technology. Several aspects need to be improved such as the design of the foundations, substructures and support structures. This paper is focused on it and specifically on the monopile type, the most used so far, total in 80% of offshore wind turbines.

Monopiles used in offshore wind facilities are generally hollow steel piles of diameter larger than 3 m. The piles used in general in maritime engineering have less than 2 m in diameter. Then, formulas used in maritime engineering for the design of the piles cannot be adequate for monopiles in offshore wind due to the different scale, in some cases more than double and even triple. It is worth mentioning the case of Veja Mate, offshore wind farm located in the German North Sea, with monopiles of 7.8 m of diameter and 1302.5 t.

The following formulas have been developed from a statistical analysis based on the database created with European offshore wind facilities with monopile foundations:

- L_T =14 D – 17, where L_T is the total length and D is the diameter. R^2 is 0.9148.
- L_D=8 D – 5, where L_D is the driving length and D is the diameter. R^2 is 0.8391 W=16.5 L_T – 392, where W is the weight and L_T is the total length. R^2 is 0.9418.

According to the input data, this study is limited to the following conditions: water depths between 5 and 30 m, pile diameter between 3 and 7 m, pile total length between 30 and 80 m, and pile weight between 200 and 800 t.

The second of previously mentioned formulas has been compared with the traditionally used Davisson and Robison formula. Some conclusions of that comparison considering hollow steel piles with diameters between 4 and 6 m, and sandy soils are: different figures of driving values are obtained, but the difference is not very important taking into account the objective of both formulas, which is to give a rough estimate that must be verified in detail geotechnical and structural calculations. In case of having calculated the wall thickness according to API formula, the difference in percentage is less than 10% in all the cases. Therefore, both formulas can be used for a rough estimate. The linear equation that related the weight and the total length of the pile can also be used for rough estimate.

With the objective to have a simple formula to be remembered by engineers in practical cases, the following rule can be used: for monopiles with 4 m of diameter, the driving length is about 9 times the diameter; in case of monopiles with 5 m of diameter, the driving length is about 8 times the diameter; and in case of monopiles with 6 m of diameter, the driving length is about 7 times the diameter. The result of the sum of the diameter and the factor of the multiplication is 13.

When more offshore wind farms with monopiles are in operations, it is recommended to validate the formula obtained in this research, and even to analyze if the formula is valid for diameter piles larger than 6 m.

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