4 ANALYSIS RESULTS

4.1 Monopile Results

4.1.1 OWTG power: 3.6 MW

3.6 MW Monopile Mass

Traditional monopile design is used in the calculations for being the most common design type so far. This means that the analysis is carried out considering that the pile diameter is maintained constant all along its length and that just the thickness varies. Figure 4.1shows a traditional type pile with the TP and the pile union at m.s.l.

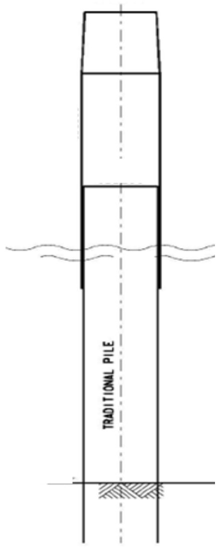


Figure 4.1. Traditional pile design [110]

Diagram 4.1 presents the monopile mass (pile + TP) and 1st natural frequency results for different input values of the wave height, soil type and water depth. This figure only accounts for the static design criterion (extreme loading) and can be compared with the static + dynamic criterion (when also the 1st natural frequency has to be within the allowable range of 0.28-0.35 Hz) in Diagram 4.2.

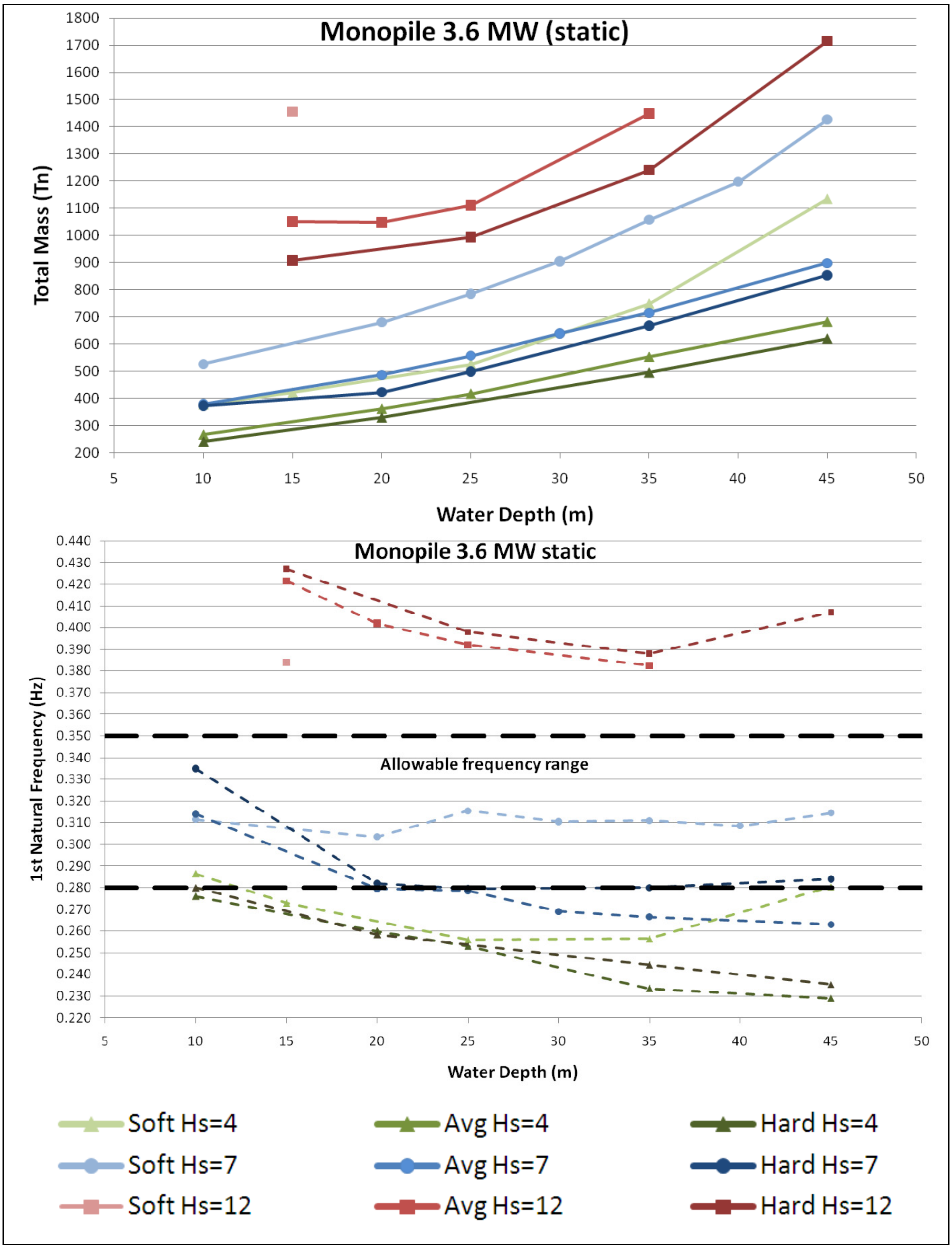


Diagram 4.1 3.6 MW pile and TP mass (only static criterion considered)

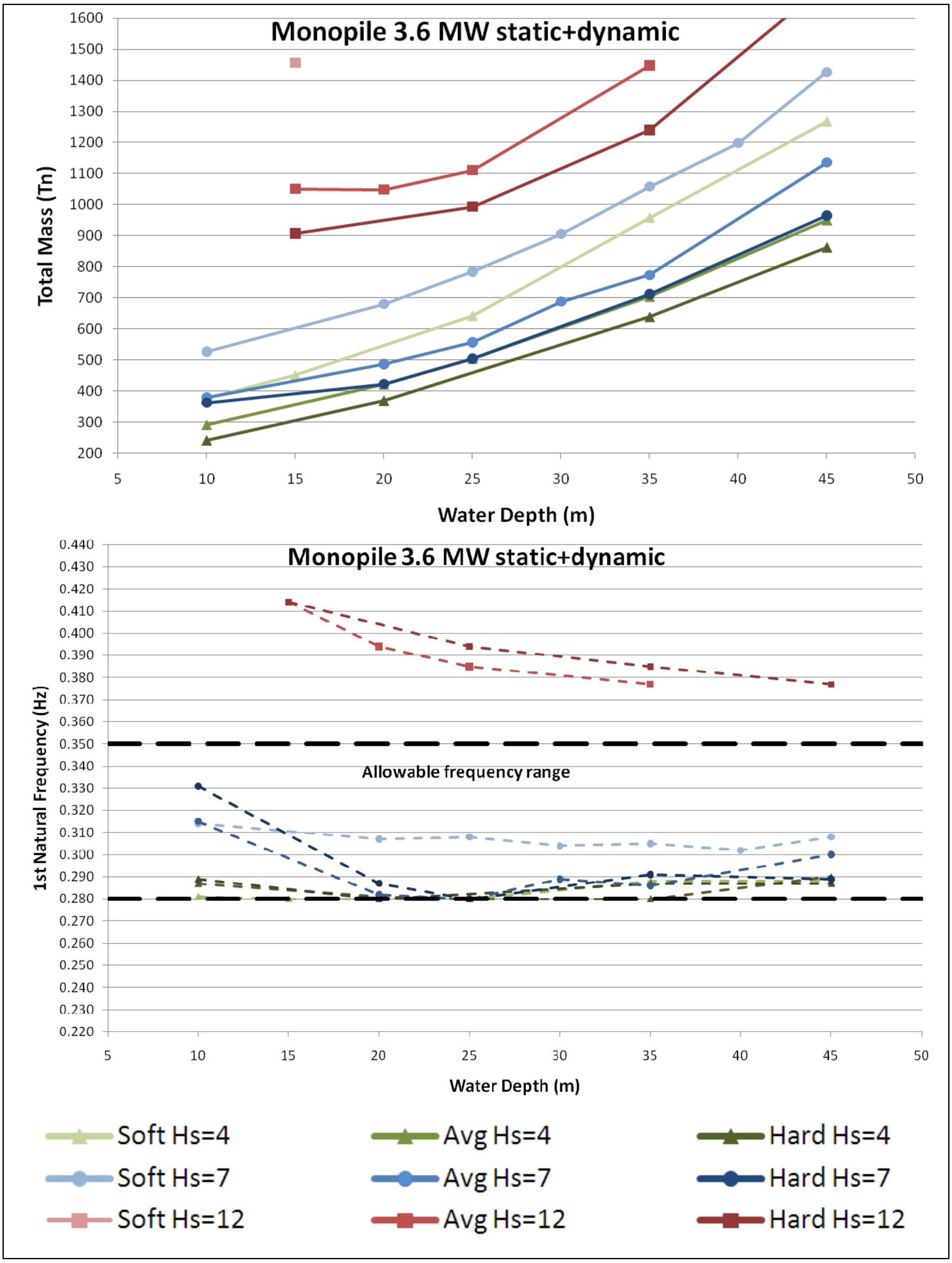


Diagram 4.2. 3.6 MW pile and TP mass (static and dynamic criterion considered)

As it can be seen in the diagrams, there is a boundary at 20-25 m water depth in which the mass slope is increased. This slope is even steeper when the dynamic criterion is to be fulfilled (which mainly affects the design at deeper waters), since the piles are stiffened by increasing the diameter and this, in the same way increases wave loading and thus, necessary pile diameter, thickness and penetration. Overall, the added mass is between 10-30% depending on the water depth and is mainly necessary for the initially softest monopiles (the ones under low wave loading).

The monopile design is very much influenced by the wave height, even more than by the soil type, as the mass difference between average and hard soil is only around 10-15%. However, it must be noted that moving to soft soils does have a big impact in mass, especially at deep waters (from 25 m on) as the design is limited by the pile head maximum tilt angle and the pile toe zero displacement, which are more difficult to achieve.

Wave height determines much of the designing. It is the main load, quickly exceeding permanent and wind loading as the H_s and pile diameter are increased.

The influence of the wave loading on the monopile can be obtained from an extreme loading comparison (global overturning moment and shear) at seabed as shown in Diagram 4.3 for a 5 m diameter pile, which is typical for a 3.6 MW WTG in a 20 m depth location. The results are normalized such that the seabed wind moment = 100% in each case for a clearer relative comparison between wind and wave loads.

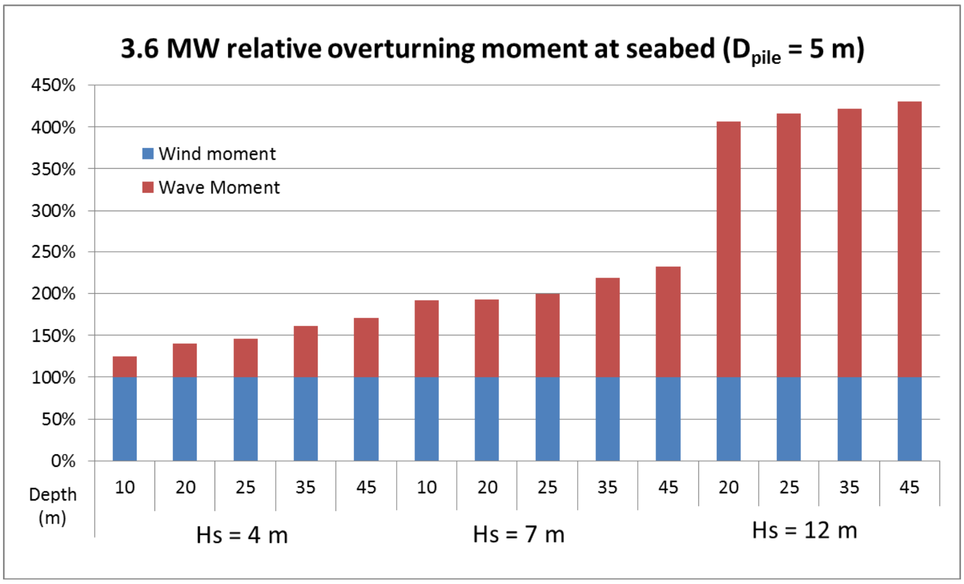


Diagram 4.3. Comparison between wave and wind overturning moment at seabed for different depths and wave heights

It can be concluded that the chosen low, medium and high sea states match correctly with the overturning moment leading load. Thus, for the Hs=4 m, wind is still the main load, for the Hs=7 case it is around a half of it and finally for the Hs=12 m case, wave is undoubtedly the principal load. The water depth has not a big influence in the relative importance between wind and wave loading, and the percentages are similar at different depths of the same wave height case.

So, at deeper sites, where higher wave heights are expected, the wave height influence is even larger due to the needed bigger diameter. Furthermore, if we take into account that deeper locations result in a lower 1st natural frequency that will need a larger diameter to be within the allowable range, it turns to be a critical parameter.

There is a higher risk in getting close to the minimum allowed frequency, that is, near the 1P, rotor turning frequency. In the lower range, wave loading will make a bigger contribution in comparison with the higher frequency range, and this could become a more difficult problem to solve.

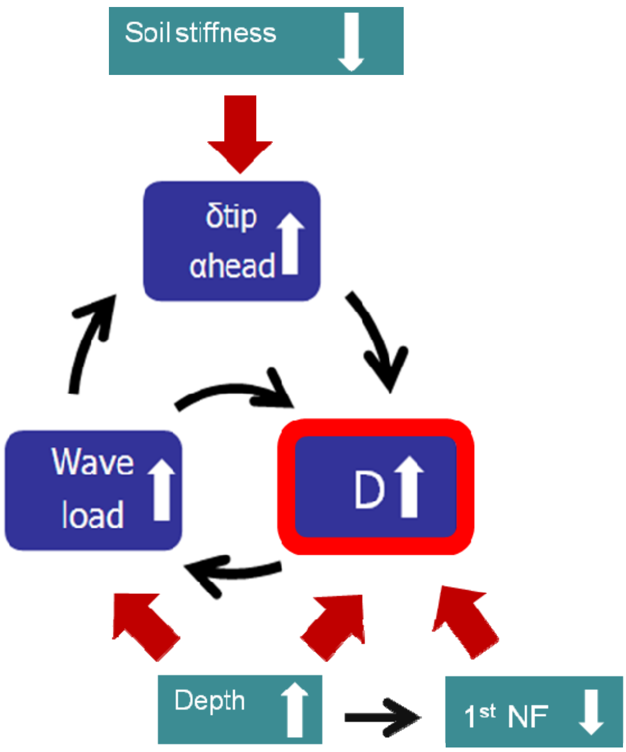
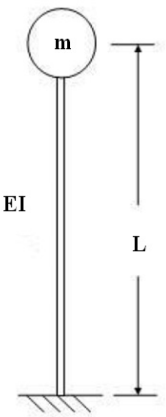


Diagram 4.4 Parameters affecting the circle to break between the wave loading and the pile diameter

All the above, makes it challenging to break the circle between the wave load and the diameter as shown in Diagram 4.4. This is the main limitation encountered for the monopile design: breaking this circle with an economical solution. That is why it was only possible to calculate the H_s=12 m and soft soil configuration at the shallowest water depth. For these cases, reduced diameter above mudline (tapered pile) could be a solution in order to decrease wave loading and reduce mass.

Regarding 1st natural frequency, it follows a logical pattern and it is decreased the deeper the water depth due to the longer length of the structure. This is the leading factor for the frequency and the explanation can be seen in Figure 4.2 where the governing equation of a mass on pole structure is shown. In this equation length is powered to 3 and this is the reason why the deeper the site, the more difficult it becomes to equilibrate the frequency by stiffening the pile (E and I increase).



$$fn = \left(\frac{1}{2\pi}\right)\sqrt{\frac{3\,EI}{mL^3}}$$

Figure 4.2. Natural frequency of a mass pole structure in which the end mass is much greater than the beam mass

Apart from this, the frequency follows similar trends to the monopile mass, as the heavier structure is also stiffer. So the same conclusions apply: bigger influence of the wave height rather than the soil type, except for soft soils, when the pile penetration needs to be very deep.

It is also remarkable that extreme waves lead to designs that are above the allowable range. This prevents 3.6 MW monopiles to be installed in waters with large waves. In this study, the total cost for these cases has also been calculated; but this is an issue that cannot be left aside. Solution for these cases could be higher hub height in order to decrease the natural frequency or another monopile type design like the tapered one, which allows wave loading and weight to be diminished.

Diagram 4.5 shows the pile penetration and diameter range for the studied cases. Smaller pile diameter and penetrations will correspond to the hardest soils and smaller waves, whereas the upper boundary corresponds to the harshest environmental conditions.

Pile diameter at deep sites with harsh conditions is close to the current installation limit (between 6-7 m). On the other hand, pile penetrations are below 40 m and their weights are mostly below 800 Tn. This weight accounts only for the pile, excluding the transition piece weight (which is around a third of the pile) and the secondary steel. This means that overall, current installation technology is capable of managing the installation of 3.6 MW OWTG monopile foundations without much trouble and need of development.

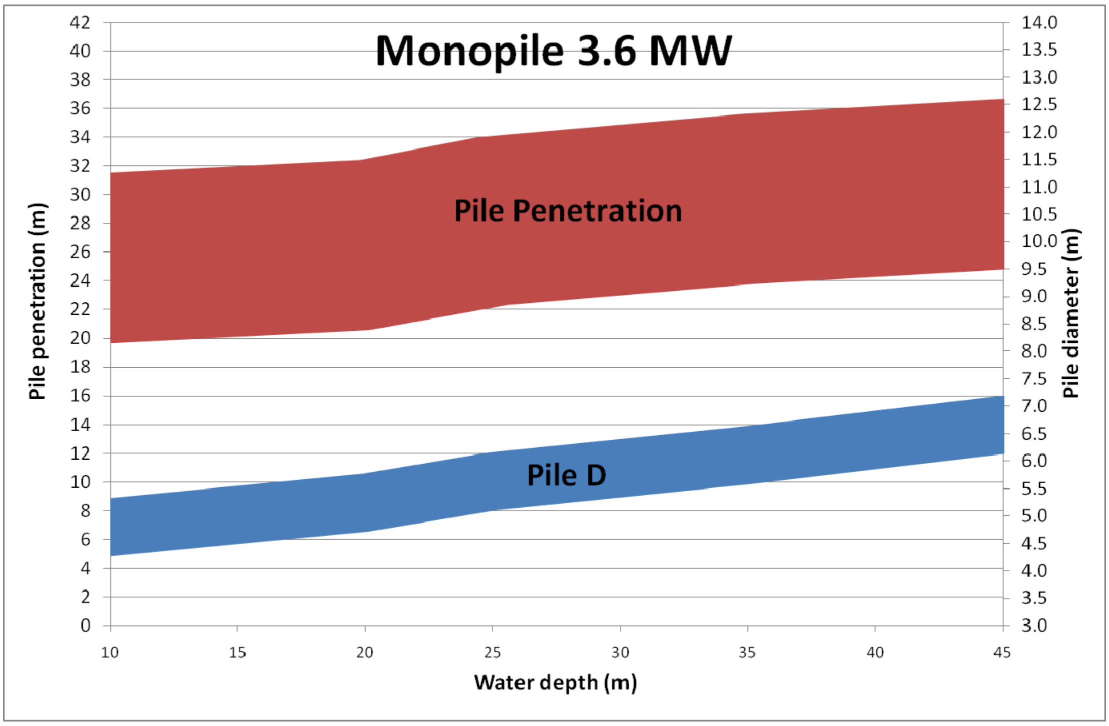


Diagram 4.5 Pile penetration and diameter variation with water depth for the 3.6 MW monopile

3.6 MW Monopile Total Costs

Manufacturing and installation costs are calculated and the total cost per MW trendline is presented in Diagram 4.6. The manufacturing costs are estimated at 2.5 €/Kg for the traditional pile.

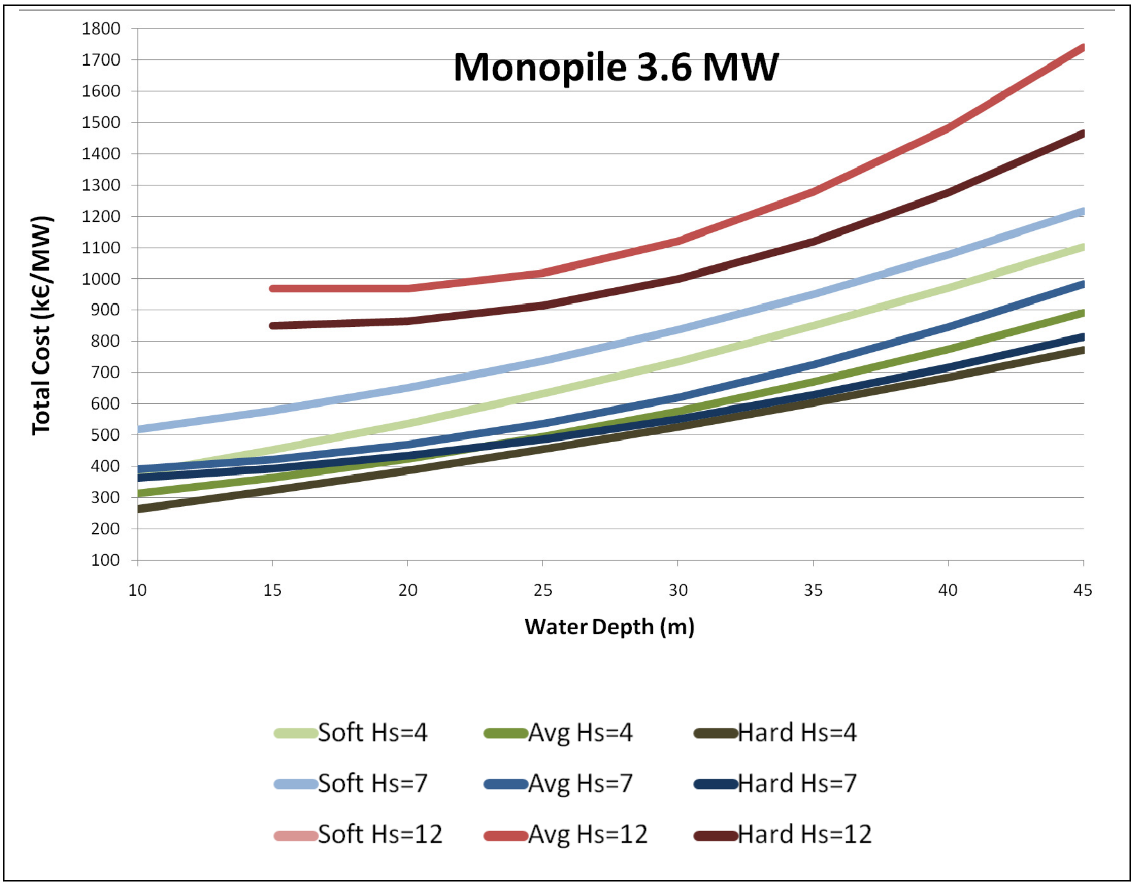


Diagram 4.6 Cost per MW trendline for 3.6 MW OWTG monopile (pile and TP)

Overall, this diagram can be divided in 3 areas:

The first one would include the average and hard soils for the H_s=4 m and H_s=7 m. These curves have a small exponential growth from the 20 m water depth on and their costs are within the same range.

The second area is for the H_s=4 m and H_s=7 m soft soils. Their cost is notably higher than the previous area.

The last area corresponds to the H_s=12 m waves. Extreme waves in soft soils have not been depicted because only one point at 10 m depth was possible to be calculated. This last area has a steep exponential growth from the 20 m water depth on.

All the above means that the costs for a 3.6 MW OWTG monopile in normal environmental conditions are similar (ranging +/- 10%). And only extreme cases make a real difference in the cost, such as soft soils (with an average 35% increase) and large waves (with 60 to more than 100% increase).

Taking this into account, Diagram 4.7shows a diagram in which these 3 areas are depicted.

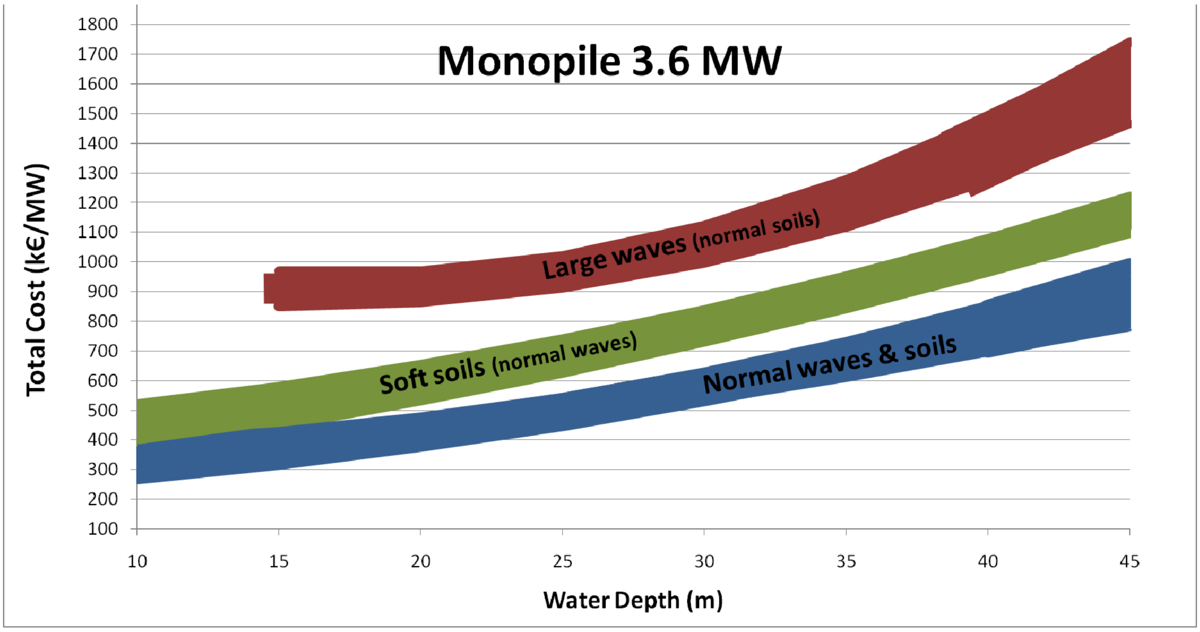


Diagram 4.7. 3 areas in the cost per MW trendline for 3.6 MW OWTG monopile (pile and TP)

4.1.2 OWTG power: 5 MW

<u>*5 MW Monopile Mass*</u>

The difficulties encountered in some cases of the 3.6 MW to break the wave load – pile diameter circle (as shown in Diagram 4.4) makes it necessary to consider a different type of pile in order to achieve a feasible design that fulfils all the static and dynamic criterions for the 5 MW WTG. Hence, a tapered pile type is considered, which reduces wave loading and pile total mass.

In the tapered pile not only the wall thickness of the pile varies, but above the mudline, the diameter also decreases with the purpose of reducing the wave loading. Figure 4.3 is a sketch of a tapered pile.

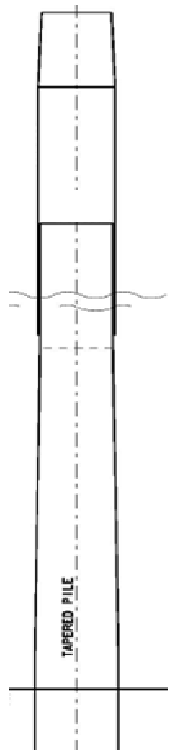


Figure 4.3. Tapered pile design [110]

However, the tapered pile entails several difficulties, especially during its fabrication due to the strict tolerances to be fulfilled. It also implies more complex design of the can weldings in which the stress concentration factors will have to take into account the cylindrical to conical section union.

Diagram 4.8 and Diagram 4.9 present a comparison of the monopile mass (pile and TP) and 1st natural frequency results for different input values of the wave height, soil type and water depth when only the static criterion is taken into account and when both the static and the dynamic criterion are considered in the calculations.

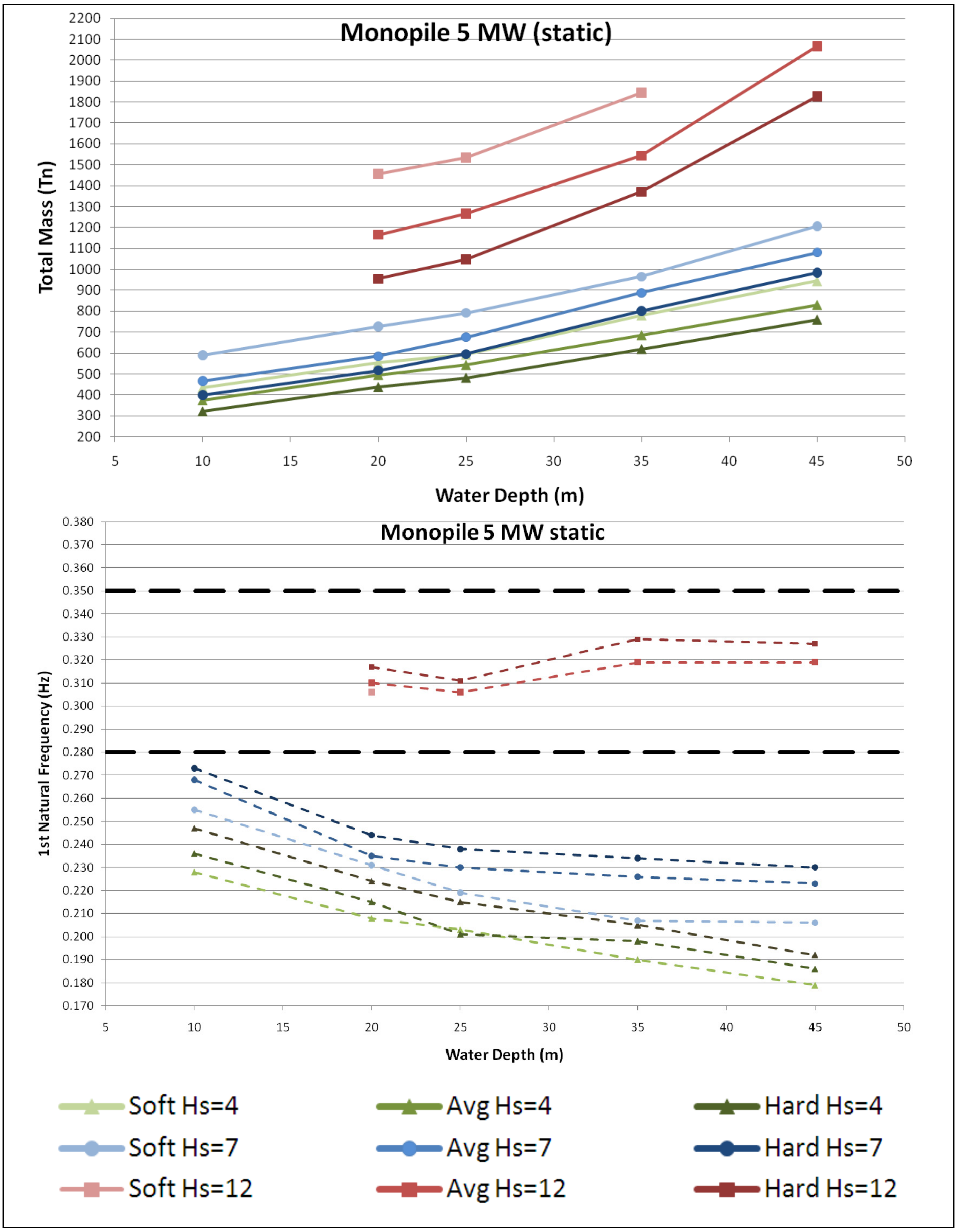


Diagram 4.8. 5 MW pile and TP mass (only static criterion considered)

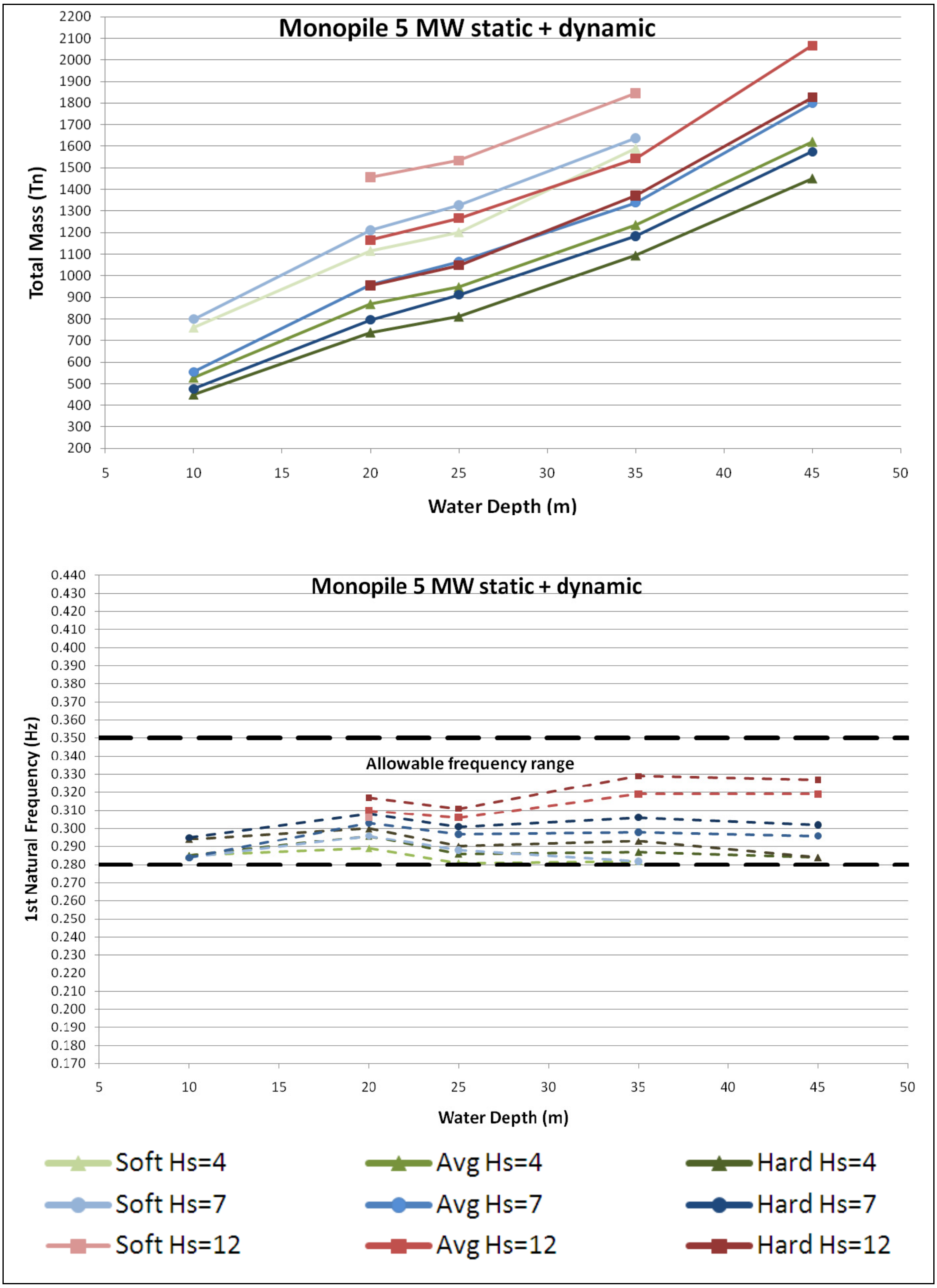


Diagram 4.9. 5 MW pile and TP mass (static and dynamic criterion considered)

In the static design, the tapered monopile made the 20-25m boundary that appeared in the 3.6 MW case less abrupt. Notwithstanding, when the dynamic criterion is fulfilled, this boundary also seems to appear, but at shallower depths. The added mass in this case is much higher and affects more cases, as none of the low and medium wave height cases satisfies the allowable frequency range.

The added mass is above 50% for the H_s= 7 m cases, above 70% for the H_s=4 m cases and up to 100% for the soft soils. This means that steel utilization ratio decreases drastically and the mass vs depth slope becomes very steep.

The tapered design also made the soft soil cases less influenced by depth than in the 3.6 MW OWTG. In this case, the soft soil follows the same line pattern as the average and hard soil. In spite of this, it continues to have a big impact on the monopile mass (30-40% increase from the average soil compared with the average and hard soils that only have a 10-15% difference).

Wave height is still the leading design factor, but the tapered design permits the monopile to be calculated even at sites with extreme significant waves. In order to understand the influence of the wave loading on the monopile and how the tapered design can decrease these loadings, global overturning moments are compared at seabed for the wind and the waves. As it has been demonstrated in Diagram 4.3 for the 3.6 MW OWTG, the relative weight of wind and wave does not change with depth. In this case, the comparison is made for a 6 m diameter and an 8 m diameter monopile for different wave heights in a 20 m deep site.

Results in Diagram 4.10 show that the pile diameter above mudline will have a significant impact in the wave loading and that taking into account the typical 5MW diameters, the relative weight of the waves become even more important than with the 3.6 MW monopile.

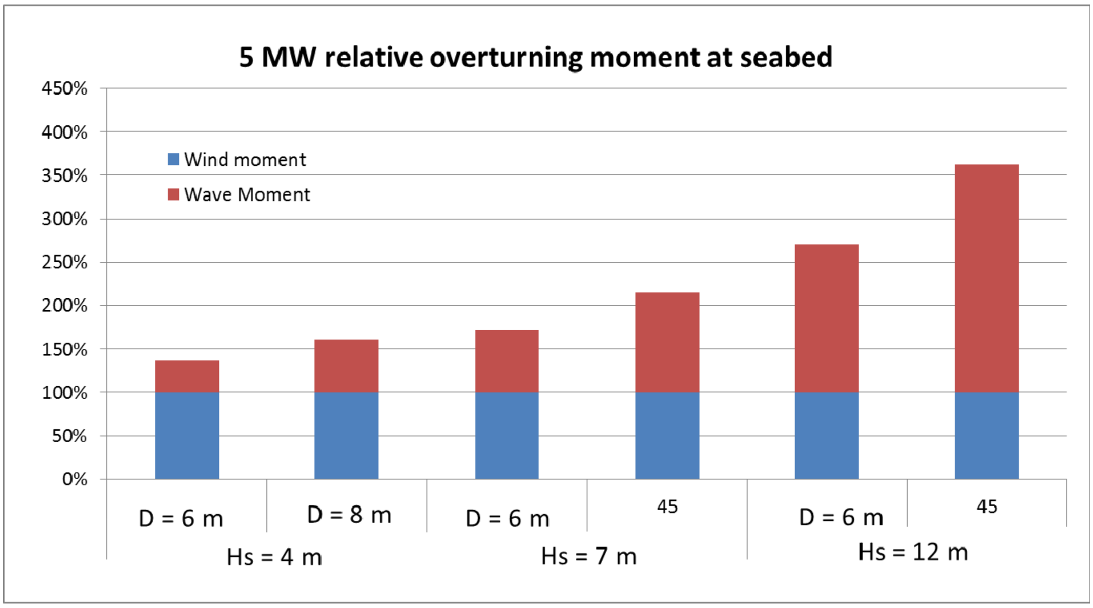


Diagram 4.10. Comparison between wave and wind moment at seabed for different pile diameters and wave heights

1st natural frequency decreases rapidly with depth except with high wave loading due to excessive stiffening of the structure. This is due to the reasons explained in Figure 4.2. Accordingly, the wave height has a bigger impact on the frequency than soil type just as with the 3.6 MW OWTG.

Besides, the heavier THM of the 5 MW OWTG made the 1st natural frequency decrease below the allowable range for all the cases except the H_s=12 m. The resulting structures with the necessary added mass to increase the 1st natural frequency within range are mostly above 800 Tn and up to 1500 Tn, which could lead to installation vessels limitations.

Diagram 4.11 shows the pile penetration and diameter range for the studied cases. Smaller pile diameter and penetrations will correspond to the hardest soils and smaller waves, whereas the upper boundary corresponds to the harshest environmental conditions. The presented diameters correspond to the biggest ones of the tapered pile, that is, below mudline.

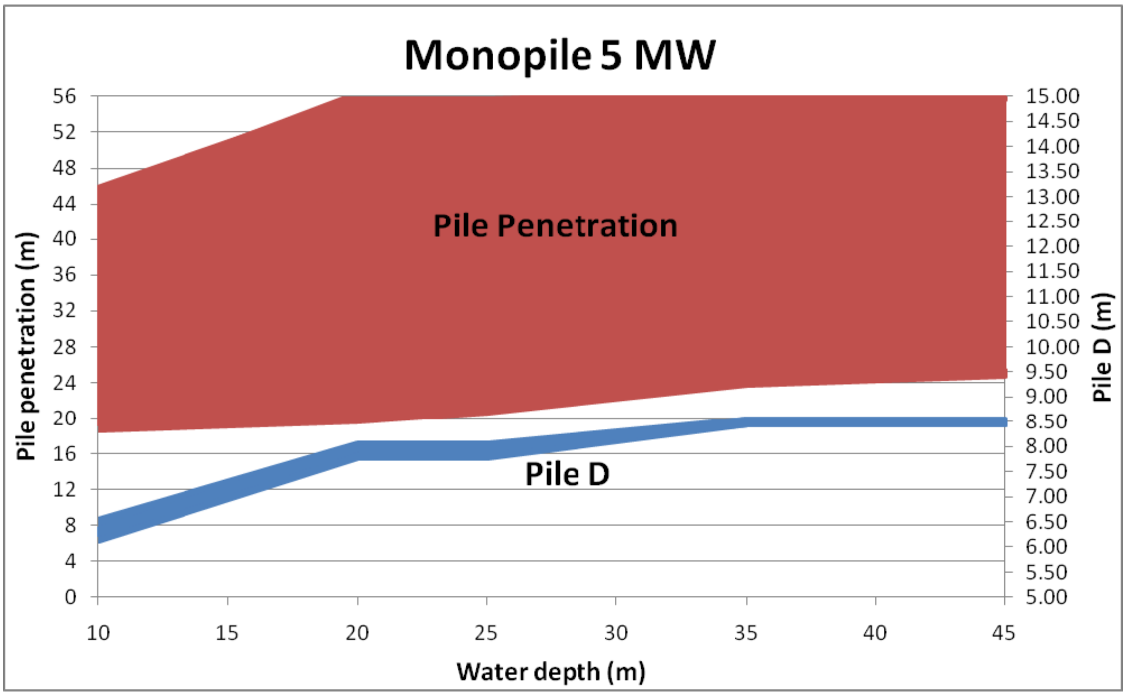


Diagram 4.11. Pile penetration and diameter variation with water depth for 5 MW monopile

It is remarkable that the pile diameter range is considerably thinner than in the 3.6 MW case. This is a consequence of the dynamic design. As almost all the cases were far below the allowable frequency, a similar diameter was necessary for all of them to be just above the lower allowable limit. Besides, it was tried to increase the pile diameter the minimum possible, in order to avoid monopile designs too far from the current technology. For all these reasons, the pile penetrations range is wider.

In any case, the pile diameter is beyond current installation technology and only at very shallow waters (less than 15 m deep) they are below 7 m. Pile penetration in the most unfavourable cases increases very fast and goes far beyond 50 m depth, which is a big challenge for the current hammers in the industry. Moreover, in case drilling were the chosen installation method, the spoil soil volume would be too large with such diameters and penetrations, as it was explained in Diagram 3.7.

These limitations along with the pile manipulation limitations due to the large weights of the piles mean that 5 MW OWTG monopiles have got many installation difficulties with the current technology. Furthermore, fabrication of such large diameters (up to 8.5 m) and thickness (fulfilling D/th > 100) piles is far from the actual manufacturing industry capabilities. In spite of this, total costs are being calculated as future development of the industry could ease some the encountered handicaps.

5 MW Monopile Total Costs

Manufacturing costs for the 5 MW WTG monopile are estimated at 2.8 €/Kg. This cost is set a little higher than for the 3.6 MW monopile because the tapered type monopile has a higher manufacturing cost than the traditional type due to the bending and welding of cone type cans in the monopile and the challenge involved in fabricating such huge pile diameters and thickness.

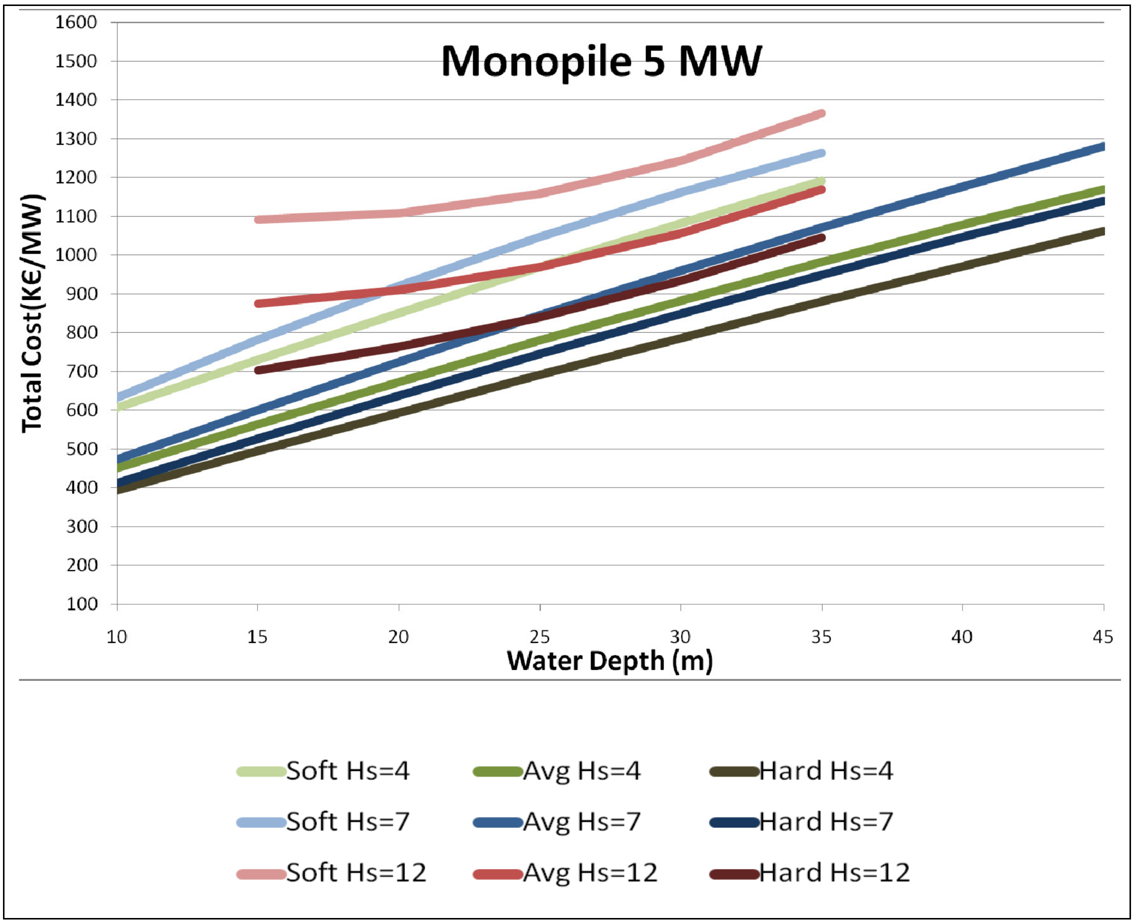


Diagram 4.12. Cost per MW trendline for 5 MW OWTG monopile (pile and TP)

The cost slope very slightly decreases with depth (in the Hs=12 m cases this tendency is less visible, because in the beginning the slope increases, but at deeper depths the slope decreases again). This effect is caused by the scour protection cost that, as shown in Diagram 3.10 decreases with depth. In the case of the 5 MW monopile, the scour protection absolute cost is higher when compared with the 3.6 MW monopiles due to the installed larger pile diameters. So when scour protection cost decreases in the 5 MW cases, it is appreciated in the total cost.

It is also remarkable that if the diagram is divided in the same 3 areas as in the 3.6 MW, large wave cases are mixed with the soft soils and even the normal waves & soil cases (see Diagram 4.13). This is because the tapered type monopile has deeply affected the cost curve especially for the H_s=12 m cases, which are even more economical than in the 3.6 MW cases.

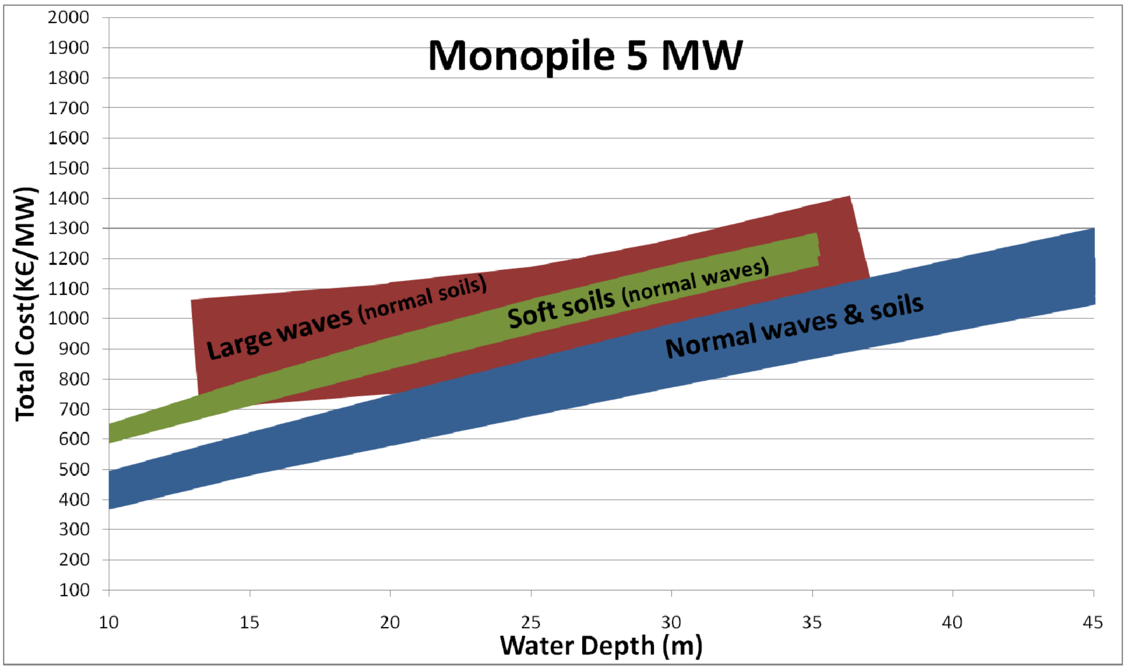


Diagram 4.13 Cost per MW trendline for 5 MW WTG monopile (pile and TP)

This time, the 3 soil types in the large wave height case, are nearer from their corresponding low and medium wave heights. So, in this case, it is better to divide the diagram in 3 areas corresponding to the studied 3 soil types: soft, average and hard as shown in Diagram 4.14

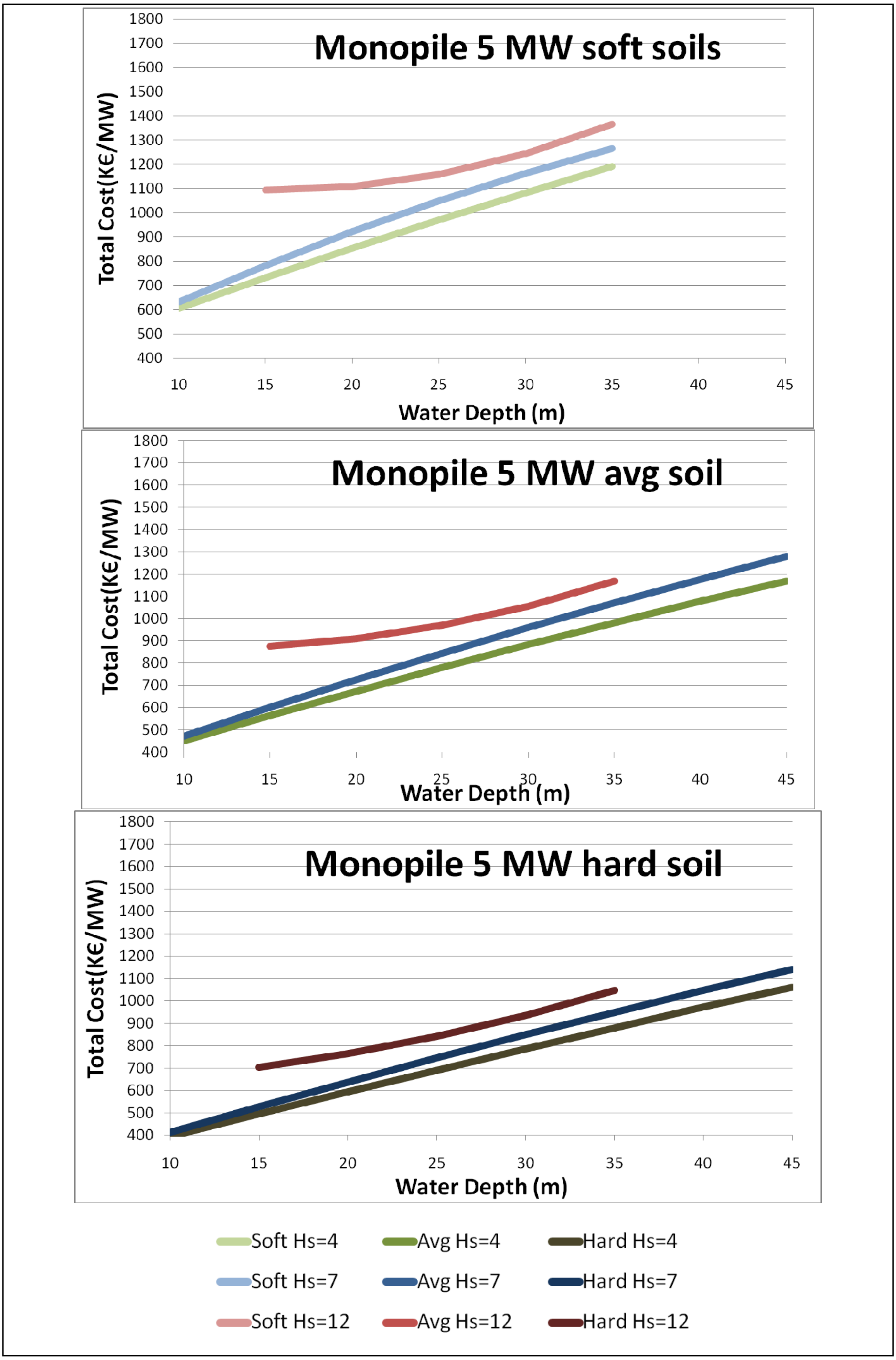


Diagram 4.14 Cost per MW trendline for 5 MW WTG monopile (pile and TP)

Differences between hard and average soils is just around 10%, whereas soft soils makes a real difference and moving from average to soft soil types means a 20-25% increase.

Regarding wave heights, for the same soil type there is less than 10% increase when moving to larger waves except at shallow waters for the H_s=12 m case. The reason for this, is the extra material that has to be added the deeper the location in order to fulfil the dynamic criterion. This extra material rapidly reduces the cost difference between the low-medium wave heights and the initially stiffer Hs=12 m cases.

So it can be concluded that for the 5MW OWTG monopile, the soil type has a bigger impact on the final cost at deep sites (deeper than 25 m) as long as the tapered type design is used in order to counteract the wave loading influence on the monopile weight. In shallow waters (below 20 m depth) all the cases have similar costs excepting the extreme cases (large waves and soft soils).

4.1.3 OWTG power: 7 MW

Taking into account the fabrication and installation limitations that the 5 MW OWTG monopile presented in the carried analysis, the monopile is not seen as a feasible support structure for a 7 MW WTG, at least in waters deeper than 10 m and unless further development in the industry occurs. As the water depths in which most of the offshore wind farms to be constructed in the coming years are deeper than 20 m, this case is dismissed as a viable possibility for the monopile.

4.1.4 Conclusions

Monopile type support structure cost analysis was carried out in order to understand its main driving factors and obtain cost specific curves that can provide enough information for an initial assessment of this structure’s suitability in a certain offshore location.

The analysed costs include manufacturing, installation and scour protection costs. Their average weight in the final cost varies with water depth as can be seen in

Diagram 4.15. Deeper waters make manufacturing cost percentage increase due to heavier monopile designs. Consequently, scour protection and installation costs relative cost decrease.

The 27% for installation and scour protection costs obtained for current constructing sites (20 m water depth) match correctly with what it is stated at [6], in which a fourth of the total support structure cost was estimated for them.

As it has already been explained, the monopile manufacturing is already a rather automated process in which steel and commodities account for around 45-50% of its costs. However, installation (including scour protection) can mean up to 30% of its total costs. This means that when looking into the technology development to achieve a cost decrease, installation process and scour protection should be prioritised.

Furthermore, depending on the vessels availability, these costs could be significantly higher as the hiring costs could be doubled or even tripled in peak seasons when there is not enough offer in the market to absorb the existing demand.

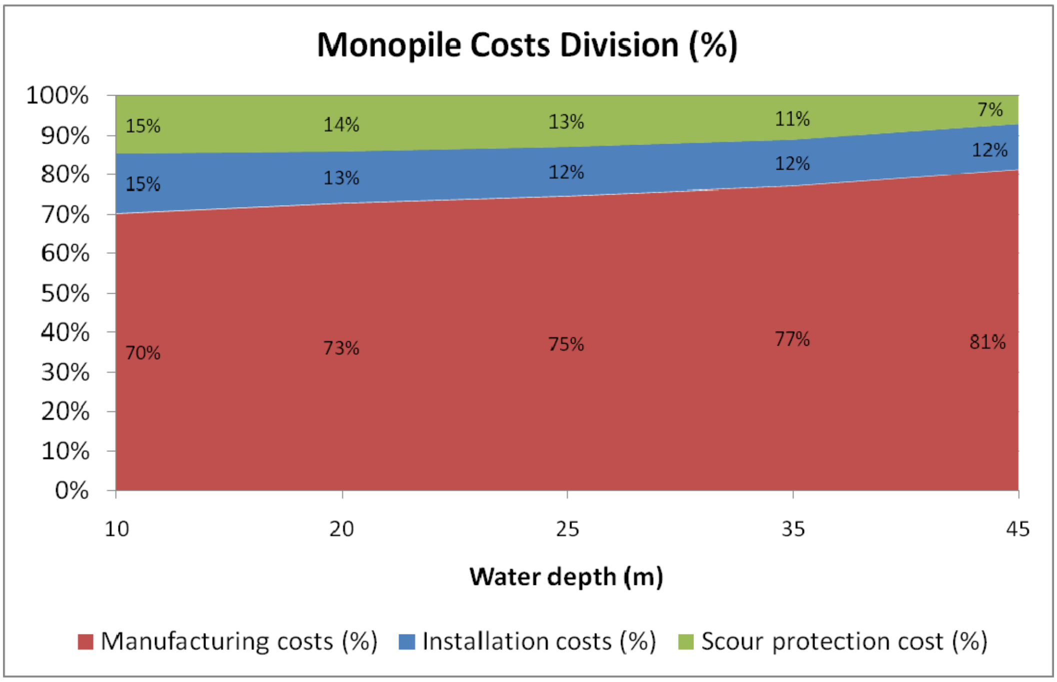


Diagram 4.15. Monopile costs division in varying water depth

Specific costs results for the different turbine powers are depicted in Diagram 4.16.

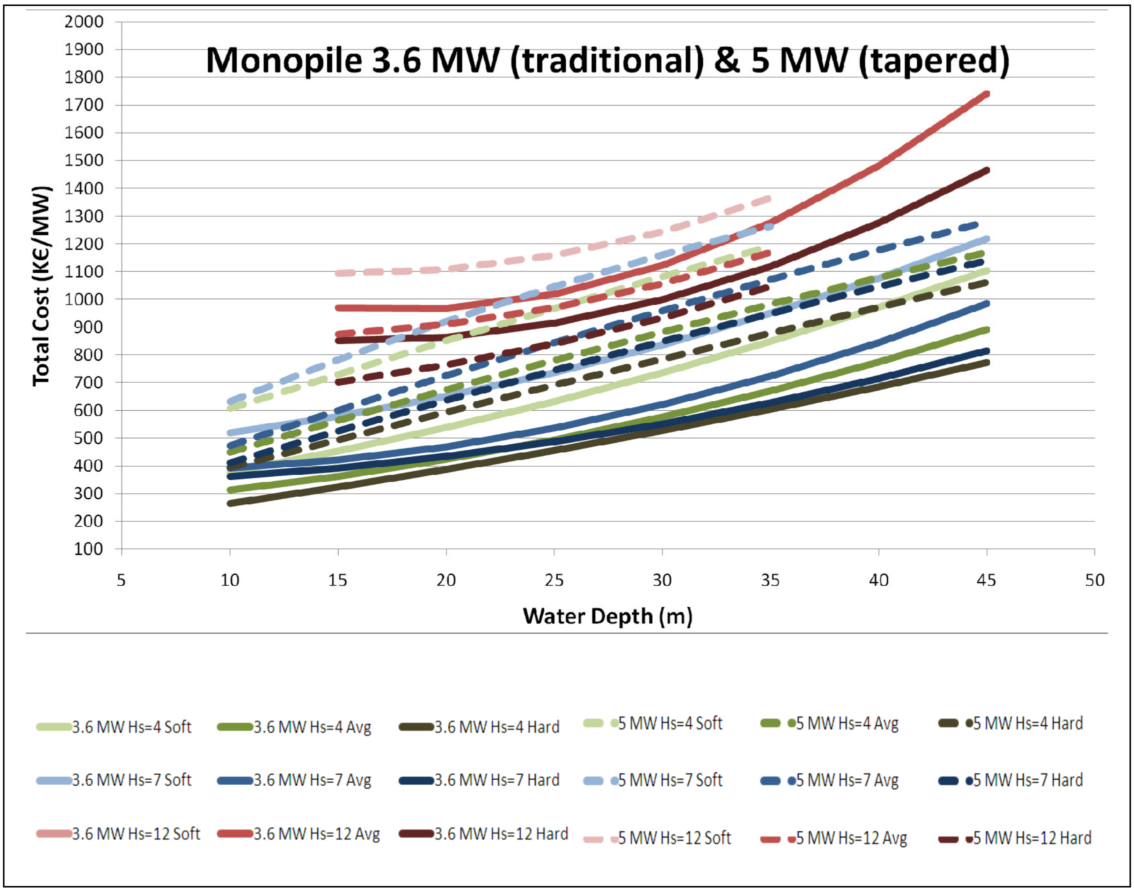


Diagram 4.16 3.6 MW and 5 MW OWTG monopile (pile and TP) costs comparison in several soil and wave heights conditions

The main conclusions that can be extracted from this analysis are summarised hereafter:

- Cost curves show a quadratic relation with depth, steeper for larger waves.
- Monopiles are significantly affected by wave loads and soil properties, making it difficult to break the wave load – pile D circle in the worst case scenarios.
- Extreme cases (H_s=12 m and soft soils) tendency stands out from the rest of the cases, having a bigger impact in cost than the average-hard soil and H_s=4-7 m cases which have closer costs (10% difference) for the same power.

- Higher OWTG power increases the slope of the curves. Around 180 k€/10m per MW for the 3.6 MW and 220 k€/10m per MW for the 5 MW (except extreme cases).

- 5 MW monopiles are 40 to 50% more expensive, except at large wave heights, in which the tapered design permits to decrease wave loading and save weight, thus reducing total costs even below the 3.6 MW monopile. So, the same pile type were compared, the higher the power, the specific cost increases.

- Tapered monopile design makes a great contribution to reduce costs when wave loads are important, that is, when the wave heights are high or the pile diameters large (> 6 m).

- 1st natural frequency allowable range is a key factor for the costs because mass increases rapidly when natural frequency governs the design. This is around 25 m water depth for the 3.6 MW and 15 m depth for the 5 MW.

- Current manufacturing and installation limitations prevent the use of the monopile for 5 MW OWTG, except at shallow waters (below 15 m). 7 MW OWTG are not even considered.

It has been demonstrated that analysis of monopile costs is not an easy to assess task. Average cost values given from the experienced based analysis do not reflect the real complexity hidden behind all the variables involved in a certain location. On the contrary, multivariable diagrams are necessary and detailed information about the environmental conditions of the OWF.

Overall, natural frequency limitations are an important issue to be tackled with the monopile, especially if the structure is in the lower allowable range, where due to the wave loading interaction (especially below 4 s periods), the engineer has little margin to modify the design in an economical way. In the case of the higher limit, there are several solutions that can be taken like to reduce the natural frequency of the structure like increasing the weight in the nacelle or the hub height of the OWTG.

The monopile is seen suitable for up to 3.6 MW OWTG. Their maximum economically viable water depth limit will be mainly influenced by the relative costs calculated for other support structures as technologically they are feasible up to 40-45 m depth.

On the contrary, 5 MW OWTG would require further manufacturing and installation industry development if their installation is to be considered above 15 m water depth. Such installations could be undertaken depending on the total savings that moving to a larger OWTG could suppose for the utilities involved in the project. Even though the monopile support structure specific cost increases with the OWTG power, the total specific cost of the project should be decreasing. In spite of all, it seems difficult for the 5 MW monopile to compete against other support structures.

The 7 MW OWTG is not considered suitable taking into account the future OWF sites that will be located at deeper waters.

4.2 Jacket Results

4.2.1 OWTG power: 3.6 MW

Jacket support structure total weight (4 piles, lattice, transition piece and secondary steel) are presented in Diagram 4.17. It is remarkable that weight increases linearly with water depth, and so decreases first natural frequency. A small soil influence can be perceived, especially in the f0 results, where almost the same values are given for different soil types. In the case of the weight, the effect of the soil grows with the significant wave height, but it is still modest. Hence, when H_s=12 m, the difference is around a 10%.

Compared to the monopile, wave height shows a smaller impact in the results, which is logical due to the transparent nature of the jacket structure. Differences between wave heights are diminished and the slopes of the curves are smaller too. Moving from H_s=4 m cases to H_s=7 m means an average 30% weight increase and from H_s=7 m cases to H_s=12 m around 70% increase, which is substantially less than with the monopile.

This can be appreciated in Diagram 4.18, where the wind and wave generated moments at mudline are compared and wind appears to be the main load, except in the H_s=12 m case. Even in this case, the wave loading is around double of the wind moment, compared to 4 times more that resulted in the monopile case (see Diagram 4.3). In the case of shear force, logically wave loading is more important than wind (see Diagram 4.19), but its effect in the structure design is much smaller.

Regarding the first natural frequency, the wave height determines if the structure is inside the allowable frequency range. This is because the interface height between the transition piece and the tower depends on the wave height, and in order to maintain the total hub height constant, the tower length diminishes with the wave height.

For this reason the cases with the shorter tower length (when H_s=12 m) are too stiff. On the contrary, the longest tower cases (when H_s=4 m) are too soft at deep water depths. In this case, no mass is added in the substructure in order to put these soft structures inside the allowable frequency. The reason is that the influence of adding extra mass in the substructure by increasing diameter and thickness of the legs and braces is very little in comparison with the effect of changing the tower dimensions. So in reality, the natural frequency should be accommodated by lengthening or shortening the hub height or changing the tower dimensions, rather than costly modifications of the jacket substructure.

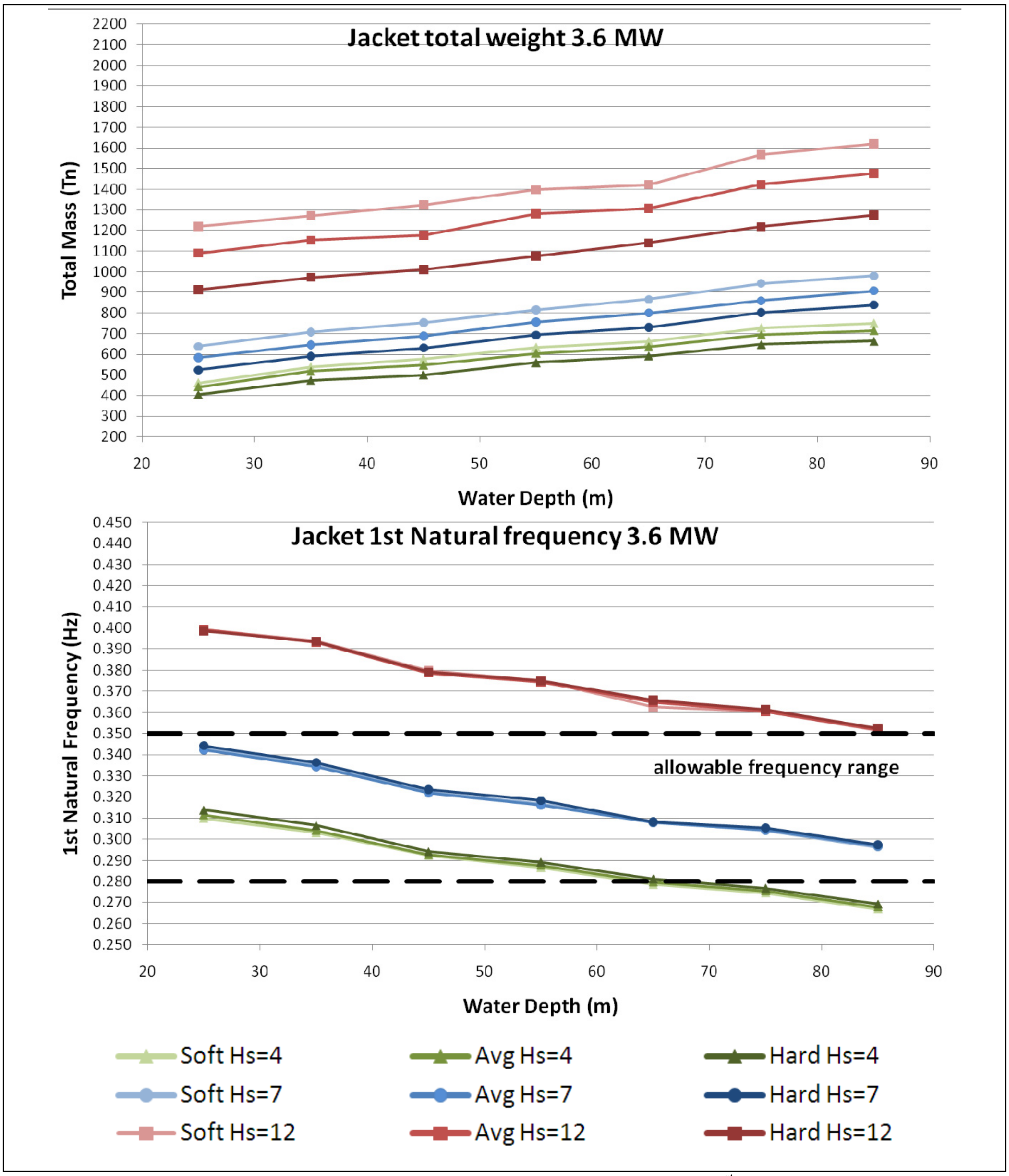


Diagram 4.17 3.6 MW jacket support structure total weight and 1st natural frequency

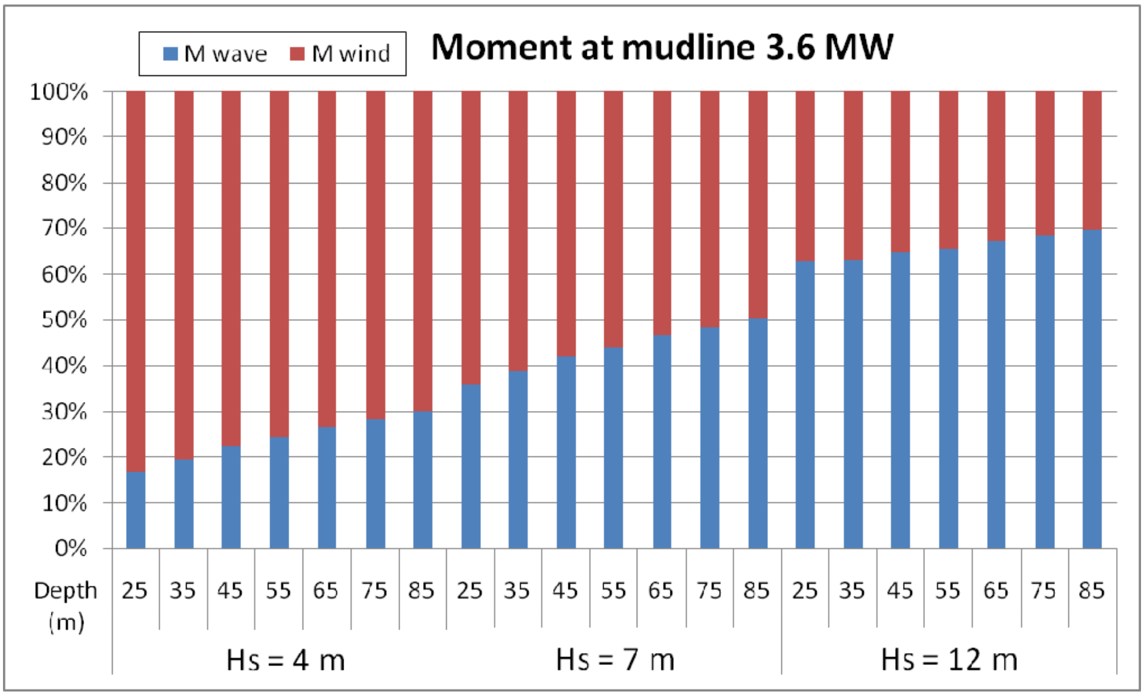


Diagram 4.18 Wind and wave generated moment comparison at mudline for the 3.6 MW jacket case

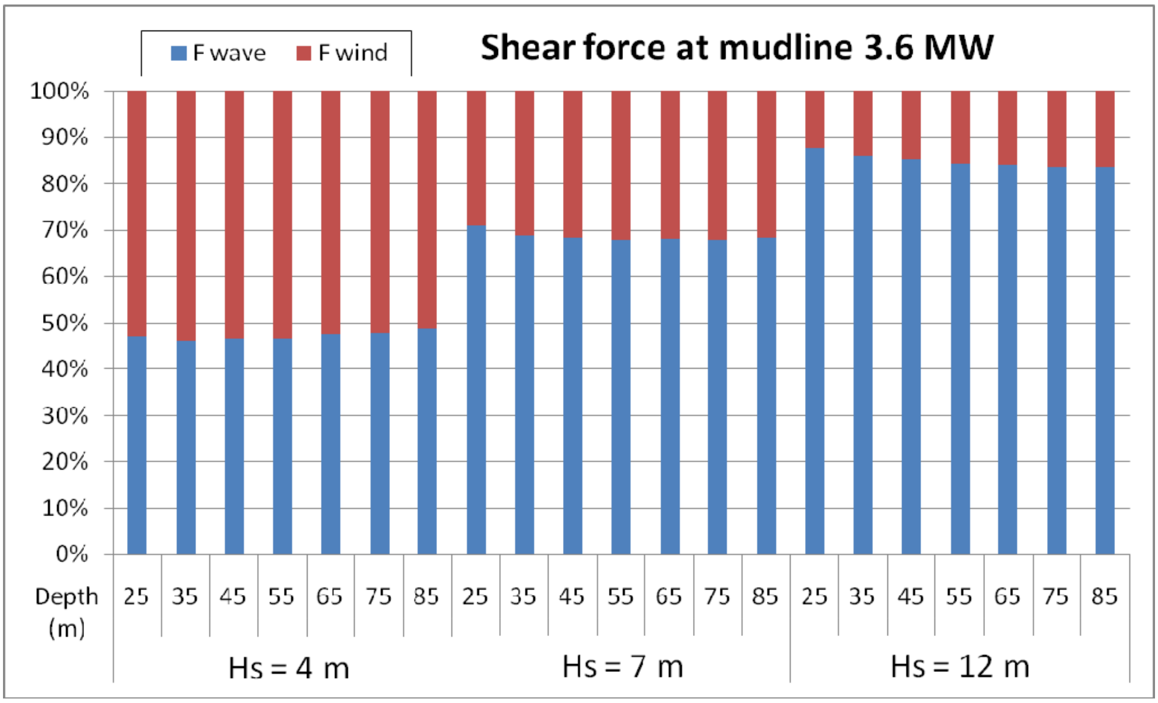


Diagram 4.19 Wind and wave generated shear force comparison at mudline for the 3.6 MW jacket case

In

Diagram 4.20, the total pile weights are depicted almost horizontal. The jacket substructure withstands the loads by a "push and pull" system that transfers the loads to the soil axially. This axial load hardly varies with the water depth and as a consequence the minimum necessary pile weight maintains constant. Pile diameters are within 1.2 to 2 m and penetrations between 22 and 61 m depending on the soil and wave conditions.

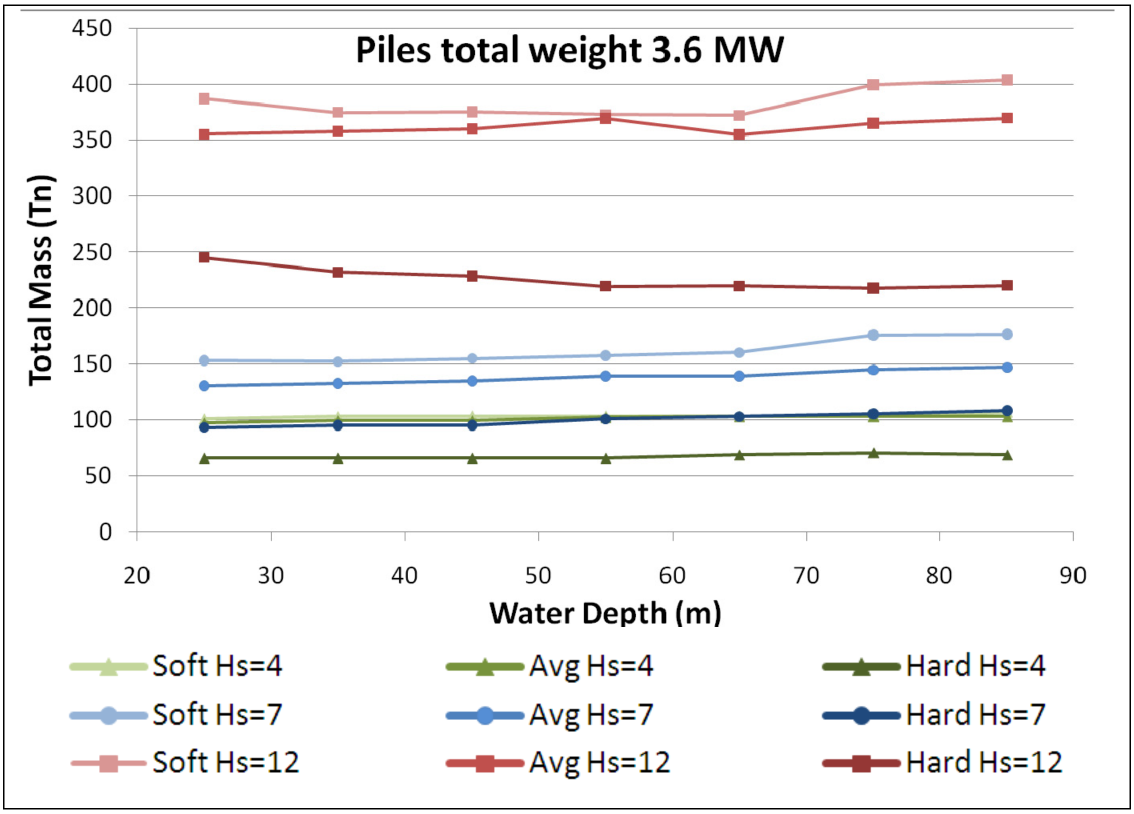


Diagram 4.20 Piles total weight for the 3.6 MW jacket case

Finally, total specific cost trendlines are presented in Diagram 4.21. This cost includes manufacturing and installation for the 4 piles, lattice, transition piece and secondary steel of the support structure.

A linear relation between the cost and the water depth is depicted. Soil type does not have any important effect in the total cost, especially for smaller significant waves.

Actually, installation from one soil type to another involves a 4% difference for H_s=4 m cases, 7% for H_s=7 m cases and 10% for H_s=12 m cases.

So the diagram can be divided in 3 areas, one for each sea state case. The highest the significant wave height, then the slope of the curve also increases. In this case, changing installation from a H_s=4 m sea state to a H_s=7 m, means around 25% increase in the costs, while from a H_s=7 m to a H_s=12 m location would mean around 60% cost more.

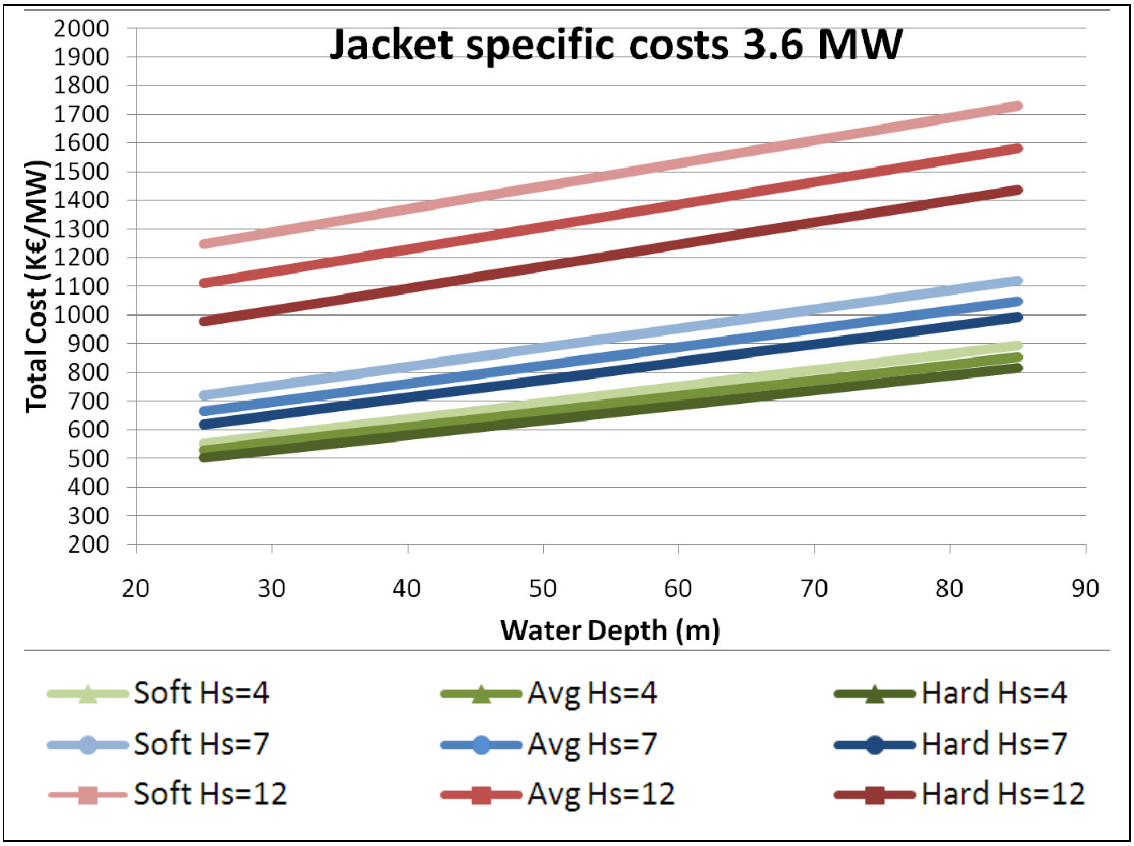


Diagram 4.21 Cost per MW trendline for 3.6 MW OWTG jacket support structure

4.2.2 OWTG power: 5 MW

Jacket support structure total weights are presented in Diagram 4.22 for the 5 MW turbine. A linear relation can be seen in this case too, similar to Diagram 4.17, but in this case, weights have increased 20% in average. However, the power has been raised almost 40%, which is a good sign for decreasing total costs per MW.

Obviously due to the heavier THM, first natural frequency has decreased, an average 10%, which means that most of the Hs=4 m are below the allowable frequency and some of the medium sea state cases at deep waters.

The reason for this was explained in the 3.6 MW results, that is, the hub height is being maintained constant for all the wave heights, which implies that the smaller Hs have longer a tower, which is softer than the jacket, and consequently the natural frequency decreases.

Move these cases inside the allowable frequency range by only modifying the jacket design would not be a sensible approach. In fact, calculations carried out, showed that an average 25% weight increase would be needed, with up to 60% increment for the worst cases. Hence, the best approach to increase natural frequency would be to reduce the hub height.

Moving from Hs=4 m sea state to Hs=7 m means an average 26% weight increment, whereas from Hs=7 m to Hs=12 m is around 58%, which is slightly less than with the 3.6 MW turbine. Similarly, Diagram 4.23 and Diagram 4.24 show that wave loading impact has diminished in comparison with the wind loading, especially regarding the moment at mudline, which is logical for the bigger turbine.

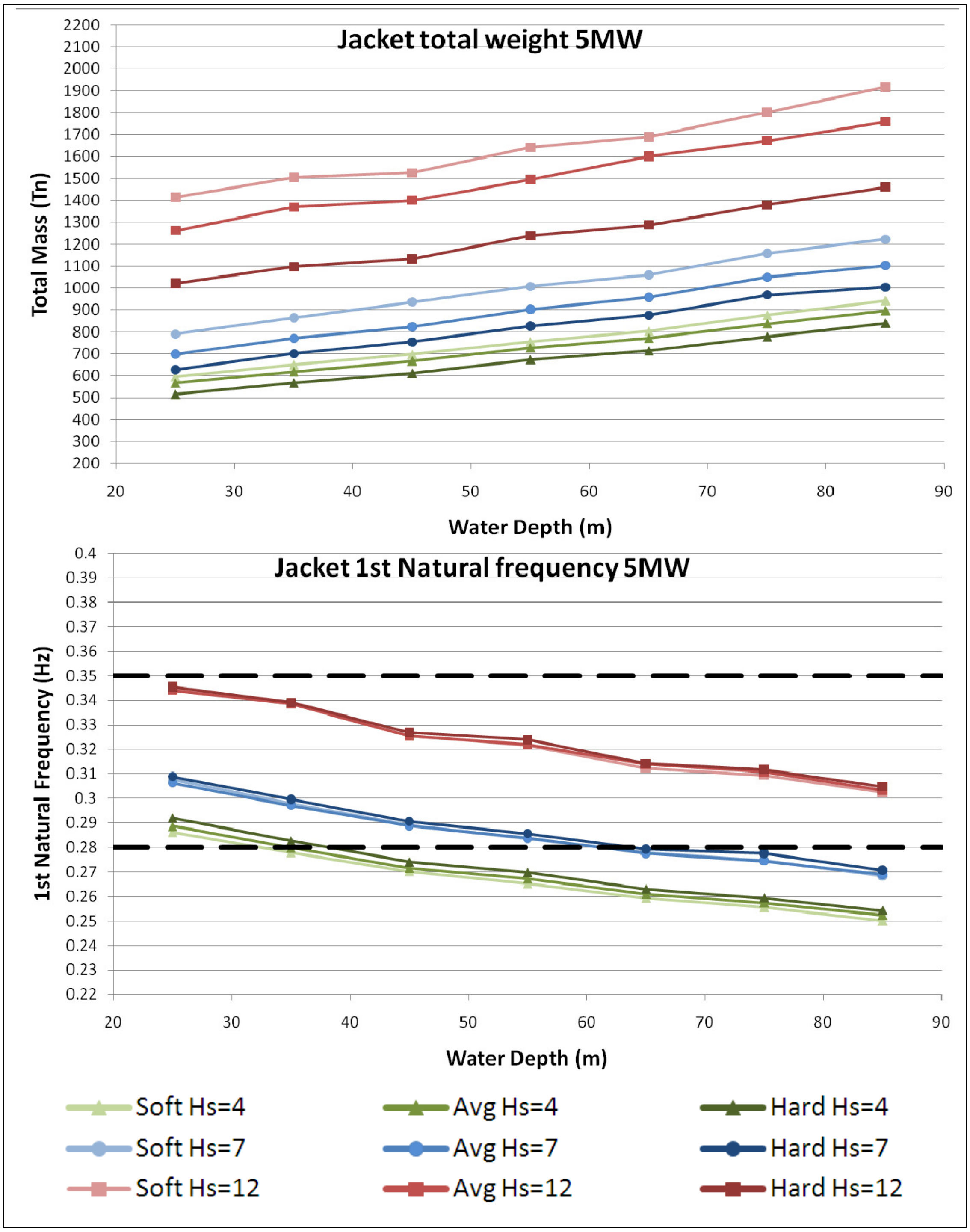


Diagram 4.22 5 MW jacket support structure total weight and 1^{st} natural frequency

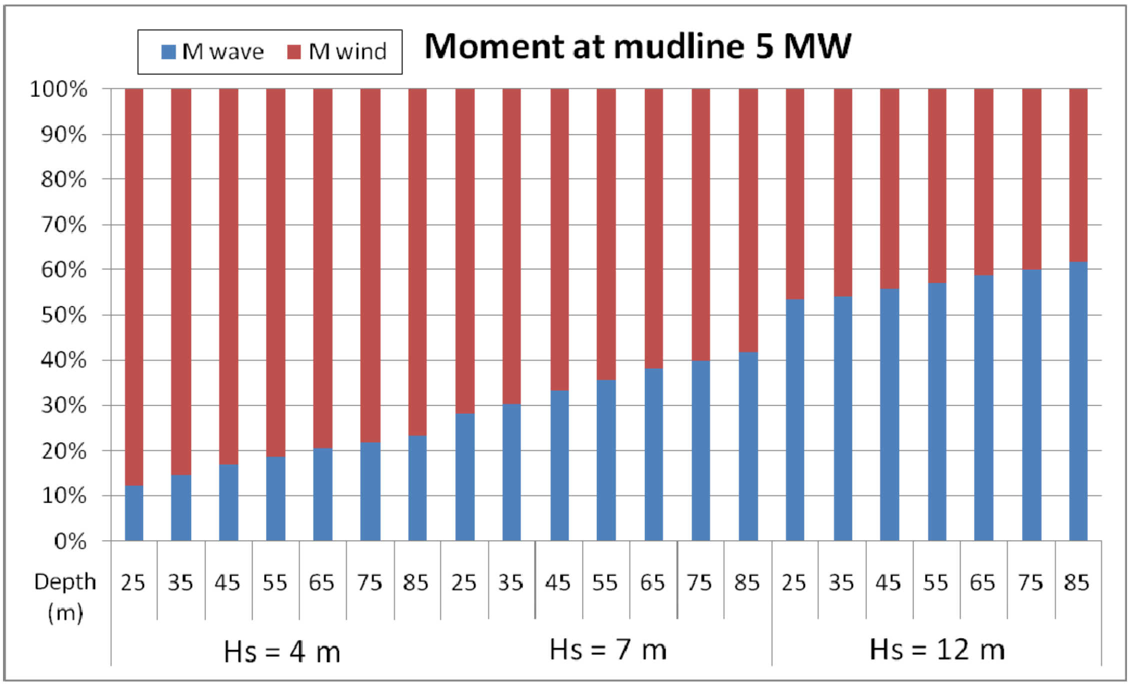


Diagram 4.23 Wind and wave generated moment comparison at mudline for the 5 MW jacket case

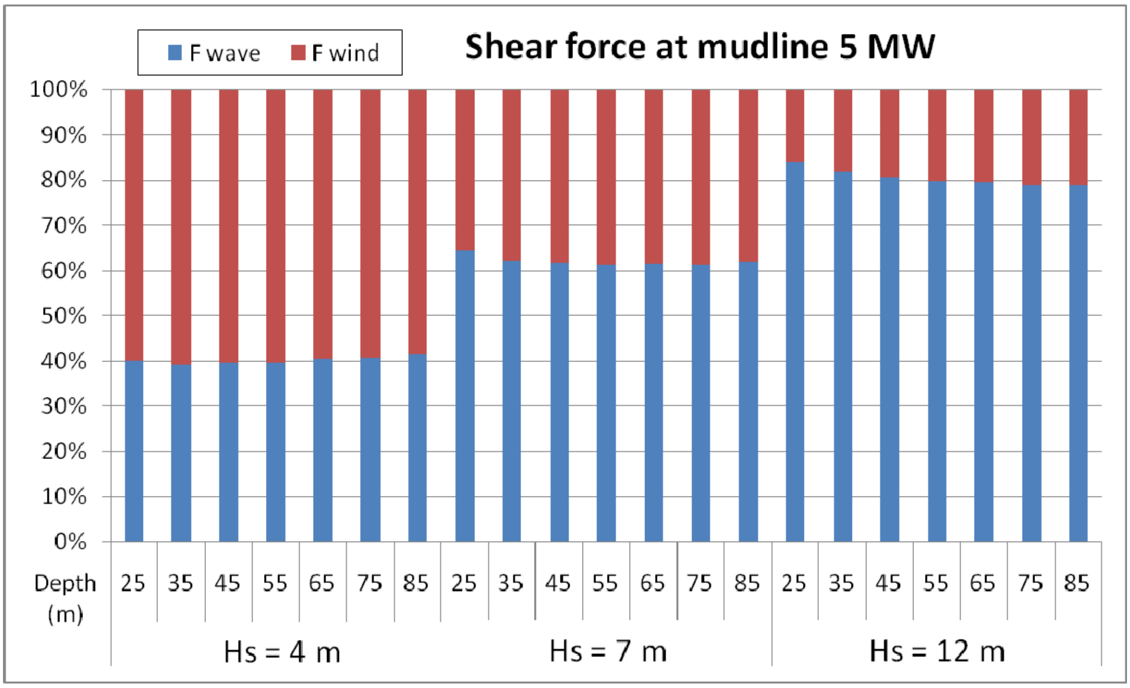


Diagram 4.24 Wind and wave generated shear force comparison at mudline for the 5 MW jacket

Once again it is demonstrated in Diagram 4.25 that pile weights maintain constant with water depth. For each sea state, soft and average soils have similar values, which are almost double of the hard soils. Skin friction will be the most important factor in this case, as the piles are mainly axially loaded. Pile diameters will range from 1.4 m to 2.2m, and penetrations from 27 m to 68 m.

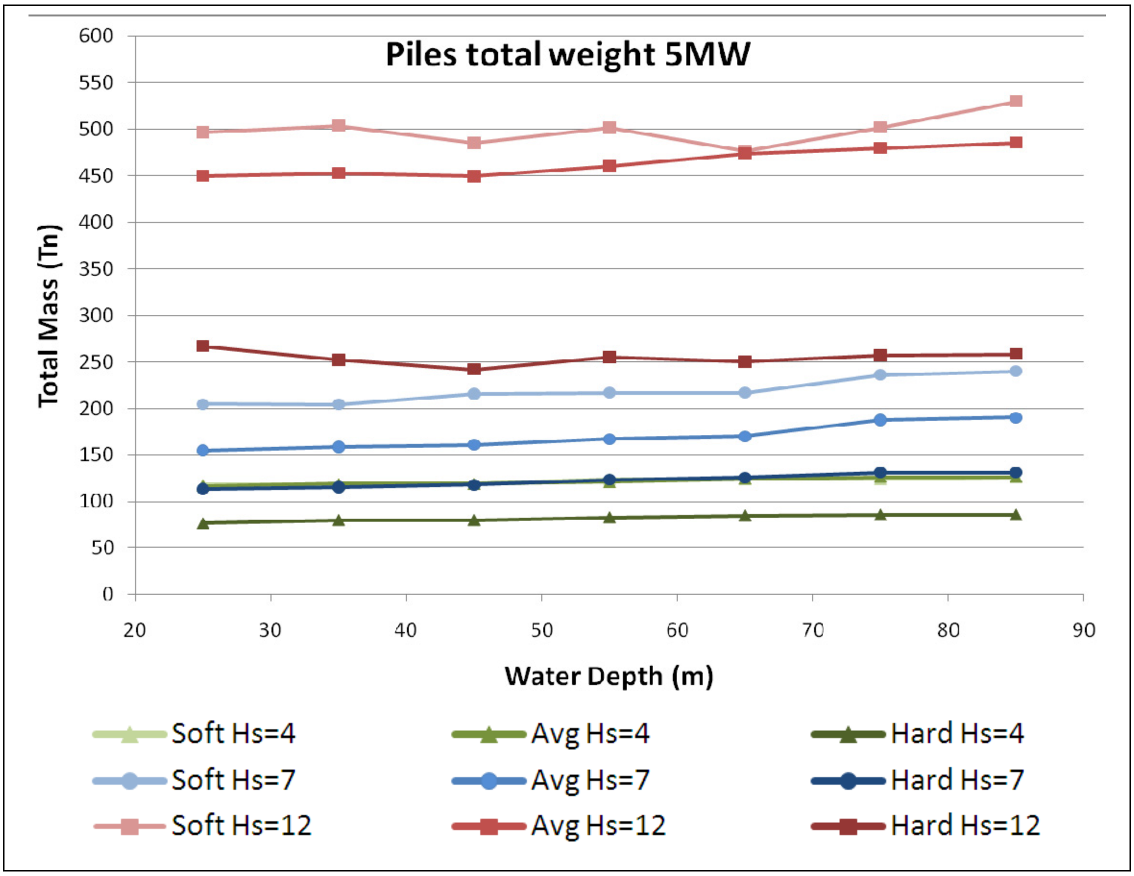


Diagram 4.25 Piles total weight for the 5 MW jacket case

Total costs in Diagram 4.26 show similar conclusions to the 3.6 MW wind turbine case. The tendency is clearly linear with a small soil type effect in the costs. In fact, installation from one soil type to another involves a 5% difference for H_s=4 m cases, 6% for H_s=7 m cases and 10% for H_s=12 m cases.

Wave height has a bigger impact than soil type, but small if compared to the monopile. Hence, changing installation from a H_s=4 m sea state to a H_s=7 m, involves around 22% increase in the costs and from H_s=7 m to H_s=12 m it would be around 55% more.

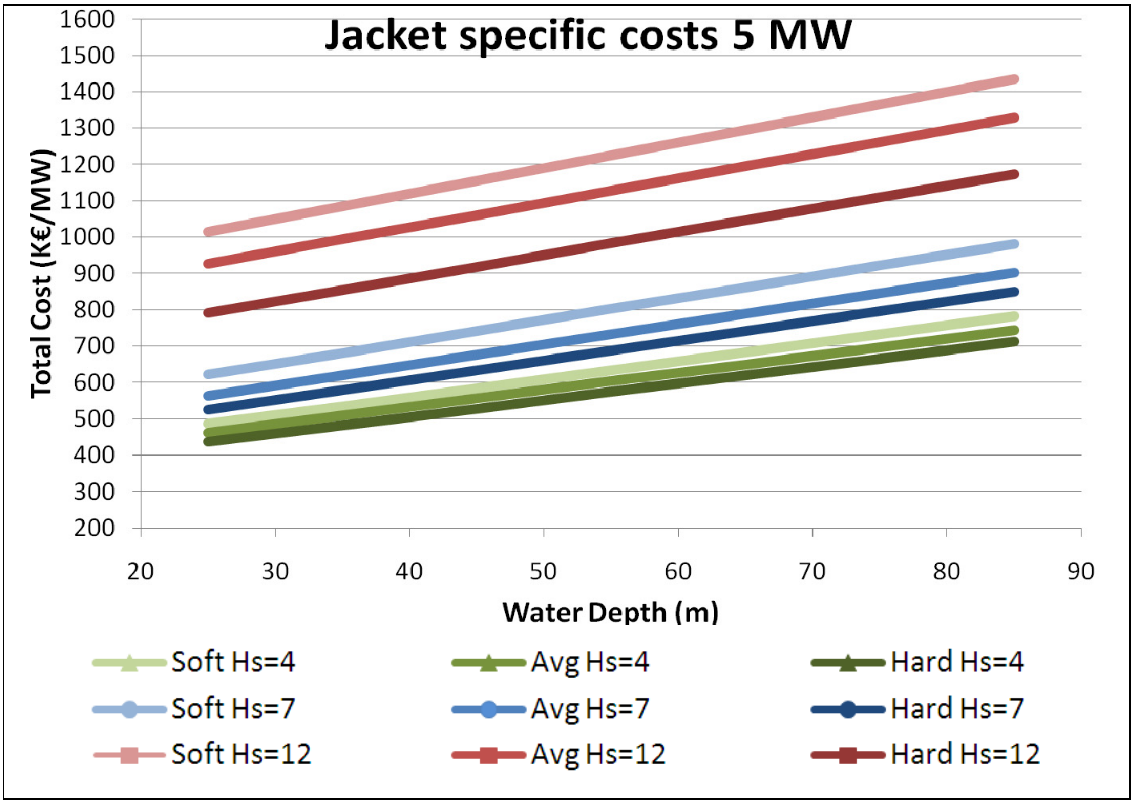


Diagram 4.26 Cost per MW trendline for 5 MW OWTG jacket support structure

4.2.3 OWTG power: 7 MW

A 40% increase in the wind turbine power (from 5 MW to 7 MW) only means an average 18% heavier structure as it can be seen in Diagram 4.27. Thus, specific weight of the jacket support structure improves significantly.

THM is slightly heavier but the first natural frequency results are rather similar when compared to the 5 MW OWTG and values have only decreased by an average 3%. Besides, the soil type has no influence in the results.

However as it was explained before, if the first natural frequency is intended to be amended by modifications in the jacket design, an average 30% weight increase would be necessary with maximum values up to 80%. For this reason, the most realistic and efficient way would be to modify the tower height and not maintaining the hub height constant as it was done in this analysis.

Wave effect is been reduced too as Diagram 4.28 and Diagram 4.29 show. Hence, moving from H_s=4 m to H_s=7 m means an average 24% weight increment, whereas from H_s=7 m to H_s=12 m is around 55%, just below the 5 MW turbine values.

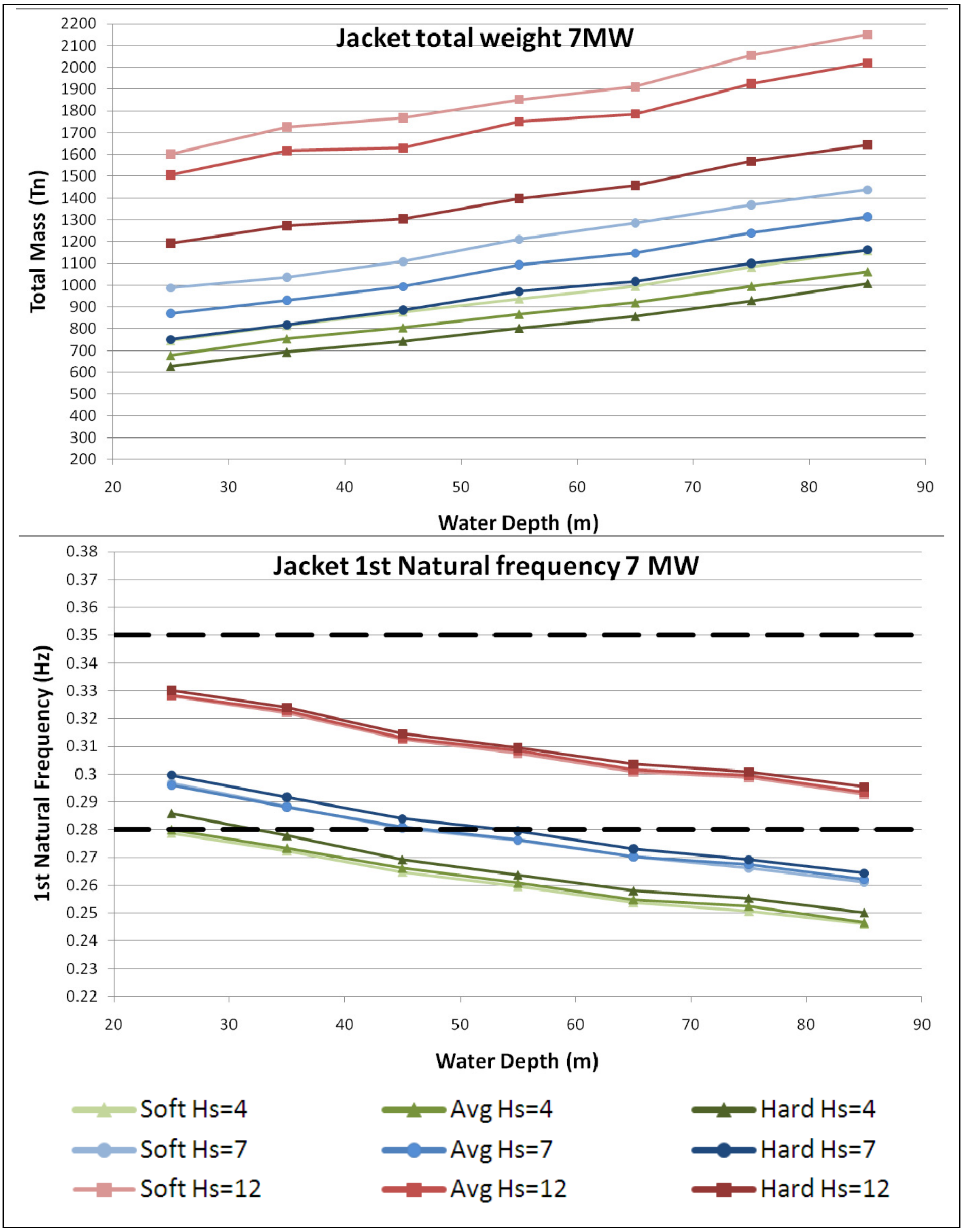


Diagram 4.27 7 MW jacket support structure total weight and 1st natural frequency

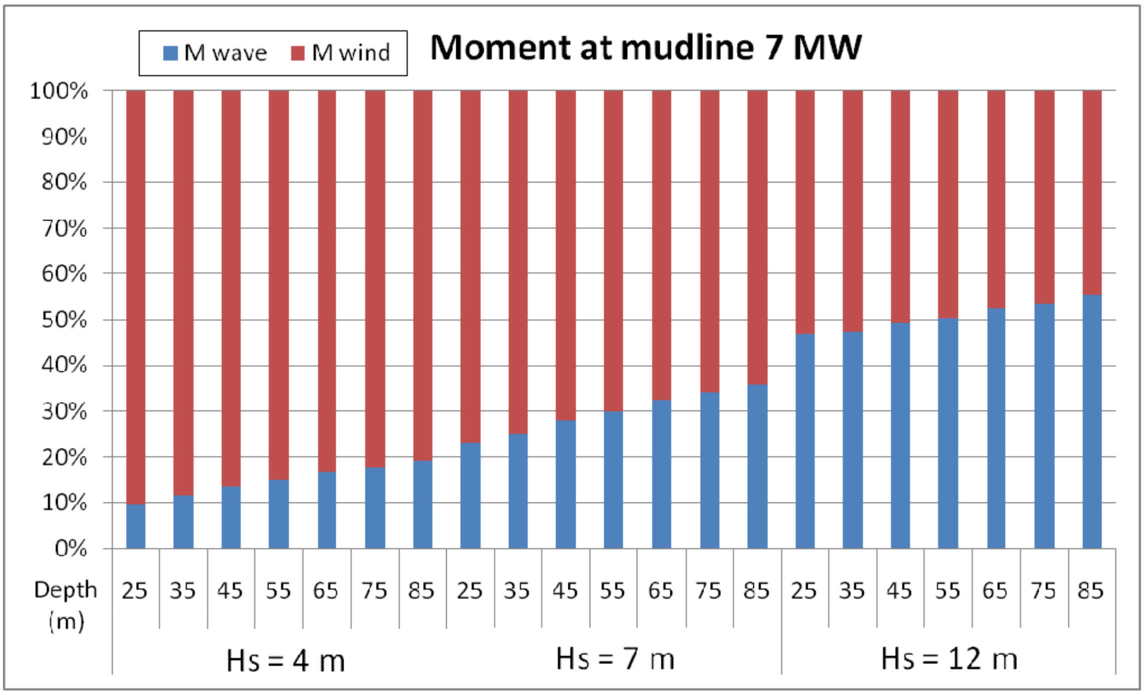


Diagram 4.28 Wind and wave generated moment comparison at mudline for the 7 MW jacket case

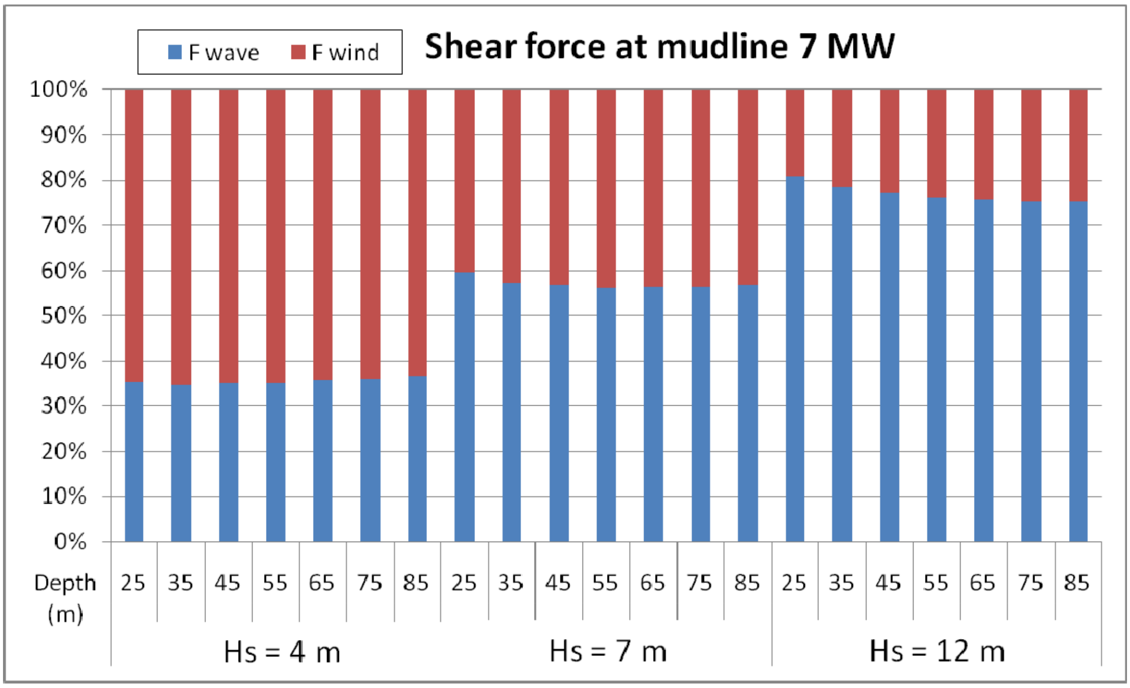


Diagram 4.29 Wind and wave generated shear force comparison at mudline for the 7 MW jacket

Piles are around 30% heavier than the 5 MW turbine case, but still show the same constant tendency for different water depths. Pile diameters range from 1.4 m to 2.35 m and penetrations from 33 m to 75 m.

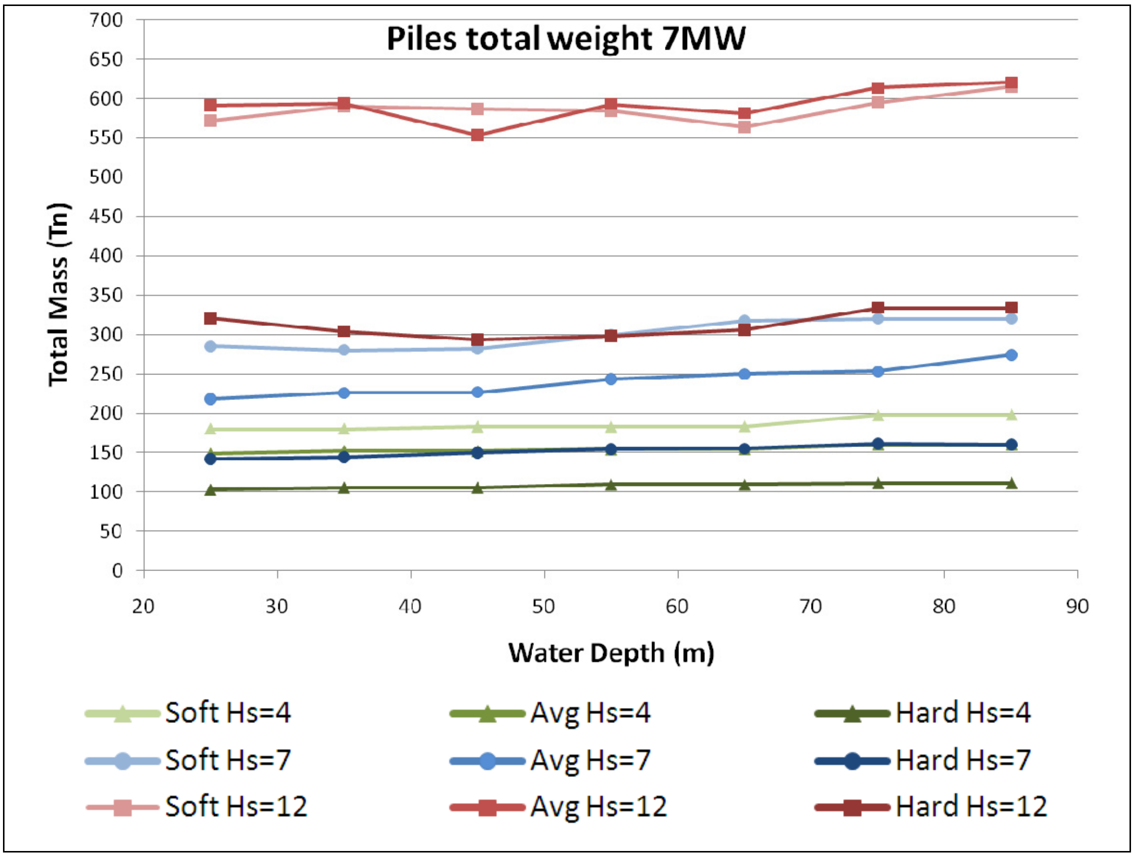


Diagram 4.30 Piles total weight for the 7 MW jacket case

Once again, total costs in Diagram 4.31 show a linear relation with water depth. Soil type effect is minimum too, with a 6% difference for H_s=4 m cases, 8% for H_s=7 m cases and 10% for H_s=12 m cases.

Wave height impact is reduced when compared to the 5 MW cases. Hence, H_s=7 m, cases are around 20% more expensive than H_s=4 m, while H_s=12 m cases are 50% costlier than H_s=7 m.

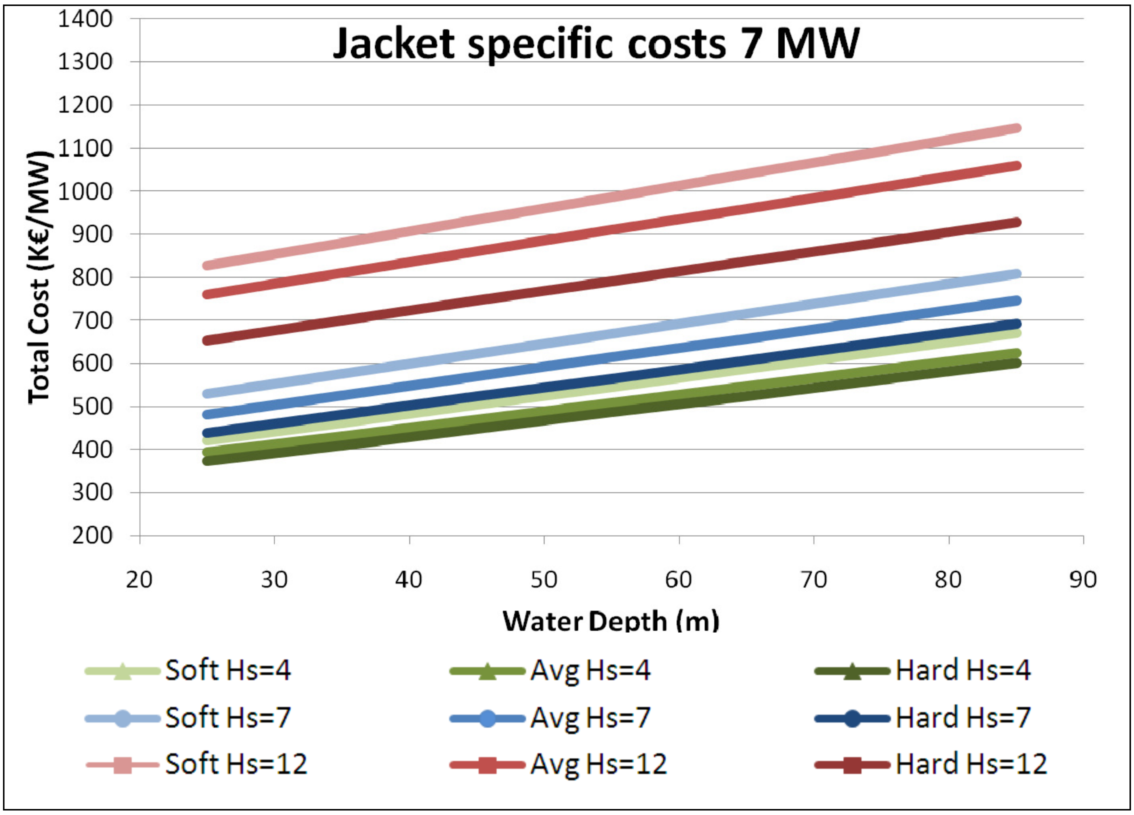


Diagram 4.31 Cost per MW trendline for 7 MW OWTG jacket support structure

4.2.4 Conclusions

Jacket type support structure cost analysis was carried out in order to understand the influence of different input factors. It has been proven that the soil type has a small impact in the jacket final cost and that different wind turbine powers show the same general tendencies in all the assessed factors.

For this reason, values for different soil types and turbine powers have been averaged in Diagram 4.32. This diagram shows the cost division percentage for the manufacturing of each part of the structure and the installation of the whole structure.

As expected, the lattice manufacturing cost entails the biggest part and increases with both water depth and significant wave. However, the transition piece can also involve a big chunk of the costs when the turbine is installed in sheltered and shallow locations.

The pile costs significantly increase with the H_s as it was seen in the pile weight diagrams for each studied case before. And the total installation costs are maintained more or less constant, between 10 and 13% of the total costs, which is around half of the percentage obtained for the monopile (taking into account the scour protection).

Hence, it can be concluded that in order to decrease jacket support structure costs, manufacturing costs should be prioritised by decreasing substructure weight or improving manufacturing methods.

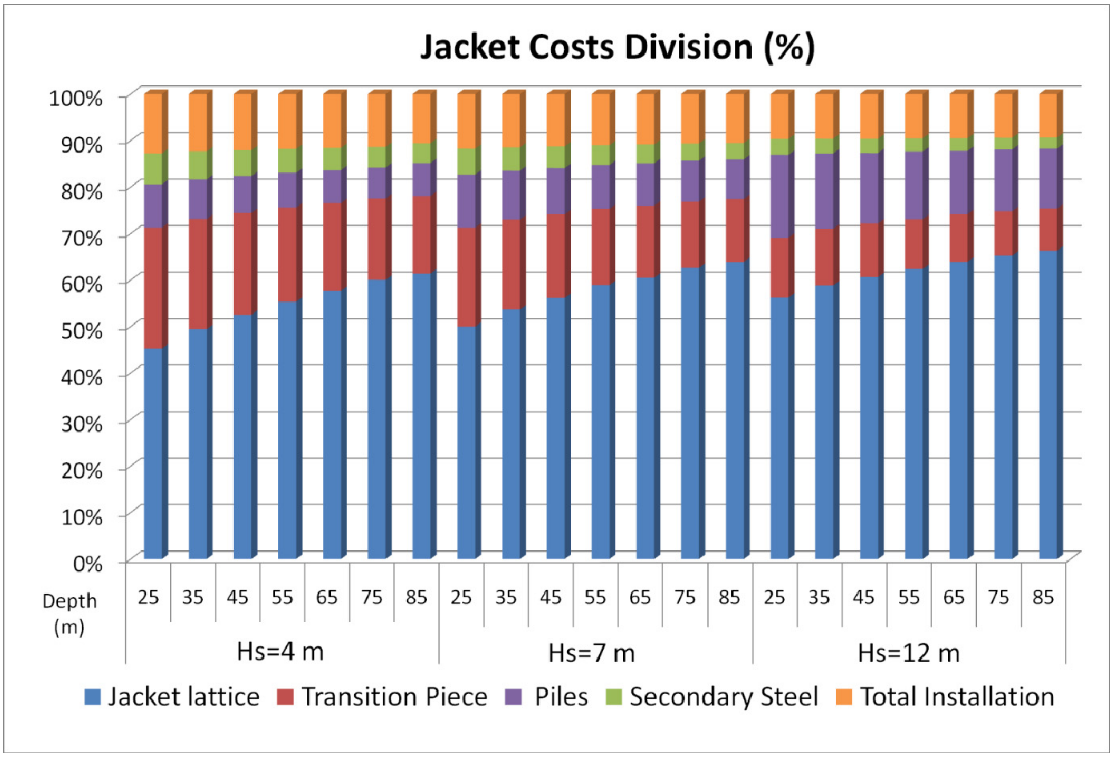


Diagram 4.32 Cost division for jacket support structure at different conditions

The obtained specific costs for the different turbine powers are depicted in Diagram 4.16 for average soil values. As it was explained for each turbine case, jacket weight increases slower than rated power, and as a consequence, installing more powerful turbines is beneficial and diminishes specific cost. In fact, moving one step higher regarding the turbine power, involves cost savings ranging from 13% for the Hs=4 m case to 20% in the harshest environment.

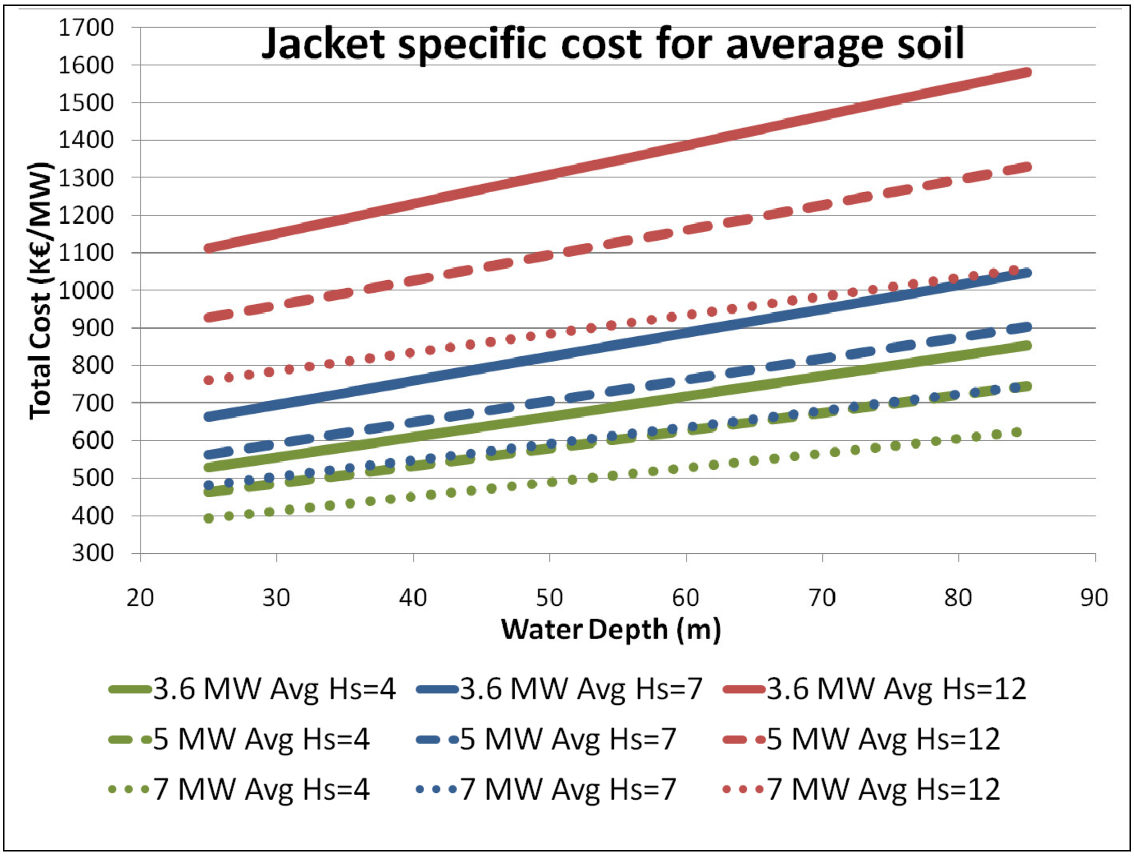


Diagram 4.33 Cost per MW trendline of the jacket support structure for different turbine powers in average soil conditions

Overall, the jacket support structure has demonstrated a great flexibility and is feasible in a wide range of environments with minor changes in its design. The following conclusions can be summarised from the carried analysis:

- Cost curves for the jacket show a linear relation with depth, steeper for larger waves.

- Soil impact is not significant in the jacket weight and therefore costs (4 -10% differences).

- Significant wave height impact is bigger but still much lower when compared to the monopile, due to the transparent nature of the jacket structure. 22% average increase from H_s=4 m to H_s=7 m cases and 55% from H_s=7 m to H_s=12 m cases was obtained.

- Pile weight and therefore cost barely depends on water depth.

- Higher OWTG power diminishes the slope of the cost curves. Average values range from 65 k€/10m per MW for the 3.6 MW, 55 k€/10m per MW for the 5 MW and 45 k€/10m per MW for the 7 MW OWTG.

- Moving to higher OWTG power is beneficial and involves important savings in the specific cost (up to 20%).

- The jacket is already a stiff structure and it is more effective to address the cases with the 1st natural frequency below the allowable range by modifications in the tower stiffness and/or height rather than by increasing the jacket diameter and thickness.

- Current manufacturing and installation technology can cope with the obtained pile diameters and penetrations. Also with the needed jacket lifting capacity which averages 750 Tn (for lattice and TP). Only in some extreme cases up to 1500 Tn lifting capacity would be needed. For these, less capable HLV are available, but still other installation methods like launching could also be proposed.

4.3 Monopile – Jacket costs comparison

Individual calculations have been accomplished for the monopile and jacket support structures in order to understand the factors driving their costs.

In Diagram 4.34 both of them are compared for different water depths and in average soil conditions.

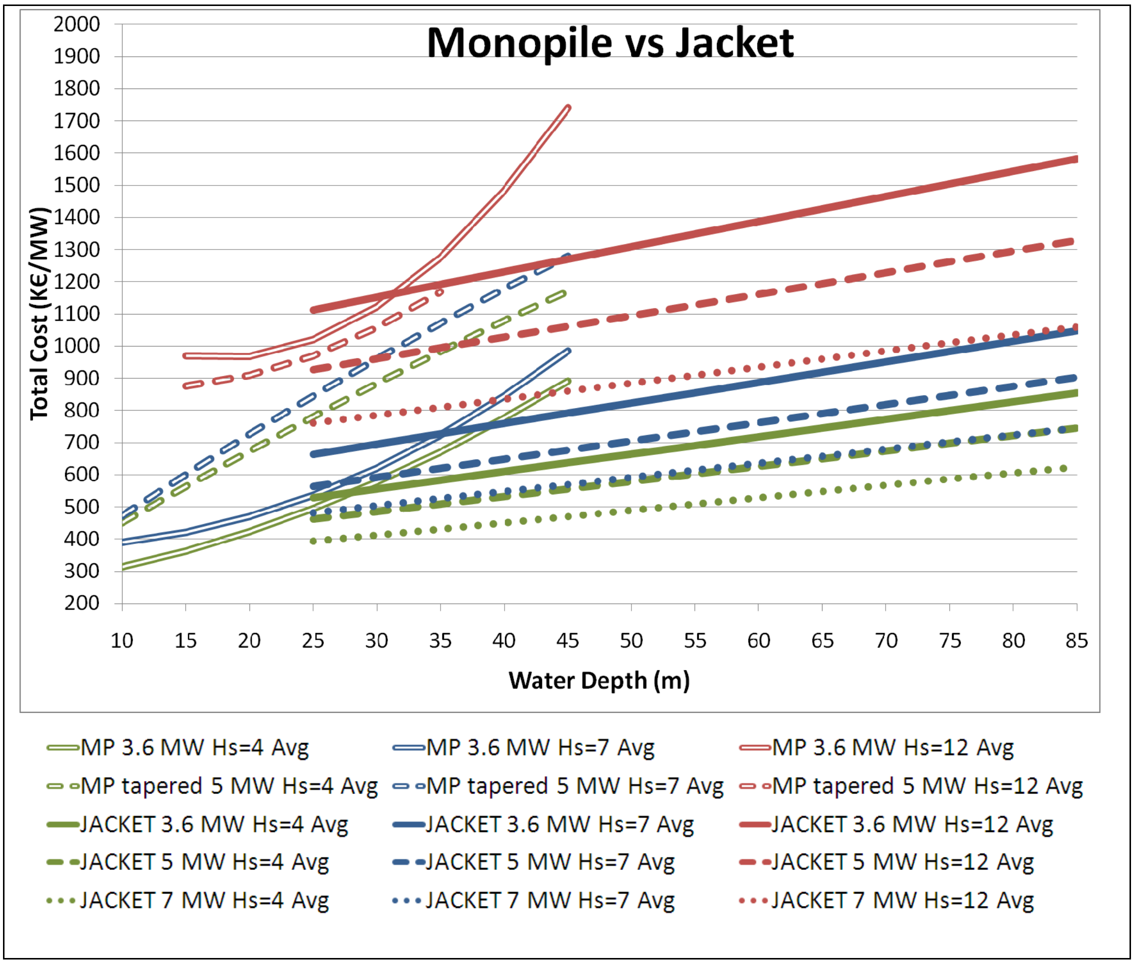


Diagram 4.34. Monopile and jacket support structures total costs comparison for average soil

The characteristics of the turbines exceeding 3.6 MW power, make them more suitable for jacket type support structures. The monopile 5 MW cases have a substantial specific cost due to the extra weight necessary to allocate the structure within the allowable frequency range. Even if tower design modifications were carried out along with the monopile diameter and thickness, the 5 MW turbine specific costs for the monopile would still be higher than for the 3.6 MW.

For this reason, the monopile is only competitive up to the 3.6 MW turbines. The limit water depth is around 25-35 m depending on the significant wave height. Then, the jacket starts to be more economical.

This transition depth is very dependent on the allowable frequency range because the monopile weight is very sensitive to this parameter. Therefore, for minimum allowable frequency ranges below 0.28 Hz or even with tower design modifications, this transition depth could be slightly increased.

Overall, in spite of the monopile initially being the most economical option for shallow waters, its cost increase quadratically with depth and rapidly surpasses jacket costs that increase linearly.

Besides, fixed costs are similar in spite of supporting heavier and more powerful wind turbines; therefore, the specific costs for the jacket are reduced the higher the OWTG power is. This is a big advantage over the monopile and therefore the jacket becomes competitive in a very wide range of depths and environmental conditions.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Costs of offshore wind turbine support structures have been analysed. First of all, based on actual industry experience, recently constructed offshore wind farms costs and driving factors were studied. This showed that only the monopile is a completely mature technology from which costs could be estimated in the 0.6-0.8 M€/MW range.

Then, based on these results, the currently available support structure technology and the recently consented offshore wind farm locations, monopile and jacket type structures were chosen for a detailed study.

A numerical calculation tool was developed in Mathcad (for the monopile) and Matlab (for the jacket) that allowed their design for different environmental conditions and turbine models. With these designs, manufacturing and installation costs were estimated and finally total specific costs could be compared.

The analysis of the designs did not include fatigue calculations and therefore, the presented results and conclusions should not be taken as definitive.

The monopile was demonstrated to be a very soft structure and rather sensitive to all the modified factors: soil type, significant wave height, water depth and turbine model (which accounts for different THM weights and tower heights). This means that the relation of the cost with water depth is quadratic, especially in extreme environmental conditions (soft soils and high waves) in which monopile weight grows rapidly.

As a soft slender structure, the monopile is not suitable for heavy THM and long towers because the first natural frequency decreases significantly and raising it by increasing the pile diameter and thickness is costly. Furthermore, current manufacturing and installation limitations (below 7 m diameter and 100 mm thickness) prevent the use of the monopile for the 5 MW turbines in waters deeper than 15 m. For the 7 MW it was not even considered. It is clear then, that the minimum allowable frequency is the key designing factor that will determine the monopile scope.

On the contrary, the jacket support structure is rather stiff and not so sensitive to the modified factors, which means that the cost relation with water depth is linear. Because it is a quadrapod and it relies on the axial resistance of the soil instead of the lateral resistance like the monopile, soil type is no longer an important driving factor. Besides, its transparent geometry allows for the wave relative load to be diminished, and therefore significant wave height sensitivity is also reduced.

As a stiff structure, the jacket is more suitable for heavier turbines, as small THM could lead to too high first natural frequencies. For this reason too, it is more efficient to accommodate f0 by modifications in the tower design rather than the jacket lattice design.

The monopile is the most economical and feasible choice for the smallest turbines (up to 3.6 MW) and its depth limit is in the 25-30 range, which slightly varies depending on the soil and significant wave height. Offshore locations with larger periods for the most fatigue damaging smallest waves can increase this transition depth if the minimum allowable frequency is diminished. For deeper locations a jacket is preferable.

Due to the quadratic weight increase of the monopile, the jacket quickly becomes lighter and in spite of the fairly more expensive manufacturing costs of the jacket, overall it showed a better performance being suitable for a wider number of cases. Furthermore, the use of the latest higher power rated turbines is recommended as it allows savings in the specific cost (up to 20%).

Jacket lattice and transition piece manufacturing costs were addressed as the key factors in order to decrease the jacket support structure total costs by automation, serial production and design improvements. On the contrary, for the monopile, installation process and scour protection could be the key areas to search for development.

Taking into account that the offshore wind farms to be developed in the future will rarely be located in water depths smaller than 20 m, a shift in the actual market tendency is expected. Therefore, the current 65% of new installed substructures corresponding to the monopile should be taken over by the jacket.

To conclude, it must be remarked that offshore wind turbine support structures need to be designed as part of an overall system for an efficient and economical design. There are many factors in the life cycle of the structure and in different parts of the OWTG that interact among each other and have a significant impact in the final project cost. Therefore, they should be addressed in the right way.

Jacket substructure footprint or batter angle for example have a direct impact in the needed manufacturing facilities, the transportation barge dimensions or the installation process. Piles driveability will also be affected if the pile's diameter is increased too much due to a reduced batter angle.

In the same line, the control system of the wind turbine could be one of the key factors to be modified according to the needs of the site and/or substructure. The entire OWTG has to be designed as a whole and the control system allows accommodating the wind loads in a specific range where the benefits in the substructure design could be significant.

5.2 Recommendations

Several recommendations that could help to accomplish a more detailed analysis of the offshore wind turbines support structures are listed below

The inclusion of the fatigue analysis in the foundation and substructure calculations would be recommendable in order to increase results reliability. In general a big difference in the final results is not expected because the ULS calculations for both the monopile and the jacket are already more conservative than the requirements in [59]. Both the wind and wave extreme load cases were applied together at the same time, so this could compensate for some of the fatigue limitations. Nevertheless, if FLS analysis were included, the external loads should be applied exactly as stated in [59].

In order to complete the study, other support structures like deep water gravity based and tripod should also be analysed. Several new designs are being developed by the industry regarding deep water GBS (see [28], [111] as examples) and the tripod, which has already been tested in the Alpha Ventus, is projected for several more OWFs in France and Germany [112]. Both could be an efficient alternative for the jacket in certain conditions and therefore their analysis could be an important addition to this work.

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APPENDIX A Offshore Wind Farms Table

Wind Farm Name	Country	Status	Capacity (MW)	WTG power (MW)	WTG num.	Turbine Model	Rotor D (m)	Hub Height (m)	Support Structure	Mean Water Depth (m)	Distance to shore (km)	Year online	Stated Project Cost (MEUR)
Alpha Ventus	Germany	Generating Power	60	5	12	Multibrid M5000 & Repower 5M	126	92	Tripod and Jacket	29	56	2010	250
Arklow Bank Phase 1	Ireland	Generating Power	25	3.6	7	GE 3.6 MW	50	74	Monopile	18	10	2004	630
Atlantic Array Wind Farm	United Kingdom	Concept/Early Planning	1500		250	Not Decided			Not Decided	40	25		5175
BARD Offshore 1	Germany	Under Construction	400	5	80	BARD 5.0	122	90	Tripile	40	111.9	2011	
Barrow	United Kingdom	Generating Power	90	3	30	Vestas V90-3.0 MW	90	75	Monopile	14	7.5	2006	160.425
Beatrice Demonstration	United Kingdom	Generating Power	10	5	2	REpower 5M	126	107	Jacket	45	23	2007	40.25
Belwind Phase I	Belgium	Under Construction	165	3	55	Vestas V90-3.0 MW	90	72	Monopile	22.5	43.4	2010	620
Blyth	United Kingdom	Generating Power	4	2	2	Vestas V66		60	Monopile	5	1	2000	4.6
Breitling	Germany	Generating Power	3	2.5	1	Nordex N90 2.5 MW	90		Gravity Base	0.5	0.3	2006	

Burbo Bank	United Kingdom	Generating Power	90	3.6	25	Siemens SWT-3.6-107	107	84	Monopile	3	6.4	2006	181
Docking Shoal	United Kingdom	Consent Application Submitted	540	6	177	Not Decided	140	110	Not Decided	8.5	20		1725
Dogger Bank	United Kingdom	Concept/Early Planning	9000	3.6	2500	Not Decided			Not Decided	40.5	197.2		
Dudgeon	United Kingdom	Consent Application Submitted	560	3.33	168	Not Decided			Not Decided	16.5	32		345
East Anglia	United Kingdom	Concept/Early Planning	7200			Not Decided			Not Decided	36.5	44		
EnBW Baltic I	Germany	Under Construction	48	2.3	21	Siemens SWT-2.3-93	93	67	Monopile	17.5	17.1	2010	
ENOVA Offshore Project Ems Emden	Germany	Generating Power	5	4.5	1	ENERCON E-112	114	100	Monopile	1	0	2004	
Firth of Forth	United Kingdom	Concept/Early Planning	3465	5	693	Not Decided			Not Decided	46.5	52.7		

Frederikshavn	Denmark	Generating Power	11	2.75	4	Various: Nordex N90 2.5 MW, Vestas V90 3 MW, Bonus(Siemens) 82.4 2.3 MW	90	80	Monopile and Bucket	2.5	3.2	2003	
Greater Gabbard	United Kingdom	Under Construction	504	3.6	140	Siemens SWT-3.6-107	107	105	Monopile	20.5	36	2012	1738.8
Gunfleet Sands	United Kingdom	Generating Power	173	3.6	48	Siemens SWT-3.6-107	107	75	Monopile	6.5	7	2010	342.125
Gunfleet Sands extension	United Kingdom	Concept/Early Planning			2	Not Decided			Not Decided				
Gwynt Y Mor	United Kingdom	Consent Authorised	576	3.6	160	Siemens SWT-3.6-107	107	100	Not Decided	22.5	13		2300
Hooksiel	Germany	Generating Power	5	5	1	BARD 5.0	122	90	Tripile	5	0.4	2008	
Horns Rev	Denmark	Generating Power	160	2	80	Vestas V80-2.0 MW	80	70	Monopile	8.5	17.9	2002	272
Horns Rev 2	Denmark	Generating Power	209	2.3	91	Siemens SWT-2.3-93	93	68	Monopile	13	31.7	2009	470
Hornsea	United Kingdom	Concept/Early Planning	4000		1000	Not Decided			Not Decided	41.5	99.5		17250

Humber Gateway	United Kingdom	Consent Application Submitted	299	3.6	83	Not Decided	107	76	Not Decided	14.5	8		805
Hywind	Norway	Generating Power	2	2.3	1	Siemens SWT-2.3-82	82	65	Floating	220	10	2009	
Inner Dowsing	United Kingdom	Generating Power	97	3.6	27	Siemens SWT-3.6-107	107	80	Monopile	7	5	2009	172.5
Irish Sea	United Kingdom	Concept/Early Planning	4200			Not Decided			Not Decided	50	37.7		
Kemi Ajos I	Finland	Generating Power	15	3	5	WinWinD 3MW	100	88	Gravity Base	4	2.6	2007	
Kemi Ajos II	Finland	Generating Power	15	3	5	WinWinD 3MW	100	88	Gravity Base	4	2.6	2008	
Kentish Flats	United Kingdom	Generating Power	90	3	30	Vestas V90-3.0 MW	90	70	Monopile	4	8.5	2005	139.725
Lillgrund	Sweden	Generating Power	110	2.3	48	Siemens SWT-2.3-93	93	68	Gravity Base	8.5	11.3	2007	197
Lincs	United Kingdom	Consent Authorised	270	3.6	75	Siemens SWT-3.6-120	120	100	Monopile	9.5	8		833.75
Lynn	United Kingdom	Generating Power	97	3.6	27	Siemens SWT-3.6-107	107	80	Monopile	9	5	2009	172.5
Moray Firth Eastern Development Area	United Kingdom	Concept/Early Planning	1400	8	200	Not Decided	150		Not Decided	46	27.5		
North Hoyle	United Kingdom	Generating Power	60	2	30	Vestas V80-2.0 MW	80	67	Monopile	8.5	7.2	2004	92

Nysted	Denmark	Generating Power	166	2.3	72	Bonus(Siemens) SWT-2.3-82	82	69	Gravity Base	7.5	10.8	2003	248
Offshore Windpark Egmond aan Zee	Netherlands	Generating Power	108	3	36	Vestas V90-3.0 MW	90	70	Monopile	16.5	10	2007	200
Ormonde	United Kingdom	Under Construction	150	5	30	REpower 5M	126	100	Jacket	19	9.5	2011	322
Prinses Amalia	Netherlands	Generating Power	120	2	60	Vestas V80-2.0 MW	80	59	Monopile	21.5	23	2008	350
Race Bank	United Kingdom	Consent Application Submitted	620	6	206	Not Decided	140	110	Not Decided	13.5	27		1725
Rhyl Flats	United Kingdom	Generating Power	90	3.6	25	Siemens SWT-3.6-107	107	80	Monopile	7.5	8	2009	227.7
Robin Rigg	United Kingdom	Generating Power	180	3	60	Vestas V90-3.0 MW	90	80	Monopile	6	11	2010	455.4
Samso	Denmark	Generating Power	23	2.3	10	Bonus(Siemens) SWT-2.3-82	82		Monopile	11.5	4	2003	30
Scroby Sands	United Kingdom	Generating Power	60	2	30	Vestas V80-2.0 MW	80	68	Monopile	4	2.3	2004	86.871
Sheringham Shoal	United Kingdom	Under Construction	317	3.6	88	Siemens SWT-3.6-107	104	82	Monopile	18.5	23	2011	
Sprogo	Denmark	Generating Power	21	3	7	Vestas V90-3.0 MW	90	70	Gravity Base	11	10.6	2009	

Teesside	United Kingdom	Consent Authorised	90	3.6	30	Not Decided	104	100	Monopile	12	1.5		
Thanet	United Kingdom	Generating Power	300	3	100	Vestas V90-3.0 MW	90	70	Monopile	18.5	12	2010	1035
Thornton Bank phase I	Belgium	Generating Power	30	5	6	REpower 5M	126	94	Gravity Base	16	27	2009	150
Tricase	Italy	Under Construction	92	2.4	24	Blue H			Floating	118	20.2	2011	
Triton Knoll	United Kingdom	Concept/Early Planning	1200	8	333	Not Decided	180	140	Not Decided	18	33		
Vindpark Vanern	Sweden	Generating Power	30	3	10	WinWinD 3MW & Dynawind	100	90	Gravity Base	14	3.5	2009	60
Walney Phase 1	United Kingdom	Under Construction	184	3.6	51	Siemens SWT-3.6-107	107	84	Monopile	21	14	2011	631.35
Walney Phase 2	United Kingdom	Consent Authorised	184	3.6	51	Siemens SWT-3.6-120	120	90	Monopile	27	14		1380
West Duddon	United Kingdom	Consent Authorised	500	3.6	140	Not Decided			Not Decided	19	15		
Westermost Rough	United Kingdom	Consent Application Submitted	240	3.6	80	Not Decided			Not Decided	17	8		
Yttre Stengrund	Sweden	Generating Power	10	2	5	NEG Micon 2 MW	72	60	Monopile	7	2	2002	13