Chapter 12

The Tower

The high tower is an essential component of the horizontal-axis turbine, a fact which can be both an advantage and a disadvantage. The costs, which can amount to up to 30 % of the overall turbine costs, are, of course, disadvantageous. As the height of the tower increases, transportation, assembly and erection of the tower and servicing of the components also become increasingly more difficult and costly. On the other hand, the specific energy yield of the rotor also increases with tower height. Theoretically, the optimum tower height lies at the point where the two growth functions of construction cost and energy yield intersect. Unfortunately, this point of intersection cannot be specified in any generally applicable form. In larger turbines, construction costs rise more rapidly with increasing tower height than in small turbines. An even greater role is played by the choice of site. At inland sites, i.e. in regions with a high degree of surface roughness, the wind speed increases more slowly with height than at shore-based sites. Higher towers will, therefore, show better returns here than, for example, in offshore applications where the reverse effect is found. In inland regions, large wind turbines with tower heights of 80 m and more are a decisive factor for the economic use of the wind potential.

Next to its height, the second most important design parameter of a tower is its stiffness. Establishing the first natural bending frequency in the right way is an important task in the design. This determines the material required and, ultimately, the construction costs. The goal of the tower design is to achieve the desired tower height with the required stiffness at the lowest possible construction cost.

The transportation and the erection procedure is developing into an increasing problem for the latest generation of multi-megawatt wind turbines. Tower heights of more than 100 m and tower-head weights of several hundred tons require a diameter at the tower base of more than five meters, with the consequence that road transportation will no longer be feasible. This becomes a strong incentive to find innovative solutions in the tower design.

The materials available for the construction are steel or concrete. Designs range from lattice constructions to guyed or free-standing tubular-steel towers up to massive concrete structures. The technical requirements posed by the overall system can be met by almost any variant but the economic optimum is only achieved by appropriately matching the selected tower design to the requirements set. This shows clearly that, al-though the tower of a wind turbine can be seen as a conventional structure when considered by itself, its design also requires a considerable amount of understanding of the overall system and its application. Apart from these functional aspects, it should not be overlooked that the tower, even more so than the nacelle, determines the outward appearance of a wind turbine. Due attention should, therefore, be accorded aesthetics, even if this implies some additional costs.

12.1 Tower Configurations

The oldest types of "wind turbines", the windmills, didn't have towers but “millhouses”. These were low in height in relation to the rotor diameter and of voluminous construction in accordance with their function as a work space, thus also providing for the necessary stiffness. Soon, however, the advantage of increased height was recognised and the millhouses became more slender and more tower-like. But it is only in modern-day constructions, first in the small American wind turbines and then later in the first power-generating wind power stations, that "masts" or "towers" were used, the sole function of which lay in supporting the rotor and the mechanical components of the tower head. As a consequence of this development, designs and materials for towers increased in variety. Steel and concrete took the place of the wood construction of the millhouses. In the early years of the development of modern wind energy technology, the most varied tower designs were tried out and tested but in the course of time, the range has been narrowed down to free-standing designs, mainly of steel and more rarely of concrete.

Lattice Type

The simplest method of building high and stiff tower constructions is as a three-dimensional truss, so-called *lattice* or *truss towers.* Lattice towers were, therefore, the preferred design of the first experimental turbines and in the early years also for smaller commercial turbines (Fig. 12.1). More or less, they disappeared after the appearance of the free standing steel tube towers. Today, the lattice tower has again become an alternative to the tubular-steel tower in the case of the very high towers required for large turbines sited in inland regions.

Concrete Type

In the thirties, steel-reinforced concrete towers were used for the so-called "Aeromotors" in Denmark (Chapt. 2.1). These towers were also characteristic of the earlier large experimental Danish turbines (Fig. 12.2). Later, steel towers became dominant also in the commercial turbines in Denmark. Concrete towers have recently gained favour again for tower heights of more than 100 m. Today particularly the prefabricated concrete construction is a preferred solution for high towers.

Free-standing tubular-steel towers

The most common tower type currently in use is the free-standing steel tube tower (Figs. 12.3 and 12.5). Mastery of the vibrational behaviour has made it easier to use this type so that tubular-steel towers with very low design stiffness can be implemented. It has thus become possible to lower the structural mass, and thus the costs of the towers, considerably by using "soft" designs (Chapt. 12.5).

Guyed tubular-steel towers

Down-wind rotors made it necessary to use slender tubular-steel towers in order to keep the tower shadow effect as small as possible. These were anchored with steel cables or in some cases with stiff trusses to ensure the required bending stiffness (Fig. 12.4). Despite their comparatively low overall mass, guyed towers are not very cost-efficient. The guys and the additional anchoring foundations required inflate the total cost. Moreover, the guys are considered a hindrance in agricultural areas.

Hybrid construction

It seems obvious to combine the concrete and tubular steel types of construction. Some earlier experimental turbines, for example, had a solid base with a steel tube placed on the top (Fig. 12.6). The hybrid construction of towers has become very important, since the height of the towers exceed the 100 m level (s. Chapt. 12.7).

Fig. 12.1. MOD-1 with lattice tower (1982)

Fig. 12.2. Concrete tower of the Tjaereborg test turbine (1986)

Fig. 12.3. Free standing tubular steel tower of the MOD -2 (1982)

Fig. 12.4. Guyed tubular-steel tower of a Carter turbine (1985)

Fig. 12.5. Stepped tubular steel tower of a Bonus turbine (1985)

Fig. 12.6. Steel tower on a concrete base of the Dutch experimental turbine HAT-25 (1985)

Special designs

Apart from the prevailing designs, some special tower designs can be found in wind turbines. Some Danish wind turbines have towers with a tripod design. In some rare cases, slender lattice or concrete towers are also fitted with guys. Altogether, however, constructions such as these do no longer play an important role. The majority of today's turbines have free-standing lattice, concrete or tubular-steel towers.

12.2 Strength and Stiffness Design

The dimensioning of a tower is determined by a number of strength and stiffness requirements. Factors to be considered are the breaking strength required for surviving extreme wind speeds, the fatigue strength required for 20 or 30 years of operation and the stiffness with respect to the vibrational behaviour. In some cases, the buckling of the walls also becomes a dimensioning criterion.

Breaking strength

The static load is determined by the tower-head weight, the tower's own weight, and the aerodynamic rotor thrust. In turbines with blade pitch control, rotor thrust is generally at its highest level when the rotor is running at its rated speed whereas it is comparatively low in standstill due to the possibility of rotating the rotor blades into running position. The maximum bending moment at the tower is obtained with rotors without blade pitch control (stall-controlled turbines) or when the worst rotor blade position is demanded for a particular load case. In the standard case, the question of fracture load will be reduced to that of the bending moment acting on the tower base.

Fatigue

The dynamic loading caused by the rotor thrust during operation has a definite impact on the fatigue life of slender towers. Additional loads caused by the vibrational behaviour in cases of resonance must also be taken into consideration (Chapt. 11.4.2). Hence a purely static stress analysis, commonly required by the building authorities for conventional buildings, is not appropriate for all tower designs of a wind turbine.

Stiffness

The stiffness requirement is derived from the chosen vibrational concept of the turbine as a whole (Chapt. 11.4.1). It is generally focused on the requirement for a particular first natural bending frequency, even though other natural frequencies, and particularly the natural torsion frequency, must be checked with regard to the dynamics of the yaw system of the turbine. The position of the first natural bending frequency with respect to the frequency of the rotational rotor speed is characteristic of the stiffness of the tower. The tower design is called a "stiff" or a "soft" design in accordance with this criterion (s. Chapt. 11.1).

Buckling

One important criterion which plays a role at least for thin-walled tubular-steel towers with a low natural bending frequency below the 1 P excitation is the resistance to local buckling of the tube wall. As a result of the increasing weight optimisation in modern tubular-steel towers, the buckling strength frequently becomes the determining dimensioning factor for the required wall thicknesses.

Folding

The stability problem of "folding" occurs in the case of slender components which are subjected to pressure loading. This situation only occurs in lattice towers so that the appropriate certificate must be provided here for the heavily pressure-loaded lattice rods.

Example of tower-structure dimensioning

The example of the MOD-2 clearly illustrates in a real case the consequences of these load cases with respect to the required tower wall thickness (Fig. 12.7). Despite the "soft" tower design, the necessary wall thickness is determined by the stiffness requirement, a result which is typical of almost all comparable modern tower concepts. This becomes even more pronounced when the tower height in relation to the rotor diameter is greater than was the case in the MOD-2. Apart from a few exceptions, the important criterion for dimensioning the tower is, therefore, the stiffness requirement.

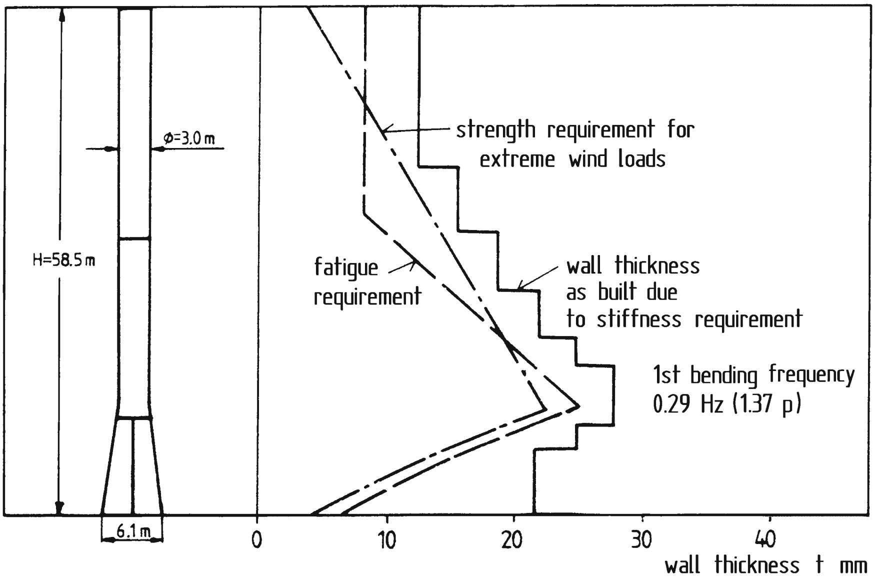


Fig. 12.7. Dimensioning criteria of the tower wall thickness in the MOD-2 [1]

12.3 Tower Dimensioning Conforming to German Building Regulations

In Germany, a wind power plant is graded as a "building" consisting of tower and foundation under building laws. The nacelle with its rotor is considered as “attached machine part". The applicable guideline for the tower design and calculation of the foundations is, therefore, the "Richtlinie für Windenergieanlagen - Einwirkungen und Standsicherheitsnachweise für Turm und Gründung" (Guideline for wind power plants - Influences and stability certificates for tower and foundation) issued by the Deutsches Institut für Bautechnik (DIBt) (German Institute for Structural Engineering). This guideline was produced in 1993 and has now appeared in its latest version of March 2004 (s.a. Chapt. 6.4.1) [2]. With regard to the load assumptions (called "influences"), the DIBt Guideline relates to IEC 61400-1. The DIBt prescribes two methods for verifying “stability", a so-called "Calculation of overall dynamics " and, as an alternative under certain conditions, the "Simplified calculation".

Calculation of overall dynamics

The loads on the overall system consisting of tower with foundation and machine part are to be determined in accordance with the "theory of elasticity". In this theory, suitable models for wind, aerodynamics, structural dynamics and function (control) must be taken into consideration as described, e.g. in Chapt. 6.7.2. As a result of the calculation of the overall dynamics, the variations with time of the stress resultants are to be shown in the relevant cross-sections. The proofs for the "limit state of the bearing strength" and for the so-called "performance capability" must be provided using these results.

Simplified calculation

A simplified calculation is permissible if sufficient space between the natural frequencies of the tower and the exciter frequencies is guaranteed in continuous operation. This is considered as given if the maximum rotational frequency of the rotor (1P) is at least 10 % below the first bending frequency of the tower and the frequency of passage of the rotor blades (3P or 2P) is spaced by at least 10 % from the integral natural frequencies of the tower. The proof of stability is to be provided with the stress resultants from a calculation of overall dynamics at the machine-part/tower interface as load assumptions for the tower. To simplify, the load values need only be stipulated with their maximum or minimum values, respectively. In this type of calculation, the proof of strength or stability is only provided without time-dependent load variations for the tower. A complete fatigue calculation according to the theory of elasticity is thus not required for the tower itself. Depending on the wind regime of the site, the standard proof of safety for tower and foundation is required in four "wind zones" having different wind specifications. As already mentioned in Chapter 6, these *wind zones* do not correspond to the "wind turbine classes" according to IEC 61400-1, so that a correspondence between wind zone and wind turbine class must always be established in order to obtain a building permit in Germany (s.a. Chapt. 6.4.2).

12.4 Free-Standing Tubular-Steel Towers

Today, free-standing tubular-steel towers are by far the preferred type of construction for commercial wind turbine installations, the main reason being the short on-site assembly and erection time (Fig. 12.8). Under favourable conditions, even larger towers can be fabricated of one piece at the manufacturer's and bolted to the foundation at the site. Higher towers of up to 100 m height are made of several sections which are bolted together so that no on-site welding is required. The preference for tubular-steel towers is also buoyed by the very low steel prices in the last twenty years.

12.4.1 Stiffness and Structural Mass

Tower stiffness is characterised by several natural frequencies, but only the first and the second natural bending frequency and the first natural torsion frequency are of any practical significance (s. Chapt.11.4.1). In most towers, the first natural torsion frequency is much higher than the first natural bending frequency. The torsion frequency of free-standing tubular-steel towers is approximately three times higher if their diameter/wall thickness ratio lies within normal limits. It is, therefore, sufficient to use the first natural bending frequency for obtaining a rough overview. With a given tower height and head weight, the tower must be designed in such a way that the required first natural bending frequency is reached.

A stiff tower design is always a simpler and safer solution with regard to vibrational behaviour, but the mass of the tower required to achieve this becomes very high. In wind turbines with tower heights of more than 80 m, a stiff tower design can, therefore, no longer be realised in practice. For economic reasons, the stiffness should be kept as low as technically feasible.

For simple tower geometries, for example a cylindrical steel tube, dimensioning models were developed which permit the required wall thickness to be calculated by using relatively simple formulae, on the basis of the said load cases with a given height, tower head mass and the chosen stiffness concept of the wind turbine [3]. These models are mainly suited to demonstrating the influence of the dimensioning parameters, thus helping to understand their significance with regard to tower optimisation. In reality, the calculated masses are often lower. Manufacturers increasingly tend to favour more complicated designs such as wall thickness varying in stages with diameter, or weight-optimised tapered shapes to minimise the tower mass and thus the costs.

Figures 12.9 and 12.10 show the specific mass of free-standing tubular-steel towers, referred to the rotor-swept area, of various turbine sizes and concepts. The shaded areas in the diagrams are based on various simplifying assumptions. A tower height equal to the rotor diameter has been assumed. For two- and three-bladed turbines, different tower head masses have been assumed as a function of the rotor diameter according to the approaches in Chapter 19.4. The stiffness requirement, i.e. the tower's first natural bending frequency in relation to the rated rotor speed, has been taken to be 1.5 P and 0.75 P (Chapt. 11.4.1).

The shaded areas of the diagrams show the specific tower mass to be expected with the above assumptions. As anticipated, the lightest towers are to be found with a first natural bending frequency below 1 P. The more recent turbines tend towards a moderately soft tower design of approximately 1.3 P. A stiffer design with a first bending frequency below 1 P comes too close to the strength limit, at least for larger towers.

Fig. 12.8. Free-standing tubular towers of GAMESA wind turbines

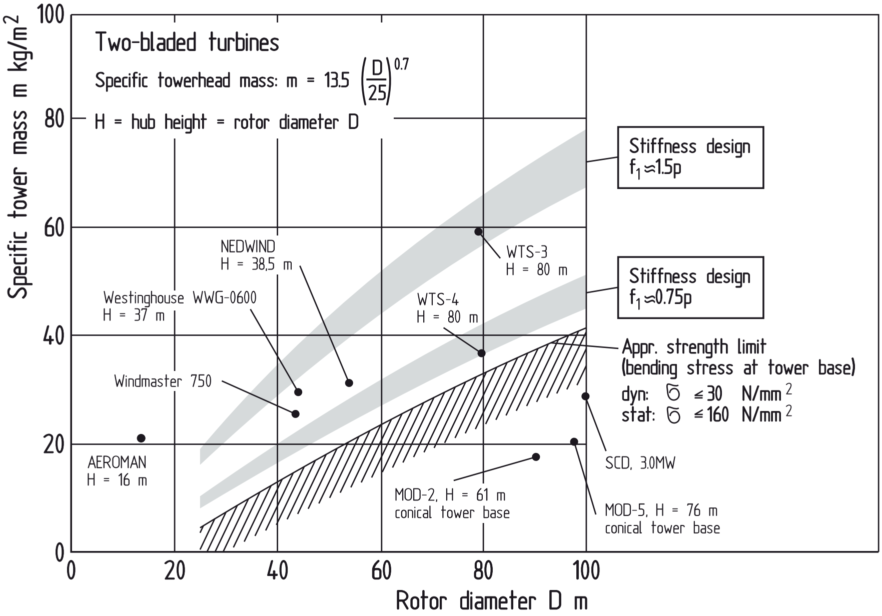


Fig. 12.9. Specific overall mass referred to the rotor-swept area of free-standing cylindrical tubular-steel towers for wind turbines with two-bladed rotor

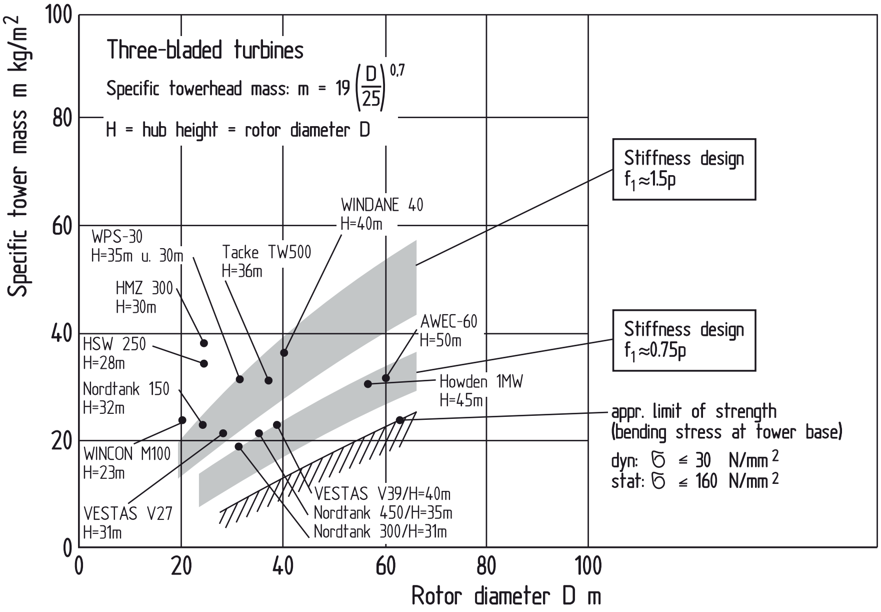


Fig. 12.10. Specific overall mass of free-standing cylindrical tubular-steel towers for wind turbines with three-bladed rotor

In some cases it is noticeable that the overall mass of some existing towers differs considerably from the calculated values. The reasons for this are differently chosen relations of rotor diameter to tower height, but also a more weight-optimised geometry. For example, a conical tower base will increase stiffness or, respectively, decrease the tower mass for a given stiffness. The same effect is achieved with a tapered change in wall thickness. The masses of finished towers will, therefore, be sometimes less than the calculated masses in the diagrams of Figures 12.9 and 12.10.

On the other hand, the tower height is much greater in relation to the rotor diameter, particularly at inland sites. The more recent wind turbines are offered with different tower heights of up to 1.5 times the rotor diameter. In these cases, the specific tower mass becomes very much higher than calculated in the model above.

12.4.2 Manufacturing Techniques and Construction

Almost without exception, the towers of the large turbines of today have a conical shape, with a diameter that diminishes from the base up to the tower head. Compared with a cylindrical geometry, this saves weight for a given required stiffness (see Chapter 12.9). In nearly all cases the towers are produced and assembled in several sections. But there are also towers manufactured in one piece if the transportation and site conditions allow this.

Standard Construction with Bolted Sections

The towers consist of a number of prefabricated sections with a length of up to about 30 m. The sections are produced from sheets of steel plate with a thickness of 10-50 mm. The sheets, which have a width of about 2 m, are rolled into a circular shape on a rolling stand (Fig. 12.11). From these segments, the tower section is welded together. In most cases, automatic welders are used for this. The welding requires special attention in view of the loading situation of the tower. The quality is checked by means of the usual methods such as ultrasonics, X-rays and examination for surface cracks. The tower sheets consist of commercially available St52 grade structural steel plate and, more rarely, St48. Higher-strength material is used for most of the forged joining flanges and the foundation section.

At the ends of each tower section, the internal flanges are welded on (Fig. 12.12). They consist of high-strength steel and occasionally of forged steel. Shaping and welding of the flanges requires some experience since the components can easily become distorted, the consequence being that the flanges will not match during the assembly. The resultant gaps between the tower sections are a quality defect frequently found in tubular-steel towers (Fig. 12.13).

In most cases, the tower is joined to the foundation by means of a so-called *foundation section.* This is manufactured separately and incorporated in the foundation when the concrete is poured (Fig. 12.14).

The tower is joined to the nacelle via the *azimuth flange.* It accommodates the azimuth bearing if a roller bearing is used. The azimuth flange is often a cast part.

Surface treatment is an important feature regarding the quality of steel towers. Corrosion must be prevented over decades even in an aggressive environment. After some blasting, the tower sections are covered with thermally applied zinc coating.

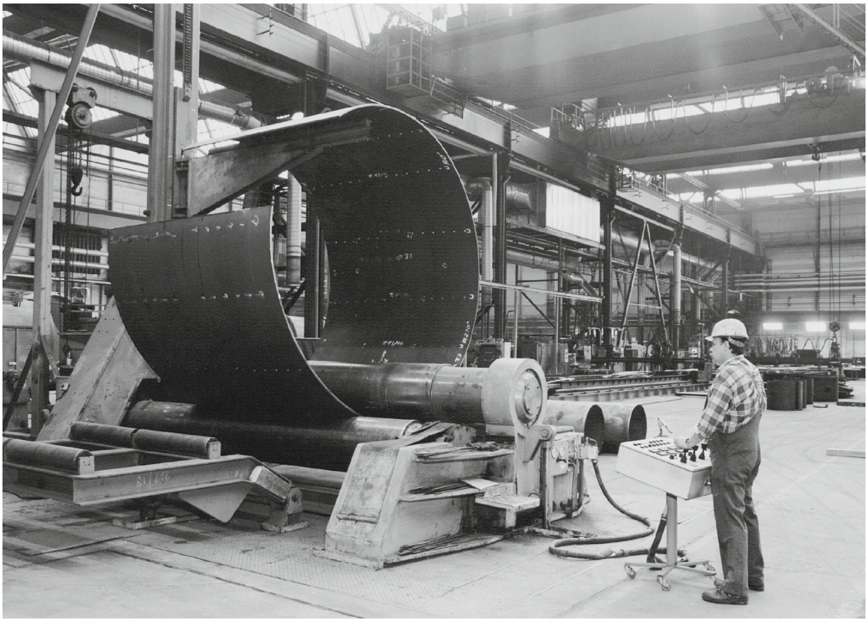


Fig. 12.11. Manufacture of tower sections (CAS)

Fig. 12.12. Welding-on of the flange (CAS)

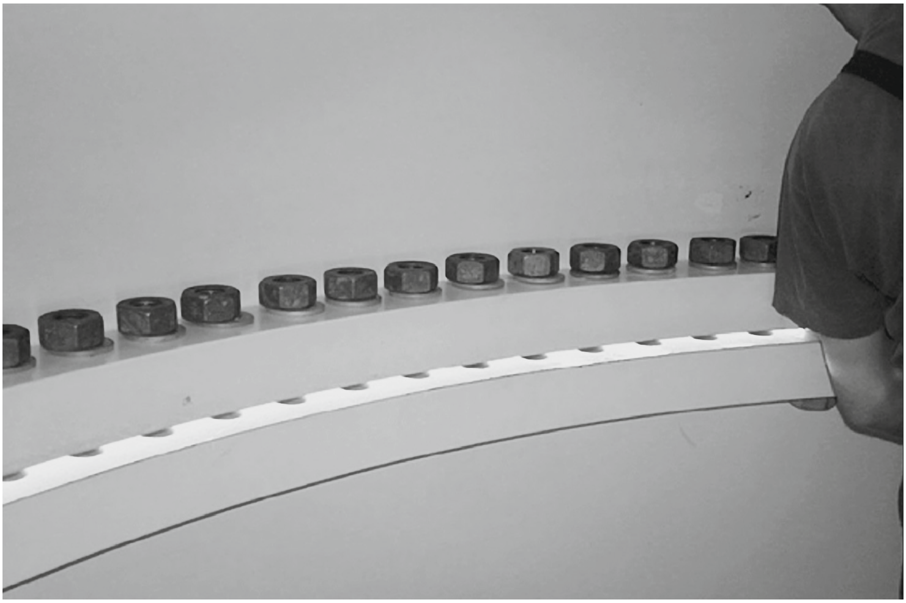


Fig. 12.13. Internal flange connection of the bolted tower sections

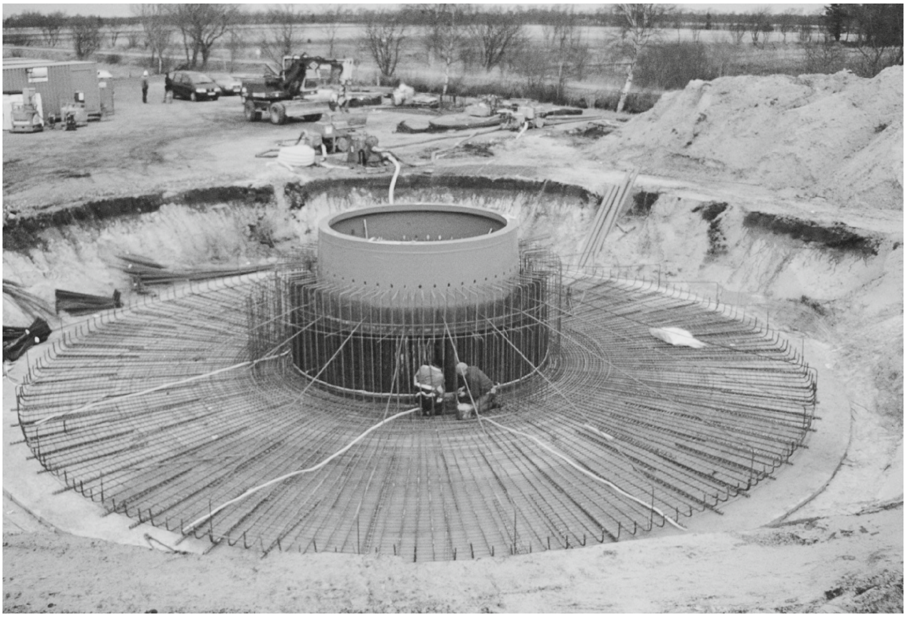


Fig. 12.14. Embedding the foundation section of a tubular-steel tower into the foundation

The outer coating consists of at least two and at most three different paint coats. Some countries or regions have regulations regarding the colour of the tower.

Manufacturing tubular-steel towers with a diameter of up to about 4 m is a conventional technology that does not make any great demands on the equipment of the manufacturers. At heights of more than 90 m, the tower base diameter becomes greater than 4.5 m and the required thickness of the steel exceeds 40 mm. Shaping the steel sheets, i.e. roll-bending them, will then require special machines which are not always available in normal structural steel works. To this is added that, due to the large diameter, the lower tower sections can no longer be transported by road. Tubular steel towers are mostly out of the question for tower heights above 100 m.

Towers of One Piece

If the transportation routes from the manufacturing plant to the installation site are without large obstacles or if on-site welding is possible, single-piece towers are also occasionally used. This saves the relatively expensive and occasionally also faulty bolted joints of the sections. The company SAM from Magdeburg produces tubular steel towers of one piece of up to a height of 97 m for Enercon for particular sites. With 5.5 m, the base part of these towers is too large for road transportation and is welded together from several segments on site. Following this, the entire tower is welded together from prefabricated sections in a horizontal position. The whole tower is then hoisted into a vertical position using a relatively small crane.

12.4.3 Climbing Aids and Internal Installations

The tower must provide for a safe ascent to the nacelle and also contain certain electrical installations, particularly the lead-down of the power transmission cables to the tower base. This requires certain internal installations. Depending on the height, a number of intermediate platforms are normally installed, typically one platform for each tower section (Fig. 12.15). Up to a height of about 60-70 m simple vertical ladders with climbing protection (safety rope or safety rail) are used for the ascent. If required by the operator, simple so-called "climbing lifts" are installed for tower heights above 80 m.

The cables for transmitting the electrical power are hanging free with a running loop in the upper tower section. The mounting elements for introducing the cables into the tower are part of the tower installations (Fig. 12.16). In addition, internal lighting is mandatory for maintenance work in the tower.

In larger turbines, it has become customary to accommodate transformer, switching panel and control lamps for reading the operating data in the tower. The transformer, in particular, requires considerable space and the installation of a ventilating and cooling system (Fig. 12.17). At the tower base, a secure entry door is required which is usually at an elevated level with respect to the building in order to prevent water from penetrating in the case of bad weather.

For some applications and depending on the internal equipment, i.e. transformers and control systems, the internal climate of the tower has to be controlled. Particularly for offshore applications, air conditioning including dehumidifying and filtering the intake

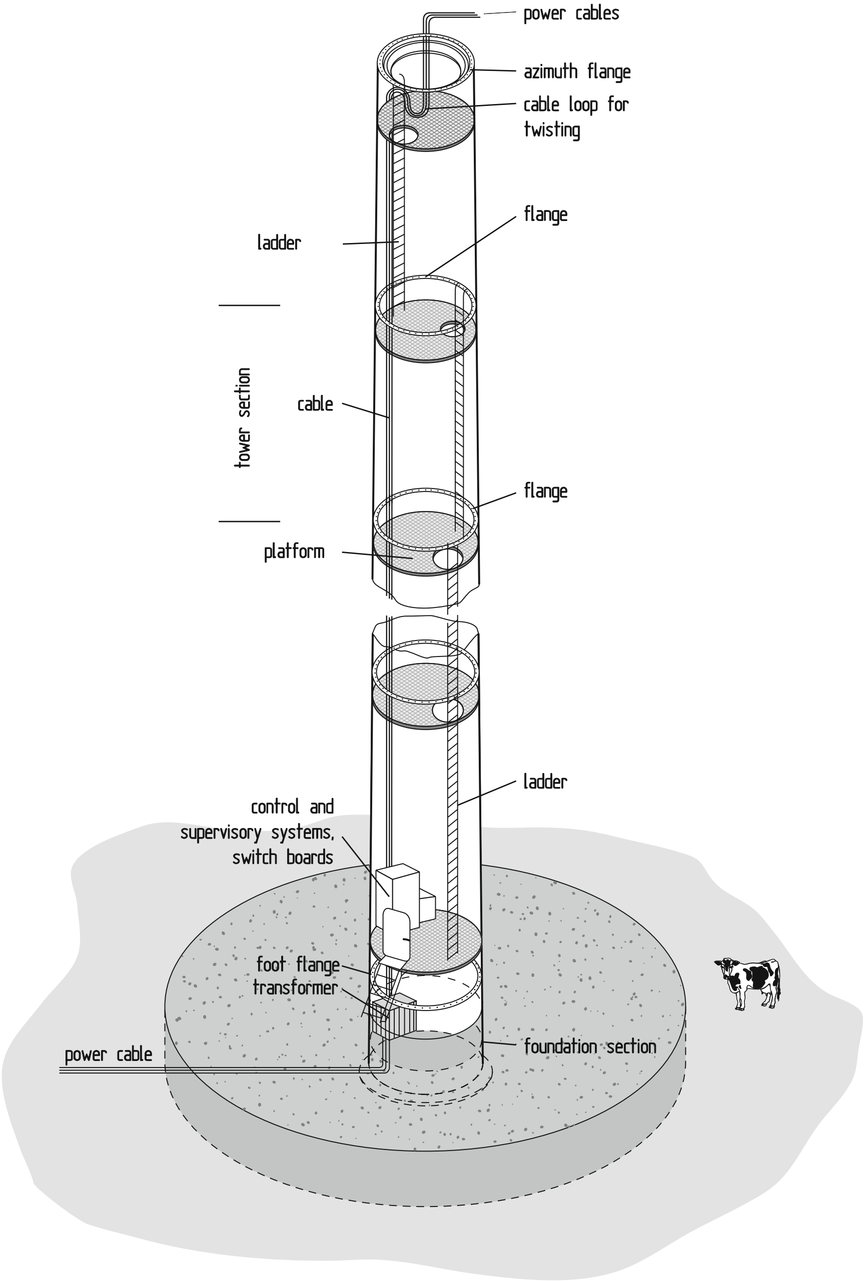


Fig. 12.15. Tubular-steel tower with installations of a large wind turbine

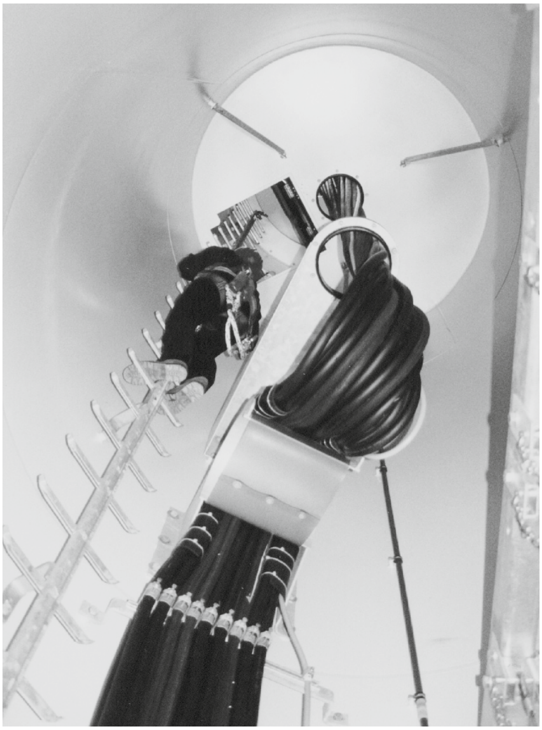


Fig. 12.16. Suspended power cables in the upper tower area of a Vestas V-66

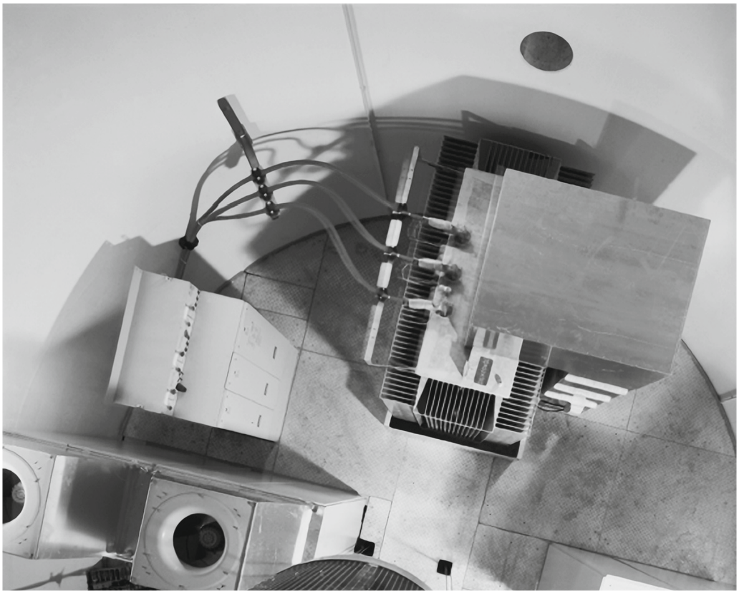


Fig. 12.17. Installation of the transformer and of the SF-6 switchgear in the tower base (Enercon)

air is necessary in order to avoid corrosion problems on the electrical and electronic equipment.

The towers of small wind turbines are of much simpler construction. In some cases, existing tubular elements from other applications can be used for the manufacture. Up to tower heights of about 15 m, the tower is climbed from the outside (Fig. 12.18). In some countries, special work protection rules and insurance requirements must be observed with respect to an external ascent so that there is a trend to provide a safe internal ascent even in relatively small turbines.

Fig. 12.18. Tubular-steel tower of a small wind turbine (Aeroman) that can be climbed from the outside

12.5 Lattice Towers

In the initial years of commercial wind energy utilisation, lattice towers were widely used in small turbines (Fig. 12.19). As their sizes increased, tubular-steel towers increasingly displaced the lattice towers. Recently, the interest in lattice towers has been rekindled, particularly in connection with large turbines with a hub height of 100 m and more.

The main argument used against the lattice towers, which were initially widely used, was the reference to their "ugliness". Considered more objectively, this objection is not as a clear-cut as it appears. Close-up, the lattice structure is not so pleasing to the eye but from a greater distance, the filigree lattice structure becomes much more transparent and begins to merge with the background. Reflection of light, which is much stronger in the case of closed structures (steel tubes), also plays a role (Fig. 12.20). Proponents of lattice towers consider the visual effect from a greater distance to be less obtrusive in the landscape than the tubular towers.

Like high-tension masts, lattice towers can be welded or bolted together from angled sections. Tubular steel struts are sturdier, however, at least for the larger elements subjected to greater loads. Although this type of construction would not be the cheapest for wind turbines, it is the better alternative. It is an indubitable advantage of lattice towers that with a given height and stiffness, the expenditure of material is less than in the case of tubular towers.

Fig. 12.19. Small wind turbines with lattice towers (1985)

The mass of the structure is less by up to 40%. In spite of the more complex assembly, this results in a cost advantage. This amounts to 10 to 20 % compared to tubular steel towers depending on the height. With increasing height the cost advantage becomes more relevant.

In particular transportation to the site is much easier in the case of very large towers. Transportation by road has reached its limits with tubular steel towers of 100 m length and tubes with diameters of more than 4.5 m. They can no longer be transported by truck on many roads whereas disassembled lattice masts can be moved to any desired site.

The much longer assembly time on site and the greater expenditure for maintenance are considered as disadvantages of lattice towers. These arguments are certainly valid but the question remains as to what extent this would influence the economic viability of the investment quantitatively. Available experience has not yet provided any reliable values in this regard, because the numbers and the life time of the existing wind turbines with modern lattice towers do not yet provide a sufficient statistical basis.

One of the highest tower of a wind turbine to date with 160 m was built for the prototype of the Fuhrländer W2E in 2006 near Magdeburg in Germany. The structure, developed by the company SeeBA, consists of special hollow-section steel rods which are joined using high-strength extension bolts (Fig. 12.21). Very high lattice towers are feasible on remote sites, where heavy lifting equipment is not available or cannot be placed without negative consequences for the environment, for example on sites in a forest.

Fig. 12.20. Wind turbines with lattice towers and with tubular-steel tower (photo Sinning)

Fig. 12.21. Lattice tower of the Fuhrländer W2E (2.5 MW) with a height of 160 m (SeeBA)

12.6 Concrete Towers

Although the use of concrete for constructing towers of wind turbines has a long tradition, at least in Denmark, the concrete towers, like the lattice towers, have been largely replaced by the tubular-steel towers prevailing today. Concrete allows very high towers to be built without this being associated with unsolvable transport problems. The long construction period, too, can be shortened today by means of various methods of using prefabricated parts.

Concrete structures are implemented in various types of construction and static principles. Curing the concrete on site is called “site-mixed concrete”. This is contrasted by the use of prefabricated concrete components that are assembled on site. The static principle is characterised by the fact whether the steel reinforcement is not prestressed or whether the reinforcement is prestressed, sometimes with special tensioning elements with the aid of which the permissible tensile stresses in the concrete can be increased. In the former case, the concrete is simple "reinforced" concrete and in the second case it is "prestressed" concrete.

The concrete towers for wind turbines are constructed in accordance with these manufacturing and static methods which in each case have their specific advantages and disadvantages. The decision for which is the best method of construction depends on the site where it is not only the position of the site with regard to accessibility that is of significance but also the availability of an appropriate infrastructure. This, too, influences the cost to no minor degree so that cost comparisons between concrete towers should not be made in an abstract manner either with regard to the different types of concrete construction or in comparison with tubular-steel or lattice towers. The same also applies to the construction time, which is also a cost factor.

Site-mixed concrete

With the traditional reinforced-concrete type of construction, the concrete is either mixed in liquid form on site or delivered in special vehicles as is done in most cases today. The concrete is poured into a timber form into which the steel reinforcement has first been inserted in the form of a steel wire mat. In this formwork, the concrete hardens so that the required shape emerges when the boarding is removed.

This type of construction, called “site-mixed concrete”, is also used for producing towers of wind turbines. The formwork is pushed upward step by step as climbing or sliding form (Fig. 12.22). Since the lower part must always have set before a new stage can be placed on top, the construction time is very long. In addition, the setting of the concrete is dependent on temperature, which is why it is not possible to work in severe frost conditions in spite of the antifreeze additives used today. In addition, the site-mixed type of construction also requires a corresponding building infrastructure with regard to the production or delivery of the concrete. For this reason, the method is normally not economic for one or only a few turbines. Site-mixed construction can only be an economical alternative for a wind park with a large number of turbines. Nevertheless, the tower of the prototype of the Enercon E-112 with a height of 120 m was built with site-mixed concrete (Fig. 12.23).

Towers with site-mixed concrete can also be constructed as prestressed-concrete towers. The prestressed-concrete type of construction originally comes from bridge building and is also used for other concrete components subjected to high dynamic loads. In this process, the steel reinforcement or the special tensioning elements (ropes or steel rods) are introduced into the concrete structure and prestressed, that is to say a compressive stress is generated in the concrete body so that tensile stresses which, for example, are caused by a bending load are largely cancelled. Because of the additional tensioning elements, prestressed concrete structures are comparatively expensive. Their load-bearing capacity is greater than that of normal reinforced concrete and it is also possible to influence stiffness (natural frequency) within certain limits by varying the pre-stressing.

Fig. 12.22. Construction of a tower for an Enercon E-66 with site-mixed concrete (Enercon)

Some large experimental turbines of the Eighties were installed on prestressed concrete towers (WTS-75, Aeolus-I and LS-1). For cost reasons, prestressed concrete towers of site-mixed concrete are normally not considered for commercial wind turbines.

Fig. 12.23. Site-mixed concrete tower of the Enercon E-112 prototype, 120 m height

Prefabricated concrete towers

To avoid the major disadvantage of the site-mixed type of construction, the long building time, various prefabrication methods have been developed in recent years. This makes it possible to shorten the building time considerably. A further advantage of prefabrication is that this makes it possible to build very high towers without causing insurmountable transportation problems as in the case of tubular-steel towers.

One prefabrication type of construction that is more frequently used for small and medium-sized wind turbines is the use of *centrifugally cast concrete towers* [5]. The tower parts of up to 35 m length and 50 t weight are manufactured on special spinning machines and are also prestressed during this process (Fig. 12.24). The concrete and the reinforcement are introduced into moulds and spun. During this process, the reinforcement can also be prestressed, resulting in a prestressed-concrete type of construction. The effect of the centrifugal forces during the spinning produces very dense concrete structures that are well suited to absorbing dynamic loads. The individual tower segments are transported to the site and placed on top of one another. A tower of, for example, 50 m height consists of two or three segments and smaller towers are made of one piece.

Another method of prefabricating concrete towers is based on segments prefabricated in the factory [6]. The segments of approximately 3.8 m length are produced with conventional formwork in the plant (Fig. 12.25). The segments are then placed on top of one another on site and "bonded" with a concrete/resin mixture. The individual segments are provided with empty tubes distributed over their circumference into which tensioning ropes are inserted during the construction. These are used for additionally fixing and tensioning the segments. This type of prefabricated prestressed-concrete construction is also suitable for very high towers of 100 m and more (Fig. 12.26).

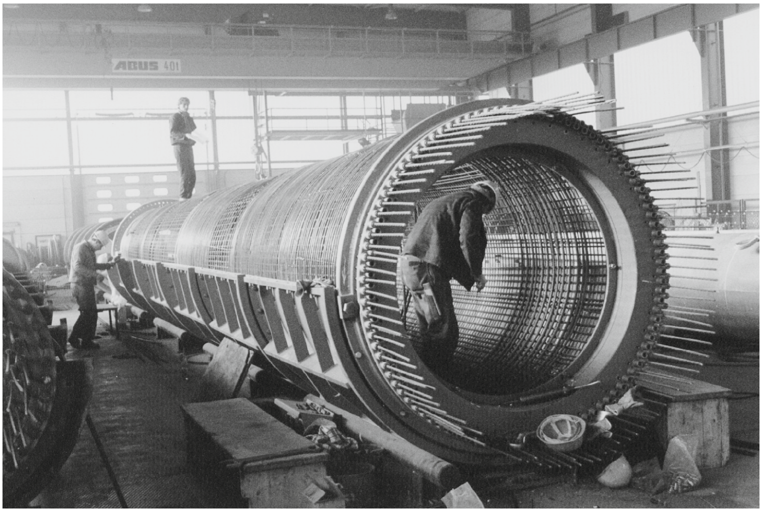


Fig. 12.24. Manufacture of centrifugally-cast concrete towers (PFLEIDERER)

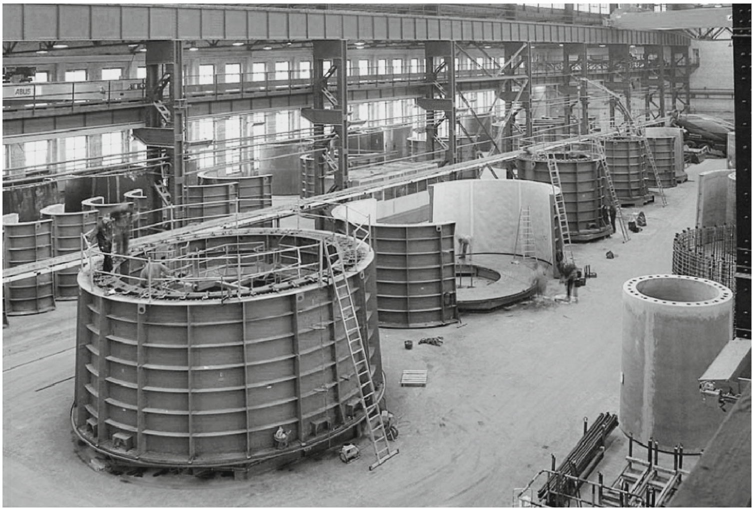


Fig. 12.25. Production of tower segments for a prefabricated prestressed-concrete tower (WEC-Turmbau)

Fig. 12.26. Erection of a prefabricated prestressed-concrete tower for an E-66 wind turbine (WEC-Turmbau)

12.7 Concrete-Steel Hybrid Towers

More recently, the trend to ever higher towers at inland sites has increasingly placed the hybrid construction into the foreground of interest. Cantilevered tubular steel towers of more than 100 m height are scarcely transportable so that either lattice towers or hybrid concrete/steel constructions are used. These towers consist of slender, mostly prestressed, concrete parts in the lower region and of tubular steel segments in the upper region (Figs. 12.27 and 12.28).

The design and construction is more complex, but some important advantages are achieved. The lower mass of the steel part in the upper section reduces the increase of mass with height and the eigenfrequency of the tower does not decrease in the same way as it is for a pure concrete construction. The dynamic characteristics of hybrid towers with more than 100 m height, are more favourable. It is possible to build relatively stiff towers with heights up to 150 m and more.

Fig. 12.27. Hybrid tower of a Repower 3.4 MW wind turbine, height 123 m (Max Bögl Group)

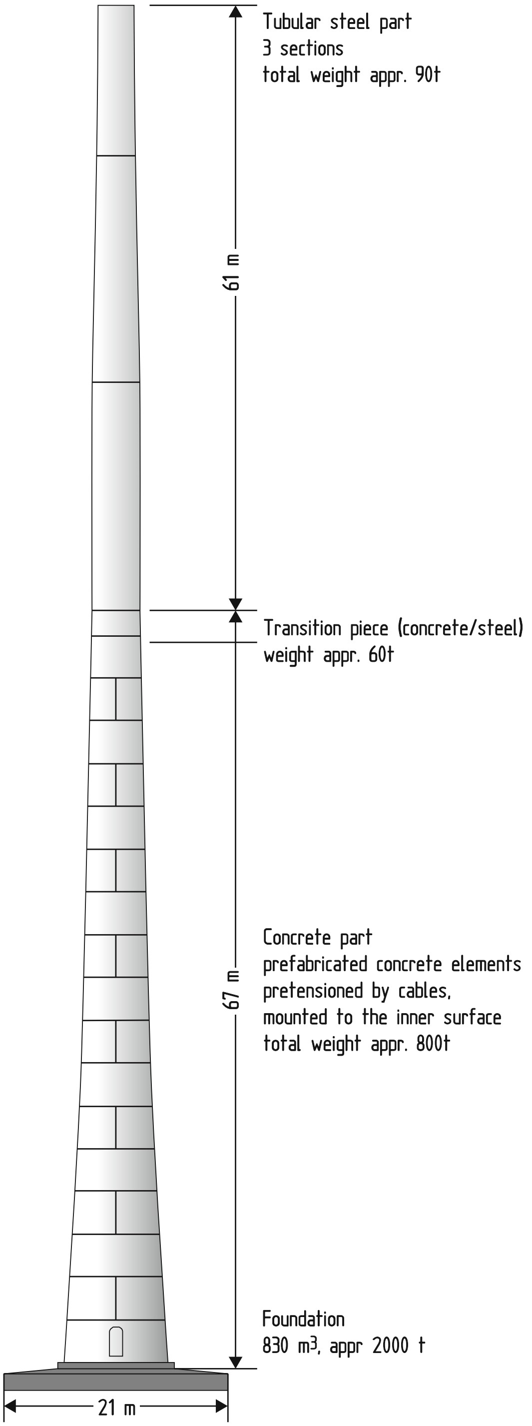


Fig. 12.28. Constructional concept of the concrete/steel hybrid tower designed for the Repower 3.3 MW wind turbine (Max Bögl Group)

12.8 Comparison of Different Tower Concepts

The various types of tower design invite a comparison. Even if the most important criterion, the costs of construction, cannot always be assessed in a generally applicable form, the most significant differences will still become apparent in a comparison. The comparison was carried out for the experimental WKA-60 turbine (Table 12.29). The characteristics of this turbine with respect to the tower head mass no longer correspond to current conditions but do not materially affect the differences between tower concepts.

The tubular-steel towers are dimensioned as soft towers with a first natural bending frequency of about 1.5 P just like the prefabricated prestressed-concrete tower. Site-mixed unstressed concrete towers are designed with a higher stiffness of approx. 2.5 P.

When the calculated masses are compared, it is found that, although a free-standing cylindrical tube with a constant wall thickness may be simple to manufacture, it is in no way optimal. With the given height and stiffness requirements, the overall mass can be reduced decisively with other configurations. Broadening the base of a free-standing steel tower conically is obviously helpful in achieving the required stiffness with a reduced overall mass. Free-standing tubular-steel towers with this geometry can, therefore, be found in most wind turbines.

Diameter and mass can be reduced significantly when the tower is anchored by guys. The disadvantages of this concept are the cost of the guying cables and the additional foundations. It is, therefore, questionable whether guyed tubular-steel towers are in fact an economical solution (Chapt. 12.1). Moreover, their stiffness is not very high with respect to their first natural torsion frequency, since the guys do not have a torsion-stiffening effect.

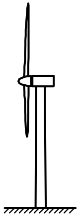
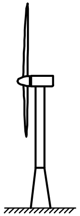
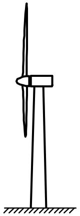
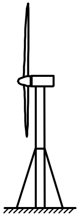
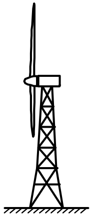
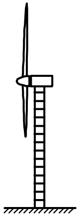
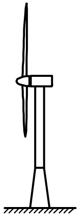
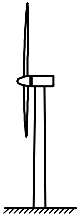
The constructional mass of the tower variants can be calculated with good accuracy whereas the costs of construction can only be estimated roughly (see Chapt. 18.8). In the case of concrete towers, a considerable cost range of about 400-600 $US per tonne is obtained for the above reasons. The cost relations specified in Table 12.29 show the differences between the calculated variants.

Although the overall mass of concrete towers is four to five times higher than that of steel towers, the differences in construction cost are obviously not serious. In practice, the lower specific material cost of the concrete compensates for the greater overall mass. On the whole, concrete designs are more cost-effective in this comparison. This especially applies when prefabricated concrete tower segments are used. However, concrete constructions are frequently not feasible. When there is no suitable local manufacturer, high costs of transport incurred for the heavy concrete components will cancel out the cost advantage.

The production costs of the calculated lattice tower variant are also comparatively favourable. The costs of the lattice design are up to 20 % less than the costs of a tubular-steel tower. However, the higher assembly and maintenance costs must not be overlooked in this comparison.

It should be noted that the results of the cost comparison may change with increasing steel raw-material costs. The prices for steel plates have shown ups and downs particularly in the last ten years.

Table 12.29. Comparison of steel and concrete tower designs for the WKA-60 experimental wind turbine

Wind Turbine	Steel					Concrete		
Rotor: 3 blade Diameter: 60 m Rotor speed: 23 rpm Towerhead mass: 180 t Hub height: 50 m Tower height: 46.6 m	 cylindrical	 cylindrical with conical base	 conical	 cylindrical with guys	 lattice	 prefabricated prestressed	 reinforced	 prestressed
1st bending eigenfrequency Hz	0.567	0.577	0.570	0.551	0.60	0.65	0.941	0.947
Multiple of rated rotor speed P	1.48	1.51	1.49	1.44	1.57	1.70	2.45	2.47
Upper diameter m	3.5	3.5	3.5	2.5	3.5	3.5	3.5	3.5
Lower diameter m	3.5	7.1	4.4	2.5	11.6	3.5	8.4	5.5
Wall thickness mm	55 ÷ 15 staged	25/15 staged	30/15 staged	20/15 staged	16/10	520/250 staged	300	300
Mass								
- Tower structure t	150	120	111	40	110	465	485	477
- Equipment t	22	22.5	22.8	20	22.5	21	22.5	22.5
Total mass t	172	142.5	133.8	60 guys	ca. 120	486	507.5	499.5
Appr. cost relation %	100	90	85	95	70	60	60	80

12.9 Increasing the Height with Different Tower Concepts

In the initial phases of modern wind energy utilisation, the larger wind turbines were being built with comparatively low towers. The large experimental turbines of the Eighties had in many cases tower heights which were less than the rotor diameter, for example the turbines of the American MOD series (see Chapt. 2.6). As the utilisation of wind power advanced into weaker inland wind regions the height of the towers increased. Higher towers with 100 m and more were found to be a decisive factor for the economical utilisation of wind energy under the given conditions. On the other hand, costs will, naturally, rise with increasing tower height. However, the rise in costs differs distinctly depending on the type of tower construction [7].

Tubular steel towers

The structural mass of self-supporting tubular steel constructions increases greatly with increasing height (Fig. 12.30). They thus become disproportionally expensive. To this is added that the tower base sections reach their limit of transportability at approx. 4.5 m for road transport (passing under bridges). But to reduce the increase of mass with height the base diameter of the towers should be larger than 4.5 m. That means the base section has to be composed by sectional shells. Very recent tower concepts are steel towers which are completely composed by slim u-shaped shells forming a polygonal section [8]. Furthermore the stiffness of very high towers has to be reduced below the 1-p excitation [see Chapt. 7.5.1]. By applying those design features steel tube towers are built up to 140 m height without losing their economics.

An argument against very high steel towers are the costs of raw material. These costs become a decisive factor, but the costs for structural steel have been subject to considerable fluctuations in recent years. After a drastic rise in the years from 2005 to 2008, the prices dropped again from 2009 onward as a consequence of the world-wide economic recession. In 2009, the specific constructional costs for tubular-steel towers were about 2 Euro per kilogramme (Fig. 12.31). For the future it has to be expected that steel prices will increase continuously.

Lattice towers

The lattice type of construction is more suitable for achieving tower heights of more than 100 m. The increase in structural mass with increasing height is distinctly less in lattice towers (Fig. 12.30). A lattice tower with a height of 150 m has virtually the same structural mass as a tubular-steel tower of 100 m height. In general, the structural mass of lattice towers is only about 60 % of that of comparable tubular-steel towers. However, the cost advantage shrinks to about 20 % because of the more complex processing and assembly up to a height of 100 m. Above that, the cost advantage becomes more obvious. But it has to be considered that the costs for maintenance are higher compared to the other tower constructions.

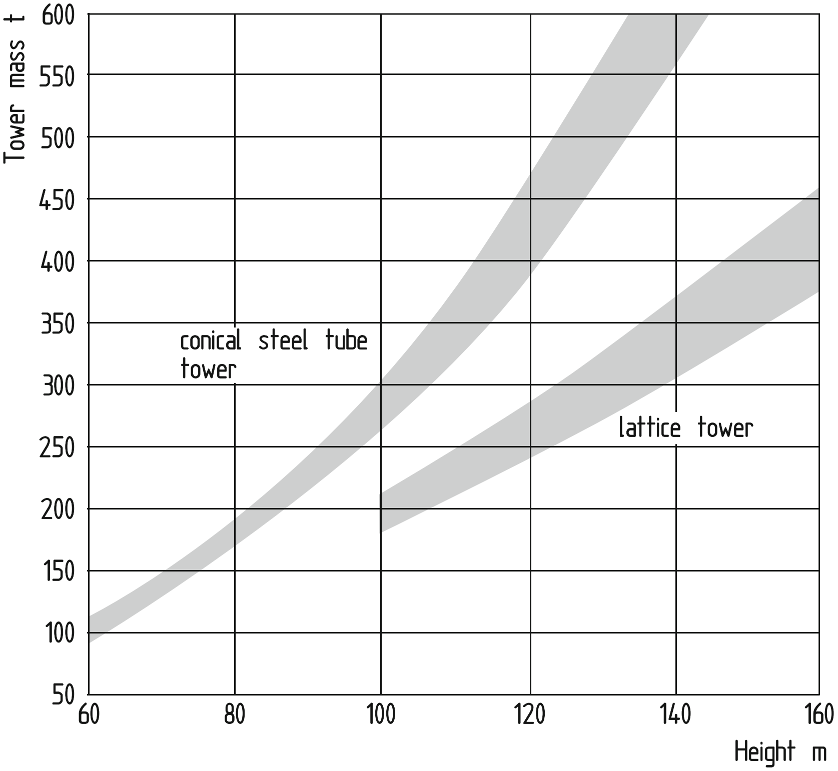


Fig. 12.30. Increase in the structural mass of tubular-steel and lattice towers with height for a 3 MW wind turbine, rotor diameter 100 m

Concrete towers

Although the mass of concrete towers is about four times higher compared to steel towers, the increase with height is less steep. With regard to the costs, the concrete type of construction shows a relatively strong dependence on the local situation. Closeness to a concrete mixing plant and the logistics involved play an important role. At present, concrete towers are produced with specific costs of between 400 to 600 $US per tonne.

The dynamic characteristics of pure concrete tubes are the limiting factor with respect to the increasing height. The first bending eigenfrequency lowers due to the mass in the upper section. Considering the rotational speed of the rotor and thus the range of the exciting frequencies from the rotor, it becomes very difficult to avoid resonances (see Chapt. 12.7).

Hybrid towers

The hybrid type of construction seems to be the best solution for limiting the increase in costs with height and to cope with the dynamic characteristics. Hybrid structures are more expensive, however, in the lower height range below 100 m and are, therefore, rarely found there. Enercon, for example, uses a hybrid construction of a prestressed-concrete tower, consisting of prefabricated elements, together with a tubular steel section of about 20-25 % of the constructional height for their towers with more than 100 m height.

Figure 12.30 shows the tendency how the tower mass increases with the height for tubular steel towers and lattice tower. The increase of costs for the steel constructions depend very much of the raw materials costs. The estimate in Figure 12.31 is based on the steel price of 2009.

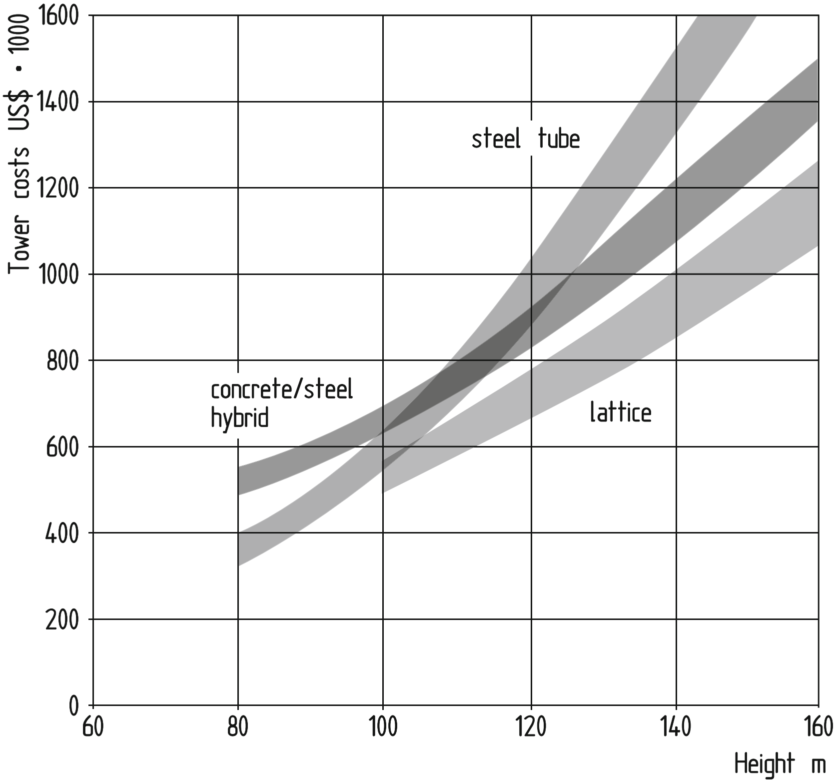


Fig. 12.31. Tendencies of tower costs in dependence on height for a 3 MW wind turbine with a rotor diameter of 100 m (2011 steel prices)

Optimal tower height

So that the optimum tower height can be determined from the point of view of economics, the increase in costs of the higher tower must be compensated for by an increased energy yield. Certainly the increase of wind speed with height depends on the wind characteristics on the site. The vertical wind profile at an offshore site demands a lower optimal height of the tower compared to an inland site.

Calculating the increase in wind velocity with height for heights above 100 m is associated with some uncertainties (see Chapt. 13). In the meantime, however, experience is available from the operation of thousands of inland wind turbines at different rotor hub heights. Accordingly, an average increase in energy yield of about 0.7% per meter altitude can be expected in the range from 100 to 150 m in the North German interior. The value fluctuated between 0.5 to 1% depending on topographic conditions. This statistically proven experience can be used for calculating the amortisation period of a higher tower but one should always take into consideration an individual case for the reasons mentioned. The result will become clear from the following example:

A large turbine with a rotor diameter of 90 m and a power rating of 2.5 MW generates about 5 million kWh per year at a height of 100 m at a typical mean inland wind velocity of 6.5 m/s, taking into consideration the usual loss deductions from the calculated gross value. The costs for a 100-m high lattice or concrete tower are about US$ 550,000. A tower with a height of 140 m will cost about US$ 1.1 million. The difference in cost is thus US$ 550,000. Since the increased costs for the foundation and the assembly also have to be taken into account, this value is multiplied by a factor of 1.4 so that additional investments of US$ 770,000 have to be financed. With an assumed amortisation period of five years, the principal repayments calculated as annuity are annually 23.1 % of the investment sum at an interest rate of 5 %, corresponding to an amount of about US$ 180,000 per year.

According to the rule of thumb of 0.7 % per meter height, the increased energy yield due to the increase in rotor hub height from 100 m to 140 m is 28 %. Based on an electricity price rate of 0.09 US$/kWh, an additional income of US$ 126,000 is achieved annually, not quite enough for compensating for the principal repayments of US$ 180,000. The amortisation period for the higher tower is thus about six years which is a completely appropriate period for commercial investments.

The result of this rough calculation also shows that there is no actual economic optimum for the tower height. If a longer amortisation period is allowed for the additional costs for the higher tower, an even higher tower height also works out. In practice, other aspects are naturally also determining for the choice of tower height. Above a certain height, the assembly and transportation problems become more and more difficult to solve also for concrete and lattice towers. In many regions, height restrictions apply to wind turbines, for example to a total height of 150 m. With a 90 m rotor, this means a maximum permissible tower height of 105 m.

12.10 The Foundation

The foundation of the tower is determined by the size of the wind turbine and by local ground conditions. With respect to the loading, it is primarily, the highest thrust loads of the rotor acting on the wind turbine which must be considered.

The first load case which must be checked is that involving the highest loads during operation (Fig 12.32). In operation, the maximum tilting moment for the foundation is determined by rotor thrust. In turbines with blade pitch control, rotor thrust reaches its peak at the rated power, whereas in stall-controlled turbines it continues to increase even after the rated power has been reached (Chapt. 5.3.1).

A second load case relates to wind turbine at maximum wind speed. The determining factor is here the highest assumed wind speed, the so-called “survival wind speed” (Chapt. 6.3). However, the technical concept of the wind turbine also plays a certain role. Turbines with stall control do not provide the option of feathering the rotor blades so that comparatively high stand-still loads can occur with his design, a fact which is of significance in the dimensioning of the foundation and thus in the costing.

The properties of the soil certainly play a role for the type and the dimensions of the foundation. Particularly on sites with weak soil i.e. on the shore of the North Sea, the foundation has to be supported by piles, which transfer the loads into deeper more solid ground-layers.

Furthermore the water flow in the ground has to be considered. The ground water causes considerable bouyancy on the foundation. The foundation needs more mass, so-called “bouyancy-foundation”. The area needed for the foundation of a wind turbine with a rotor diameter of 80 to 100 m and a tower height of 100 m amounts to about 200m². The geometric shape can be circular, octagonal or sometimes cross-shaped.

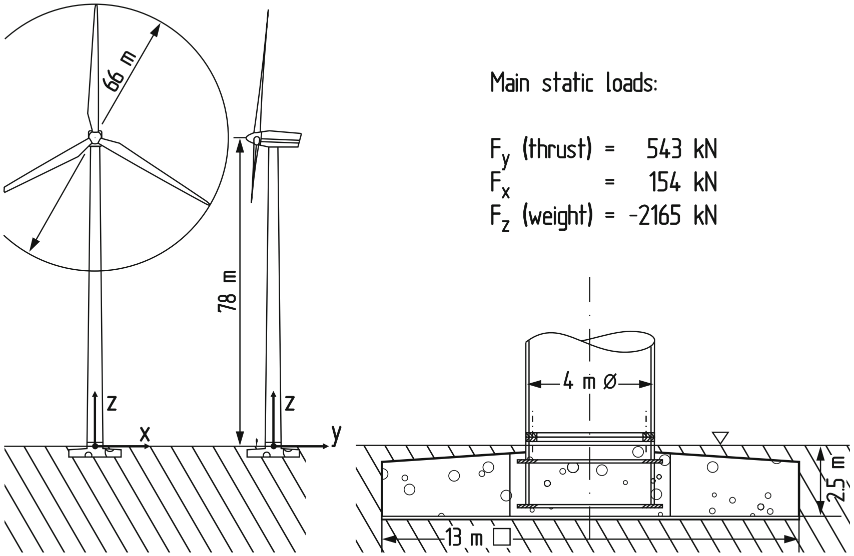


Fig. 12.32. Dimension-determining loads and dimensions of the foundation of a large wind turbine (Vestas V-66 as an example)

Slab foundations

The slab foundations, often called the *standard foundation,* are circular or rectangular or polygonal footings. The tubular-steel towers are anchored by a foundation section joined to the steel reinforcement of the concrete (Fig. 12.33). The required mass and the dimensions of the slab are determined by the overturning moment of the structure. This is resisted by the weight of the turbine, the tower and the foundation itself.

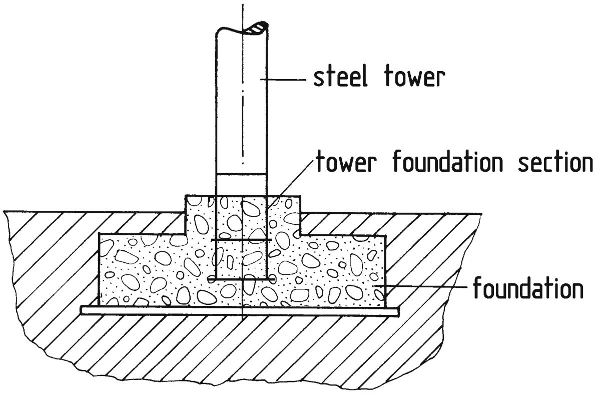


Fig. 12.33. Standard foundation (slab foundation) for tubular-steel towers

Pile foundations

Pile foundations for weak soils have a bedplate sitting on piles which transfer the loads into load-bearing ground layers. For this purpose, prefabricated "ram piles" are used (Fig. 12.34). Pile foundations are necessary, for example, in the German coastal marshland areas near the North Sea.

In these areas, the solid sand layers of the continental shelf are in some cases located at a depth of 20 to 25 m. The piles, up to 20 of which are required for a medium-sized turbine, are of corresponding length to ensure the load-carrying capability of the foundation. This increases the costs of the foundation by 30 to 50 %.

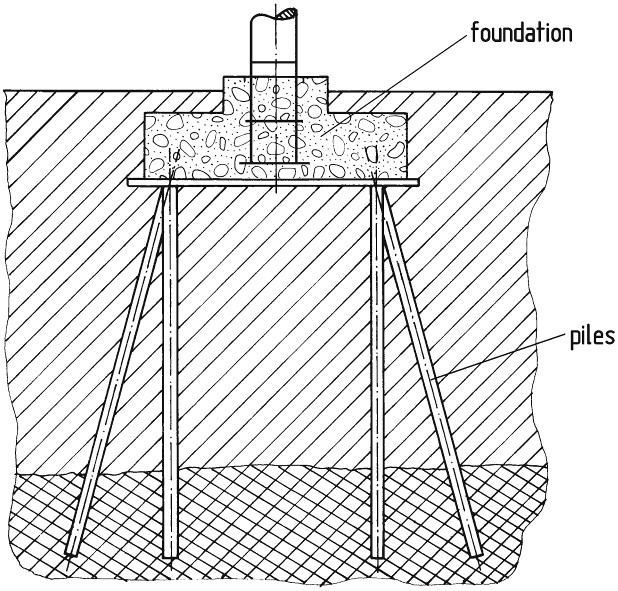


Fig. 12.34. Foundation with piles (pile foundation)

Concrete material and foundation section

As a rule the foundation of wind turbines are constructed of Category B25 concrete according to German classification. Special attention has to be paid on the quality of the construction work. Due to the heavy loading on the foundation cracks can occur, particulary on the surface, after some time. Penetrating and freezing water causes severe damages. Many turbine suppliers include the foundation in their delivery so that the foundation is covered by their warranty they grant to the custumer. It is common practice, a formwork is set up in the foundation pit and the steel reinforcement is plaited before the concrete is poured into the pit (Fig. 12.35).

Integrating the foundation section, to which the bottom flange of the tower is joined, requires some experience. The flange of the foundation section must be placed in a horizontal and level position with only a small tolerance to prevent the tower from slanting. In the foundation of a wind turbine of the 500 kW class with an foundation section flange diameter of approximately 3.6 m, the maximum allowable deviation from the horizontal is in the range of ± 2 mm.

It is obvious that the *soil consistency* or, more precisely, the “clamped stiffness” of the tower in the ground, has an influence on the natural bending frequency. This influence is small on solid ground and may be neglected in a first approximation. In very loose soil, however, this does not apply in every case. Using the example of a simple bed plate, Figure 12.36 shows the order of magnitude of a reduction to be expected in the first natural bending frequency of the system.

Fig. 12.35. Construction of the foundation and integrating the foundation section of the tower

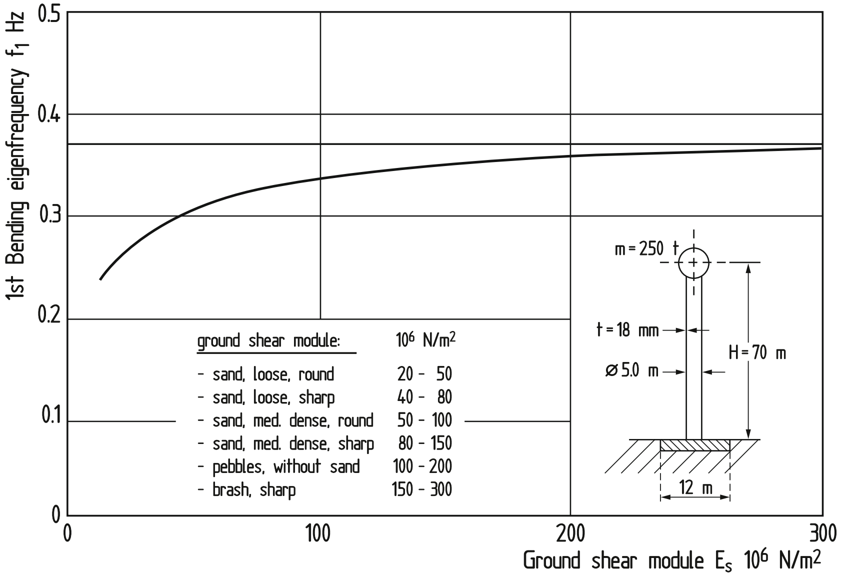


Fig. 12.36. Influence of soil consistency on the first natural bending frequency of a tower/nacelle configuration

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