

Impact of geometrical and environmental parameters on wind action in telecommunication monopoles

Impacto de parâmetros geométricos e ambientais na ação do vento sobre monopolos para telecomunicações

João Filipe
Rui Travanca
António Manuel Baptista
Manuel Pipa

Abstract

This paper presents and discusses the results obtained in a parametric study to quantify the relative influence of the most important parameters used for the definition of wind action in telecommunication monopoles, such as the location of the structure and the geometric characteristics of the shaft, as well as the existence of ancillaries mounted on the structure, i.e. antennas, headframes, ladders, and/or feeders. Following their relative influence analysis, a global investigation on these parameters is also presented and discussed, as well as more specific subjects, e.g. the interference effect between antennas and headframes, the shield effect between the ladder and the shaft, and the block effect in feeders.

Resumo

Este artigo apresenta e discute os resultados obtidos num estudo paramétrico para quantificar a influência relativa dos parâmetros mais importantes utilizados para a definição da ação do vento em monopolos para telecomunicações, como a localização da estrutura e as características geométricas do fuste, assim como a existência de equipamentos auxiliares montados na estrutura, i.e. antenas, interfaces de antenas, escadas e/ou caminhos de cabos. Seguidamente à análise da sua influência relativa, é também apresentada e discutida uma análise global destes parâmetros, assim como aspetos mais específicos, como por exemplo o efeito de interferência entre as antenas e as interfaces de antenas, o efeito de escudo entre as escadas e o fuste, e o efeito de bloco nos caminhos de cabos.

Keywords: Monopoles / Telecommunications / Wind action / Parametric study / Eurocodes

Palavras-chave: Monopolos / Telecomunicações / Ação do vento / Estudo paramétrico / Eurocódigos

João Filipe

Doutorando
Laboratório Nacional de Engenharia Civil
Lisboa, Portugal
 0009-0009-9531-1381
jfilipe@lnec.pt

Rui Travanca

Engenheiro Sénior
Universidade de Aveiro
Aveiro, Portugal
 0000-0002-6229-6324
rui.travanca@ua.pt

António Manuel Baptista

Investigador Principal Aposentado
Laboratório Nacional de Engenharia Civil
Lisboa, Portugal
ambaptista@lnec.pt

Manuel Pipa

Investigador Principal Aposentado
Laboratório Nacional de Engenharia Civil
Lisboa, Portugal
mpipa@lnec.pt

Aviso legal

As opiniões manifestadas na Revista Portuguesa de Engenharia de Estruturas são da exclusiva responsabilidade dos seus autores.

Legal notice

The views expressed in the Portuguese Journal of Structural Engineering are the sole responsibility of the authors.

FILIPPE, J. [et al.] – Impact of geometrical and environmental parameters on wind action in telecommunication monopoles. **Revista Portuguesa de Engenharia de Estruturas**. Ed. LNEC. Série III. n.º 27. ISSN 2183-8488. (março 2025) 51-66.
<https://doi.org/10.34638/rpee-sIII-n27-004>

1 Introduction

Over the last few decades, the demand for communication structures has increased due to the requirements for their use in the telecommunication sector. With the advent of mobile communications, this demand has become even greater. Unfortunately, the number of failures observed in telecommunication structures is high when compared with other structures of equal economic and social importance [1], [2], [3]. These structures are used for supporting antennas and other equipment that enables the emission of electromagnetic waves for mobile communication purposes. There are several types of communication structures, with diverse structural solutions and types of mounted equipment. Though monopoles are widely used, the current methods for their analysis and design are outdated and/or inappropriate. Several failures associated with this type of structures were observed and reported [1], [2], [3]. Thus, a detailed review of both the methods of analysis and loads definition becomes imperative. Since wind action plays a fundamental role in the behaviour of this type of structures, it is important to know which parameters have a critical influence on the analysis and design.

However, it should be regarded that the results obtained in this study only show an approximation to the real wind action influence on the structural behaviour of a telecommunication monopole, when considering the individual effects of each of several different parameters, according to the methodology stipulated in Eurocode 1, Part 1-4 (EC1-1-4) [7].

2 Materials and methods

In the present study, four existing monopoles installed in Portugal were analysed [4], [5], i.e. two 30-metre-high monopoles and two 40-metre-high monopoles; each two monopoles with the same height, include a monopole with a circular cross-section shaft and a monopole with a polygonal cross-section shaft (see Figure 1). The geometric characteristics of the studied monopoles are shown in Table 1. The section number presented in Table 1 goes in ascending order, from the base to the top of the monopole. All the results presented in this article are concerned with monopole M2, which is the most representative of the studied monopoles, except for the cases in which it is stated explicitly.

Wind action was defined according to the quasi-static approach presented in Eurocodes [6], [7], [8] and using discrete models with the application of the acting forces at 1 metre intervals from the base of the structure to the top. The wind action at a certain interval was obtained through the sum of the wind forces (F_w) applied to each separate component (monopole and equipments), calculated through equation (1) as stipulated in EC1-1-4 [7]:

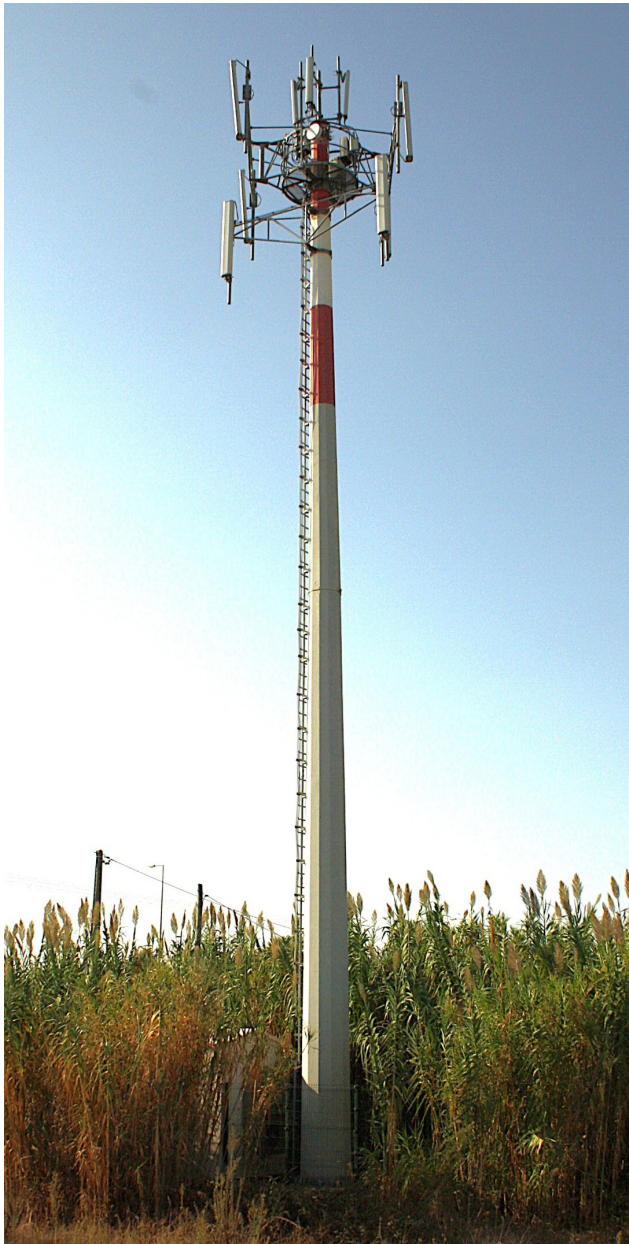
$$F_w = c_s c_d \cdot c_f \cdot q_p(z_e) \cdot A_{ref} \quad (1)$$

in which $c_s c_d$ is the structural factor, c_f is the force coefficient, q_p is the peak velocity pressure, z_e is the reference height for external wind action and A_{ref} is the reference area.

The calculation of all the necessary parameters for the calculation of the wind force (F_w) was made in accordance with EC1-1-4 [7].



a) Monopole with a circular cross-section



b) Monopole with a polygonal cross-section

Figure 1 Photographs with examples of the two cross-section type monopoles being studied

Table 1 Geometric characteristics of the studied monopoles

Monopole name		M1	M2	M3	M4
Cross-section type		Circular	Circular	Polygonal	Polygonal
Cross-section sides		–	–	16 sides	16 sides
Monopole height		30 m	40 m	30 m	40 m
Number of sections		3	4	3	4
Total mass		3108 kg	5344 kg	2273 kg	3975 kg
Section 1	Height	6,0 m	6,0 m	6,0 m	11,5 m
	Thickness	7,92 mm	9,52 mm	6,00 mm	6,00 mm
	Base diameter	812,8 mm	1016,0 mm	990,0 mm	1304,0 mm
	Top diameter	812,8 mm	1016,0 mm	852,0 mm	1044,0 mm
Section 2	Height	12,0 m	12,0 m	12,0 m	6,5 m
	Thickness	7,92 mm	7,92 mm	5,00 mm	6,00 mm
	Base diameter	609,6 mm	812,8 mm	852,0 mm	1044,0 mm
	Top diameter	609,6 mm	812,8 mm	576,0 mm	897,0 mm
Section 3	Height	12,0 m	12,0 m	12,0 m	7,0 m
	Thickness	6,35 mm	7,92 mm	4,00 mm	5,00 mm
	Base diameter	406,4 mm	609,6 mm	576,0 mm	897,0 mm
	Top diameter	406,4 mm	609,6 mm	300,0 mm	739,0 mm
Section 4	Height	–	10,0 m	–	15,0 m
	Thickness	–	6,35 mm	–	4,00 mm
	Base diameter	–	406,4 mm	–	739,0 mm
	Top diameter	–	406,4 mm	–	400,0 mm

Whenever EC1-1-4 [7] recommended a value for the calculation of a certain parameter, that value was adopted for the definition of the wind action in the present work. The elastic forces and natural frequencies were obtained by using the SAP2000 software from Computer and Structures, Inc. [9].

Regarding the definition of the structural factor ($c_s c_d$) of the monopole, it was considered the rules defined in EC1-1-4 [7] for vertical constructions and steel chimneys, and a structure width equal to the monopole diameter at the determined reference height (z_s). The necessary monopole structural response parameters for the definition of $c_s c_d$, were obtained by using the SAP2000 [9]. In the case of the equipments (antennas, headframes, ladders and feeders), $c_s c_d$ was defined as equal to 1,0.

The force coefficient (c_f) and the peak velocity pressure (q_p) defined for each monopole surface section were calculated for the largest height of the section and applied at the middle height of the section. The same method was considered for equipments placed along the monopole height, such as ladders and feeders. In the case of singular equipments (antennas and headframes), c_f and q_p were calculated and applied for the specific height that those equipments are placed. Regarding the definition of the force coefficients (c_f) for the

monopole, the calculation of the effective slenderness (λ) was made considering a type 2 structure, in accordance with Table 7.16 of EC 1-1-4 [7]. The definition of the force coefficients (c_f) for the equipments was made whether using information given by the producers (typically in the case of the antennas) or by using alternative methods given in EC 1-1-4 [7], that takes into account the geometry and the applied wind direction on the equipments.

Although this study is focused on structures located in Portugal, and consequently on wind action definition in accordance with the Portuguese Annex of the Eurocode 1-1-4 (EC1) [7], the results presented and further discussions are valid for other countries, since the Portuguese normative impositions only interfere with the values of the basic wind velocity.

In the numerical analysis here presented and discussed, the influence of loss of stiffness due to e.g. soil-structure interaction and/or connections influence will not be addressed, even if it is not negligible for this type of structure; indeed, this aspect is currently subject to further investigation [3], [10].

In the analyses performed, the maximum values for four key outcome variables will be compared and discussed regarding the influence of the different parameters being addressed. These four key outcome

variables are: i) shear force (V_0) and bending moment (M_0) obtained at the base of the monopole; and ii) horizontal displacement (u_1) and rotation (θ_1) at the top of the monopole. Their values have been evaluated by means of a first order elastic analysis of the monopole structure.

3 Results and discussion

3.1 Influence of the monopole location

The location of the structure influences the definition of wind action by means of the change of the peak velocity pressure [6], [7], [8]. Accordingly, the peak velocity pressure is influenced by three key parameters: i) the zone affecting basic wind velocity; ii) the terrain category affecting terrain parameters to be considered; and iii) the terrain orographic that could lead to the increase of wind velocities. In the following sections, the results obtained from the analysis of each of these parameters will be presented.

3.1.1 Influence of the zone and terrain category

According to the Portuguese annex for the EC1 [7], there are two different zones to be considered (zone A and zone B), depending on the altitude and distance from the sea coast, and four terrain categories (I, II, III and IV) that depend on the terrain roughness and therefore on the interference with regular air flow, as presented in Table 2 and Table 3.

Table 2 Zone definition according to the Portuguese annex for the EC1 [7]

Zone A	The Portuguese general territory except for the regions belonging to zone B.
Zone B	Azores and Madeira islands and mainland regions located not further than 5 km from the coast or at altitudes above 600 m.

Table 3 Terrain category definition according to the Portuguese annex for the EC1 [7]

Category I	Coastal area exposed to the open sea.
Category II	Areas with low vegetation, such as grass and isolated obstacles (trees, buildings) with separations of at least 20 obstacle heights.
Category III	Areas with regular cover of vegetation or buildings or containing isolated obstacles with separations of no more than 20 obstacle heights (i.e., villages, suburban terrain, permanent forest).
Category IV	Areas in which at least 15% of the surface is covered with buildings with an average height that exceeds 15 m.

For a better understanding of the influence that the variation of these two parameters has on wind action definition, all the possible

combinations of zones and terrain categories where monopoles can be installed were considered, with the exception of a terrain category I in zone A, since these two conditions are not compatible. By analysing the variation of the values of the outcome variables in the case of a monopole M2 installed in each of the six zone/terrain combination categories indicated in Figure 2, and comparing it to a baseline, i.e. a monopole M2 installed in a terrain category of type IV in zone A, it is clear that changing the type of zone and terrain category are important factors for wind action definition.

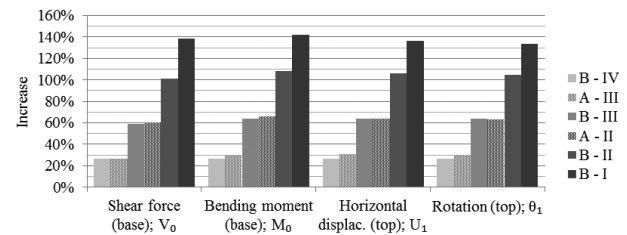


Figure 2 Variation of the outcome variables for monopole M2 located in a terrain category of type I and in zone B, to another different location

Figure 2 shows a significant increase (up to 140%) of the values for all outcome variables, when monopole M2 changes from the baseline to a terrain category of type I in Zone B, which shows the importance of these parameters for wind action definition. It is also found that the wind action variation is similar when the location of the monopole passes from a less exposed area, located in zone B, to the next category of a more exposed terrain, located in zone A, since the effects of zone change and terrain category in this case are of the same order of magnitude and therefore annul each other.

The average values of the changes observed in the outcome variables corresponding to different possible scenarios, when changing the type of zone and terrain category, are shown in Figure 3. This figure reveals that, with the exception of a monopole passing from a category II terrain to a category I terrain, the consequences of a transition between zone A and zone B are quite similar to the transition towards the immediately previous terrain category, i.e. more exposed to wind action. When changing from a category II terrain to a category I terrain, the relative increase of the key variables is about 15% to 20%, while in the other case this increase is about 25% to 30%.

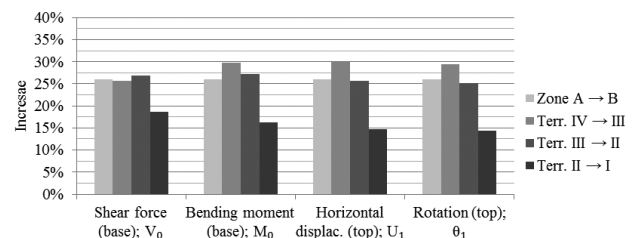


Figure 3 Mean variations of the outcome variables for monopole M2 in different possible scenarios, when changing the type of zone or the terrain category

3.1.2 Influence of orography

In addition to the location of the structure, characterised by zone and terrain category, the aggravating effect of orography should be evaluated when calculating mean wind velocity. Due to the existence of hills or cliffs, this effect causes an increase in wind speed near the ground. If this increase is over 5%, the corresponding effect should be considered in light of the orography factor. However, the effects of orography may be discarded when the average slope of the upwind terrain is below 3°; the upwind terrain may be considered up to a distance of 10 times the height of the isolated orographic feature [6], [7], [8].

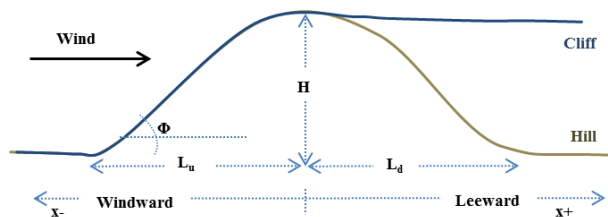


Figure 4 Definition of the dimensions of the hill and/or cliff

For reasons related to their own function, monopoles are often installed on slopes or at the top of major orographic features. In this study, the influence of this factor on wind action definition was analysed by changing the variables involved, i.e. the upstream slope Φ and the length L_u . The results obtained for monopole M2 are shown in Figure 5, with the change of the upstream slope Φ of a cliff due to the height H . Figure 6 shows the results obtained from changing the upstream slope Φ of a cliff due to the length L_u . In both cases, the variation is considered in relation to a baseline, i.e. a monopole located on flat ground. Figure 5 shows that the higher the gradient of the windward slope, the higher the average value of the addition of all the outcome variables in relation to a baseline, i.e. a monopole located on flat ground; the values presented have very significant increases. The above mentioned average value was chosen for this representation (Figure 5) since it was found that it is rather close to the individual values of the addition for each outcome variable.

It should also be noted that the biggest increase is the location of the structure at the top of the cliff since, as the horizontal distance from the structure to the top of the cliff increases, the effects of the terrain will decrease gradually. However, the results presented in Figure 5 and Figure 6 show that the increase of wind action over cliffs with equal upwind slopes is different in the two scenarios shown in these figures.

The influence that the type of orographic accident could have on wind action definition was also analysed by comparing the addition of the study variables in relation to a baseline, in the case of hills and cliffs with slopes equal to windward. The results presented in Figure 7 show that, both in the case of the cliff and the hill, with windward slopes $\Phi = 0,3$, the variation of the outcome variables present on the windward side is the same, indicating that the wind action on this aspect is independent from the type of orographic accident. However, in the present leeward, it is observed that in the case of a

cliff, the effect of topography extends over a much longer distance, when compared to the effect in the case of a hill.

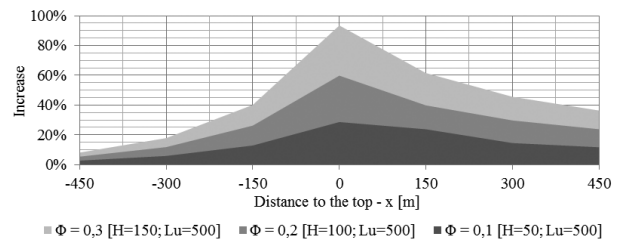


Figure 5 Variation of the outcome variables for monopole M2 located in flat ground, with the change of the upstream slope Φ of a cliff, depending on the height H

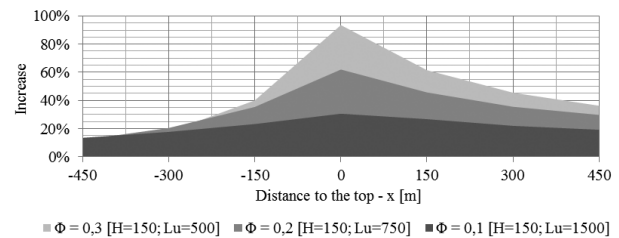


Figure 6 Variation of the outcome variables for monopole M2 located in flat ground, with the change of the upstream slope Φ of a cliff, depending on the length L_u

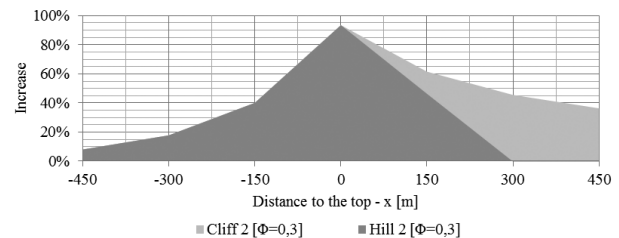


Figure 7 Variation of the outcome variables for monopole M2 located in flat ground, with the change to a cliff or a hill with the same upstream slope Φ

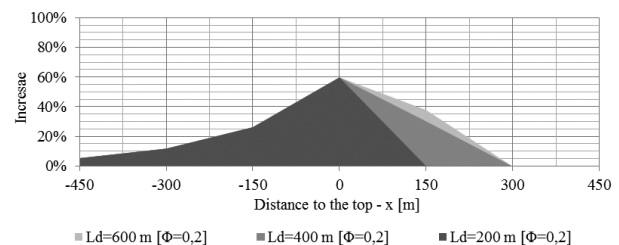


Figure 8 Variation of the outcome variables for monopole M2 located in flat ground, with the change to hills with the same upstream slope Φ facing windward and different lengths L_d on the leeward side

The fact that air flow undergoes changes in the trajectory lowers its intensity for a structure situated on the leeward of a hill, with the same distance from the top. So, in the case of a hill, it is important to analyse the influence that the length of the side facing leeward (L_d) has on the way wind acts on a monopole. Figure 8 shows the results obtained for three cases of hills with different lengths of the leeward side, but with the same slope gradient facing windward. Again, the results represent the average increase of the outcome variables in the case of a monopole M2 and in relation to a flat position.

It should be noted that when the length of the leeward slope (L_d) increases, wind action becomes greater at equal distances from the top. However, regarding the windward slope, when the length of the leeward slope changes, there is no variation in the values of the outcome variables, as the dimensions of the windward slope are equal in all cases. This proves that simply changing the tilt to windward will cause the wind action on this aspect to be different. After analysing the effects of all parameters, it is possible to conclude that orography has a great influence on the wind action definition of monopoles. As previously mentioned, these structures are often installed near the top of hills or cliffs, so it can also conclude that orography is of crucial importance to the analysis and design of such structures; therefore, its influence should not be neglected.

3.2 Influence of the monopole height

Most of the telecommunication monopoles installed in Portugal are between 30-metre and 40-metre-high [3]; there is a clear difference in terms of wind incidence area used for wind definition between monopoles of different heights. By comparing the results obtained for monopoles of the same type, i.e. monopoles M1 and M2 (type 1) and monopoles M3 and M4 (type 2), which are 30-metre and 40-metre-high, it was found that the additions of the outcome variables with increasing height are significant.

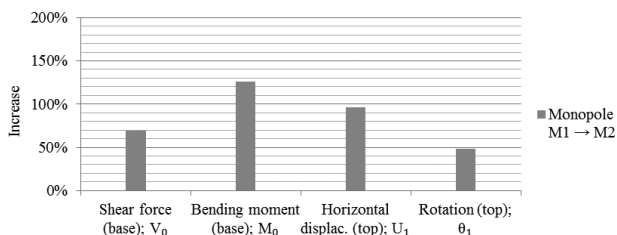


Figure 9 Variation of the outcome variables due to the height difference between monopole M1 and monopole M2

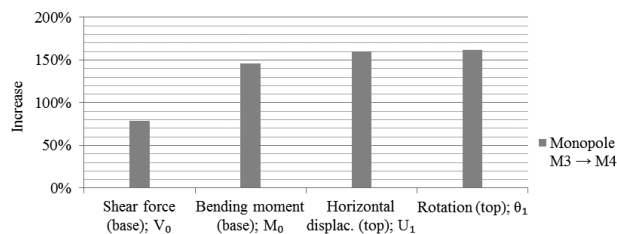


Figure 10 Variation of the outcome variables due to the height difference between monopole M3 and monopole M4

The results presented in Figure 9 and Figure 10 show that increasing the height from 30 to 40 metres, in the case of monopoles of the same type, has a great influence on the results. However, it should once again be noted that, in the analyses performed, the loss of stiffness due to soil-structure interaction and connections influence was not considered, which may make these differences even more significant. This issue is currently the subject of further studies [3], [10].

3.3 Influence of the monopole shaft cross-section

In addition to the height of the structure, the geometry of the shaft cross-section may also affect wind action definition. The force coefficients for circular cross-sections depend mainly on the surface of the coating. Thus, three different cases were defined for type 1 monopole, consisting of monopoles M1 and M2, with different coatings on their surface. The force coefficients (c_f) determined for each coating (Table 4) were obtained considering the following equivalent surface roughness (k), in accordance with Table 7.13 of EC1-1-4 [7]: fine painted surface: $k = 0,006$; spray paint: $k = 0,02$; bright steel: $k = 0,05$.

The results presented in Figure 11 show the average increase of the outcome variables in relation to a baseline, i.e. a monopole with a fine painted surface.

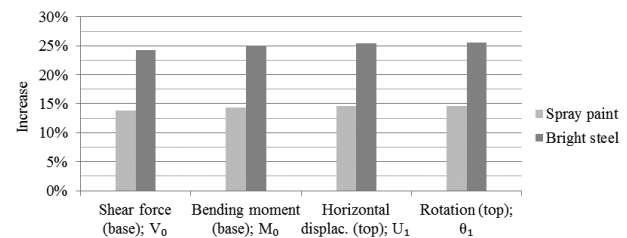


Figure 11 Mean variation of the outcome variables for monopoles M1 and M2 with a fine painted surface, with the change to different coatings on their surface

The additions observed in the outcome variables in relation to a baseline demonstrate that the choice of the type of coating has significant consequences for wind action definition. These increases are due to fluctuations of the force coefficients with the change of the surface roughness. In fact, surfaces with a greater roughness bring more difficulties to the air flow, thus explaining the values observed in Figure 11.

In the case of type 2 monopoles, determining the force coefficient depends mainly on the geometry of the cross-section. So, three different cases were defined for type 2 monopoles, consisting of monopoles M3 and M4, with polygonal cross-sections of 8, 12 and 16 sides, respectively. The results presented in Figure 12 show the average increase of the outcome variables in relation to a baseline, i.e. a monopole with 16-sided polygonal cross-sections. Figure 12 shows that the variation in cross-sectional geometry of a type 2 monopole, from a 16-sided polygonal cross-section to a 12 or 8-sided polygonal cross-section, has important consequences for the wind action definition of such structures.

Also in this case, the results show significant increases in the force coefficients assigned to the different monopoles. The comparison of the mean values of the force coefficients for different types of cross-sections shows that force coefficients are higher in the sections that are more angular and more distant from a circular geometry, therefore increasing the wind action on the structure.

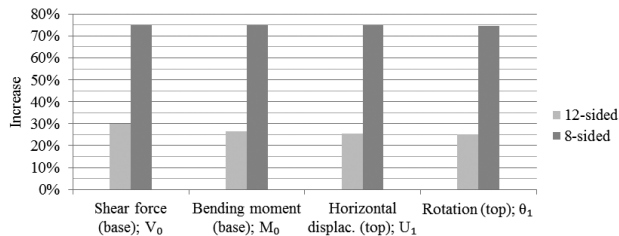


Figure 12 Mean variation of the outcome variables for monopoles M3 and M4 with a 16-sided polygonal cross-section, with the change to a 8-sided and 12-sided polygonal cross-sections

Table 4 Mean values of the force coefficient for each monopole being studied

Cross-section	Monopoles	Shaft surface	Cross-section geometry	Mean force coefficient (c_f)
Circular	M1 and M2	Fine paint	–	0,51
		Spray paint	–	0,60
		Bright steel	–	0,67
Polygonal	M3 and M4	–	16 sides	0,70
		–	12 sides	0,93
		–	8 sides	1,30

Therefore, it is possible to conclude that simply changing the surface of the shaft or the geometry of the cross-section can influence significantly the air flow and thus aggravate the wind action effects on these structures.

Furthermore, regardless of their surface, monopoles with circular cross-sections present lower force coefficients when compared to monopoles with polygonal cross-sections. The sections closest to the circular shape allow the air to flow more easily, thus reducing the values of the power coefficient and decreasing the wind action on the structure.

3.4 Influence of wind action on antennas

In order to analyse the influence of antennas in the definition of wind action on a monopole, several combinations were defined,

considering different numbers of antennas positioned along the monopole height. Accordingly, two different types of antennas were considered, including an antenna with a rectangular shape (panel antenna) and an antenna with a circular shape (microwave antenna), as shown in Figure 13. Although panel antennas could be placed along different directions, this study considered that the wind always acts on the front side of the antennas.

Figure 14 to Figure 17 show the results of the variation of the outcome variables by adding A3 type antennas to the monopole M2, in relation to a baseline, i.e. the case of a monopole M2 without any installed equipment. The placement of 4, 8 or 12 antennas of A3 type at different heights, such as 20 metres, 30 metres and 40 metres, was considered.



Figure 13 Types of antennas considered in the study

Through the same figures, it can be seen that increasing the number of antennas at the same height and changing the position of the same number of antennas to an upper height lead to a significant increase of the outcome variables. In the case of increasing the number of antennas placed at the same height, these additions are mainly due to the growth of the exposed area due to the increased amount of antennas. In the case of changing the position of the same number of antennas to a larger height, the additions observed in outcome variables result from an increase in the dynamic pressure due to the longer distance from the antenna to the ground and a different distribution in height. In the light of this analysis, it may also be noted that changing the position of the antennas to larger heights leads to a more onerous scenario than increasing the quantity of antennas at the same height. For example, it was found that placing only 8 antennas at the top of a 40-metre-high monopole leads to a greater increase in the shear force at the base of the structure than placing 12 antennas in a 30-metre-high monopole, in relation to the baseline. This is even more noticeable when observing the values of any other outcome variables, in which the variation is much higher. For instance, in these cases it is possible to conclude that mounting 4 antennas at the top of the monopole is far more onerous than having 12 antennas at a 20-metre height, i.e. at half height.

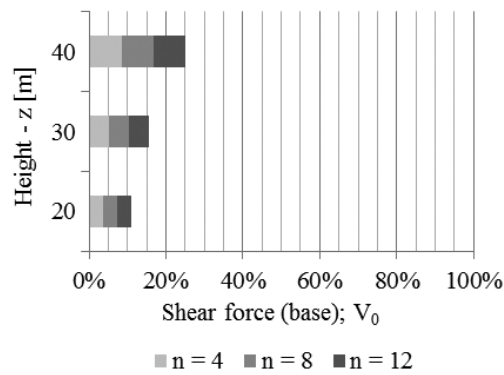


Figure 14 Variation of the shear force at the base of monopole M2 without any ancillaries mounted, with the placement of A3 type antennas

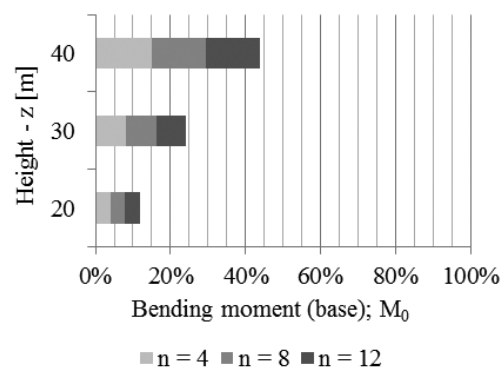


Figure 15 Variation of the bending moment at the base of monopole M2 without any ancillaries mounted, with the placement of A3 type antennas

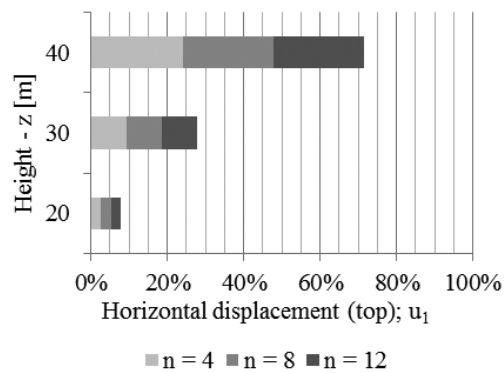


Figure 16 Variation of the displacement at the top of monopole M2 without any ancillaries mounted, with the placement of A3 type antennas

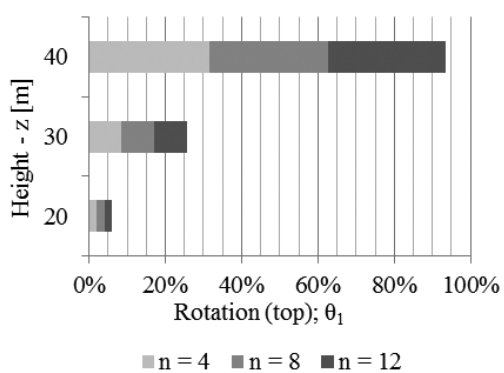


Figure 17 Variation of the rotation at the top of monopole M2 without any ancillaries mounted, with the placement of A3 type antennas

3.5 Influence of wind action on headframes with antennas

Several authors stress the difficulties in defining the wind action on ancillaries [1], [3], [11], [12]. In fact, the shield effect is a well-known fact. However, a well-defined method for quantifying this important phenomenon does not exist. Therefore, there may be a significant reduction of the current design values of the wind pressure in areas with headframes and multiple antennas, which are often determined by a simple sum of the wind action on each element. The headframe is generally a lightweight steel structure located at the top of the monopole, being used for mounting multiple antennas or other equipment, and allowing access for maintenance purposes. Fortunately, with the implementation of

new technologies, e.g. upgrades to the 4G/LTE, the distribution of ancillaries has been corrected in many cases, leading to safer structures with a better performance, as a result of the necessary dialogue between the structural engineer and the radio engineer, as presented in Figure 18.

Since there are a wide variety of possible scenarios, four possible cases were used in this study, with different shapes and dimensions, as shown in Figure 19. This study considers: i) a maximum area corresponding to the sum of the areas of all ancillaries; and ii) a minimum area corresponding to the sum of the areas of the ancillaries in one of the faces; the minimum areas are represented with a shading in Figure 19. For each case study, the placement of each of these four headframes with different numbers of antennas was admitted.



a) Before the 4G/LTE upgrade



b) After the 4G/LTE upgrade

Figure 18 Example of the configuration of the ancillaries for an upgrade to 4G/LTE

The results presented in Figure 20 represent the addition in the outcome variables for multiple scenarios, as presented in Figure 21, and in relation to a baseline, i.e. the case of a monopole M2 without any type of mounted ancillaries. Also, it was only considered antennas of type A1 and A2, with different dimensions and shapes. The results obtained, given the minimal area corresponding to the sum of the areas of the ancillaries at one side, and as presented in Figure 19, are indicated in bold in Figure 20. From Figure 20, it can be observed that placing a headframe at the top of a monopole has a significant influence on the increase of the values of outcome

variables. Also, it is possible to conclude that, regardless of the successive increase in the number of antennas, it is clear that mounting a headframe at the top of the monopole without any antennas causes itself a considerable increase in the values of the outcome variables.

In the remaining scenarios that were analysed, it was observed that the additional values of the outcome variable, due to a larger reference area and/or more antennas being considered, are lower than those due to mounting a headframe at the top. Still, it is concluded that these additions are non-negligible.

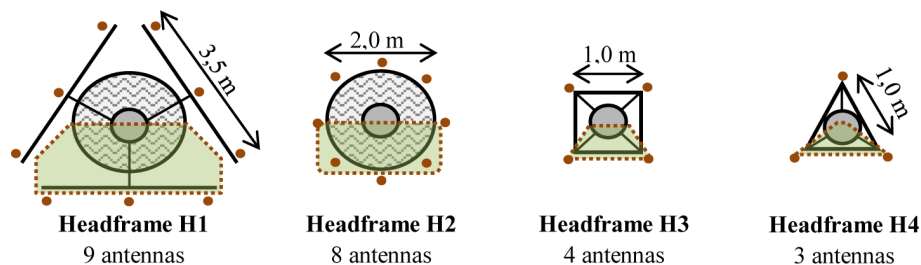


Figure 19 Headframes with the representation of the minimum area in shading

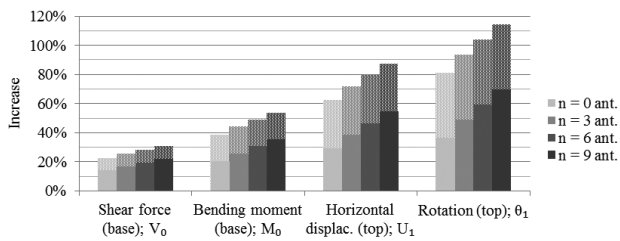


Figure 20 Variation of the outcome variables for monopole M2 without any ancillaries mounted, with the placement of a H1 headframe mounted at the top of the monopole, with different numbers of antennas

The results obtained also demonstrate that the definition of the headframe reference area is very significant to the definition of wind action. The areas defined for a type H1 headframe allow us to observe that considering the maximum area for the headframe at the top of the monopole without any mounted antenna is a worse scenario than considering the minimum area for the ancillaries, which includes the headframe with 9 antennas mounted at the top; the differences obtained for the outcome variables are more significant for the values of displacements and rotations increments at the top of the monopole.

It should be underlined that the lack of studies, including wind tunnel testing, raises serious doubts about the validity of the simple sum of the wind action on isolated elements, such as headframes and/or antennas, without considering a proper shielding effect. It is recognised that the shielding effect is relevant; however, as previously stated, an appropriate method, experimentally validated for its quantification, does not exist. The work developed by Wood [11] allows to demonstrate that the sum of the effects of wind action on each individual element is different from the overall effect on both headframes and antennas. These results were obtained from wind tunnel tests.

In this study, an interference coefficient was defined for each situation in order to quantify the influence of this effect for wind action definition, calculated in a simplified approach using the relationship between the results obtained for both headframes and antennas, and the sum of the results obtained for each individual ancillary. Based on a headframe used in the experimental work of Wood [11], with a shape and a dimension that are both similar to the headframe H1 used in this study, it was possible to relate the interference coefficient with the frontal area of the antennas, marked as AF in Figure 22, taking into account the wind direction and the antenna configuration shown in the same figure.

It was found that, for a considerable area of antennas mounted on the front side, there may be a significant reduction of wind action. Although it may only depend on the area of the antennas mounted on the front face, it is proven that this effect exists and, consequently, it has an important role in the wind action definition of telecommunication monopoles. By placing a type H1 headframe at the top of a monopole M2, considering the same wind direction and the same amount and arrangement of the antennas presented in top right corner of Figure 22, the interference coefficient in scenarios with 6 and 9 antennas within type A1 and type A2 was determined. The following values for the interference coefficient were obtained: 0,90 for 6 antennas and 0,79 for 9 antennas; these values were applied to the resultant wind force at the top of the monopole. In Figure 23, the application of the interference coefficient is indicated with a (i) mark in the graphic label.

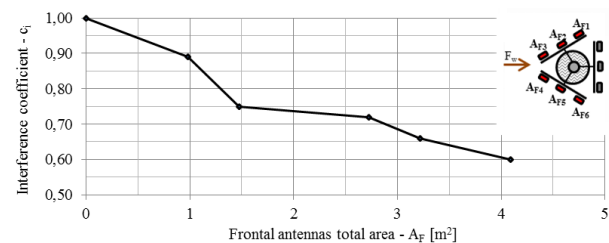


Figure 22 Values of the interference coefficient for a H1 headframe, depending on the total area of antennas mounted on the front side of the headframe

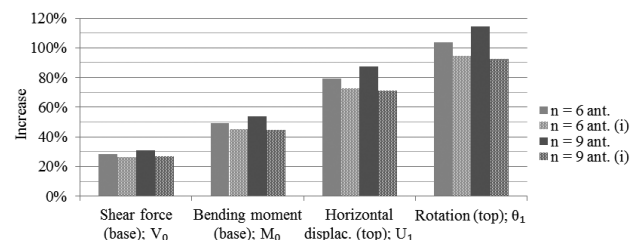


Figure 23 Variation of the outcome variables for monopole M2 without any ancillaries mounted, due to the effects of a H1 headframe placed at the top of the monopole, considering the interference effect

Figure 23 allows us to observe that the allocation of the interference coefficients to both headframes and antennas (i) does not have a significant influence on the increase of the outcome variables.

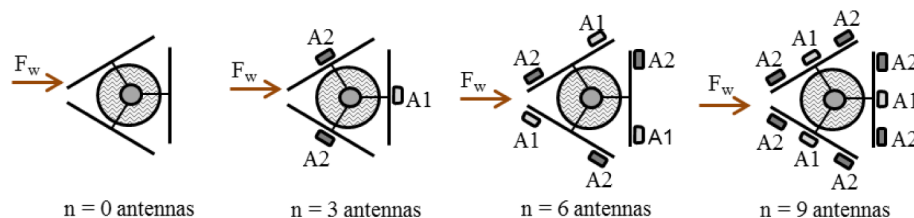


Figure 21 Scenarios considered when studying the placement of H1 headframe at the top of the monopole

However, it is clear that there is a reduction in the wind action and therefore in the outcome variables. Still, these coefficients were obtained using a simplified procedure that lacks experimental testing, so more research is needed about the interference between headframes and antennas, as already stressed by several authors. However, it is a fact that this effect occurs in mounted headframes and antennas with a high density of antennas and, consequently, with a large overlap of elements. As there may be other types of equipment at the same height, air flow can be affected more significantly, therefore not depending solely on the number of antennas.

3.6 Influence of wind action on feeders

Feeders are generally arranged in two or more paths in the same plane of the ladder. To analyse the influence of these ancillaries on wind action definition, several scenarios of feeders were set up, arranged in groups of two paths, in a total of 12, 16 or 24 cables, as shown in Figure 24. Changing the arrangement of feeders will change the exposed area and the air flow, consequently changing the reference area to be considered and the force coefficient to be applied. For this reason, an optimized layout was considered for each group, indicated with (a) in Figure 24 and Figure 25, in order to analyse the influence of this parameter on wind action definition. The results are the additions observed for the outcome variables in monopole M2 and in relation to a baseline, i.e. the case of a monopole M2 without any mounted ancillaries.

Figure 25 shows significant increases in the outcome variables; it is clear that these increases are much higher with the increase of the reference area. By analysing the results obtained for the optimized arrangements, it is possible to conclude that a smaller number of cables implies not only a reduction in the reference area, but also a decrease in the force coefficient. The reductions observed in the outcome variables are very significant when compared to scenarios of non-optimized feeder arrangement. It should be noted, for example, that in the case of a total of 12 cables placed in a non-optimized configuration, the values obtained for the outcome variables are similar to those obtained for the case of 20 cables placed in an optimal arrangement. Another important aspect about feeders is their interference with the shaft, since this group

may not be permeable to air flow. This means that air flow can change dramatically if this block effect is considered, as illustrated in Figure 26.

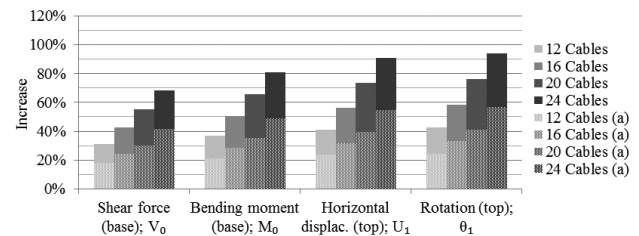


Figure 25 Variation of the outcome values for monopole M2 without any ancillaries mounted, with the change of the number and arrangement of the feeders

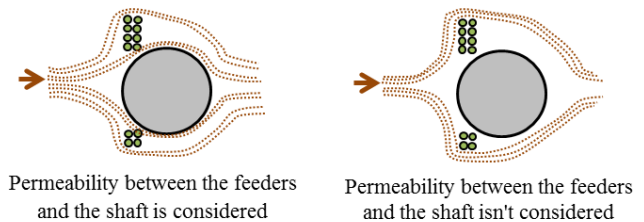


Figure 26 Representation of the air flow around the feeders-shaft group

The results in Figure 27 show that the force coefficient changes dramatically between these two scenarios presented in Figure 26. The cases where the shaft-feeders group is considered as a single block, is marked with a (b) in Figure 27.

When admitting the permeability between the feeders and the shaft, an isolated force coefficient for each element could be assigned. If the group is taken as one single block, a single force coefficient is assigned, whereas the width of that block is equal to the sum of the widths of both feeders and shaft. Taking into consideration the optimized arrangement presented in Figure 24, there is an enormous increase in the outcome variables when considering the shaft-feeders group as a single block (see Figure 27). These increases result from the rise in the force coefficients for the shaft-feeder group,

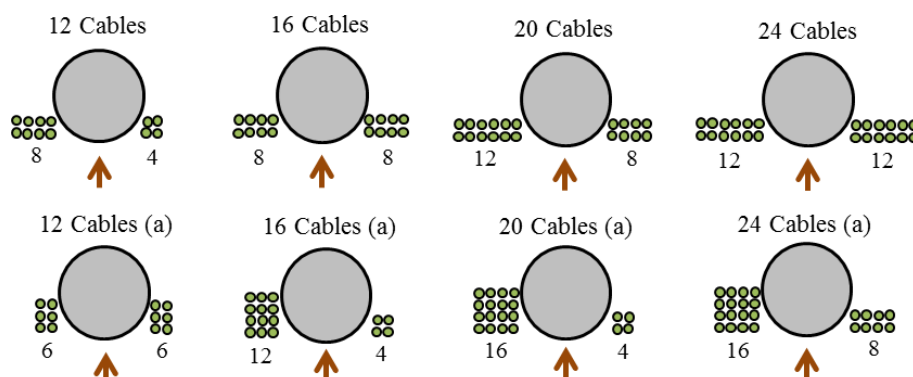


Figure 24 Illustration of the arrangement of feeders used in this work

in comparison to the situation in which separate force coefficients are used for the shaft and the feeders. In general, the scenario of a single shaft-feeders group seems relatively rare, since there are substantial gaps between the shaft and the feeders which allow the air to flow freely between these elements. However, it is necessary to underline that, in some cases, this effect may substantially affect wind action definition.

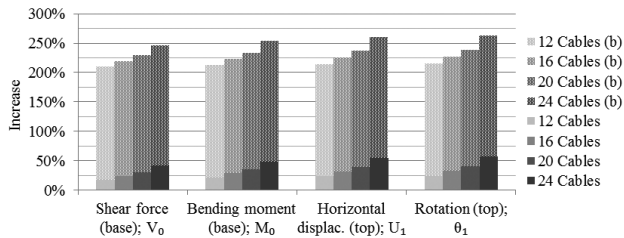


Figure 27 Variation of the outcome values for monopole M2 without any ancillaries mounted, considering the block effect between the shaft and the feeders, for different numbers of feeders

3.7 Influence of wind action on ladders

Similarly to feeders, ladders also have the particularity of presenting a linear disposition, being placed along the entire height of monopoles. There are various types of ladders, with different step dimensions and shapes, or different types of devices to ensure user safety. The main goal of this analysis is to quantify the increase in wind action due to the placement of various types of ladders in the monopoles analysed. This work has defined four typical types of ladders used in monopoles, with different reference areas (see Figure 28). For the analyses, a force coefficient of 1,60 was admitted, regardless of the type of steps being used, obtained through the force coefficients of the different elements used in ladders.

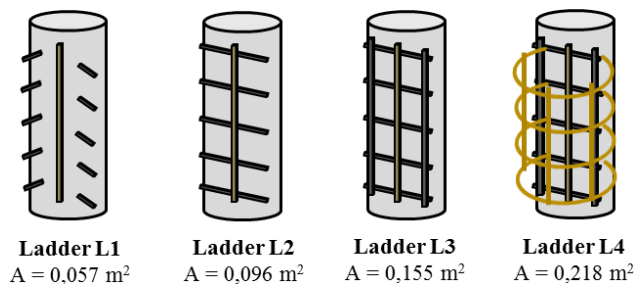


Figure 28 Illustration of the four types of ladders considered in this study

In this study, one of the most discussed aspects was the fact that there may be an overlap of ladders and shaft. Since ladders are placed on the shaft, there is the possibility of a shielding effect between these two elements. In this case, and as previously discussed about the interference between headframes and antennas, the sum of the

isolated wind forces applied to both the shaft and the ladders may not represent the resultant wind force of the group. Once again, the need to carry out experimental studies is emphasised, using wind tunnel tests so as to reach reasoned answers to these questions. Nevertheless, by placing each of the four types of ladders considered in each of the four monopoles, the additions of the values for the outcome variables in relation to a baseline, i.e. a monopole M2 without any mounted ancillaries, were calculated. From Figure 29, it is possible to observe that placing a type L1 ladder (see Figure 28), with a smaller reference area implies a significant increase of the outcome variables. In the other cases, when placing ladders with a larger reference area, the variation in the outcome variables is even more pronounced, confirming that any change in this type of equipment will have a very important influence on the definition of the wind action for these structures.

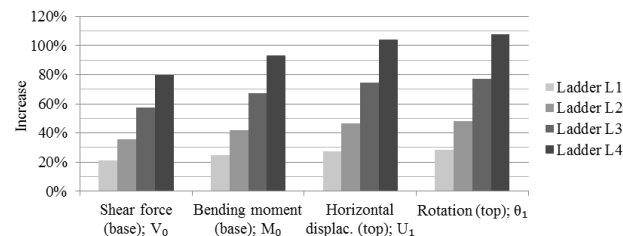


Figure 29 Variation of the outcome variables for monopole M2 without any ancillaries mounted, with the change of the type of ladder placed along the height of the monopole

3.8 Influence of wind action on ladders, feeders, headframes and antennas

Having presented and discussed the results for each individual element, it is important to provide an overview of the combined influence of all these non-structural elements. So, we now compare the wind action of the effects on each of the studied monopoles, considering all the mounted equipment, for some real cases of existing monopoles (Table 5).

Table 6 shows the relative influence of the monopole shaft and of each one of its equipments. The values presented on this table correspond to the average relative influence for the whole outcome variables, since it was found that these average values are rather close to the individual relative influences for each outcome variable.

From the results presented in Table 6, it can be observed that, with the exception of monopole M1, the effects of wind action on non-structural elements, i.e. ladders, feeders, headframes, and antennas, are superior to the wind action on the shaft. A simple observation of Table 6 allows us to evaluate the importance of the influence of each element on the analysis and design of these structures. This influence should not be ignored, particularly when the growing progress of technology is leading to a successive increase of the different equipment mounted on existing structures.

Table 5 Real cases of existing monopoles providing an overview of the combined influence of ladders, feeders, headframes, and antennas

Monopole	Zone	Terrain	Equipments					
			Antennas		Headframes		Feeders	Ladders
			z (m)	n	z (m)	Type		
M1	B	III	21	1	30	H2	12	L2
			30	5				
M2	A	II	16	2	16	H3	20	L4
			18	1				
			32	1	40	H1		
			40	9				
M3	A	III	20	2	30	H2	12	L2
			30	8				
M4	A	IV	30	1	16	H3	24	L2
			35	3				
			40	9	40	H1		

Table 6 Influence of non-structural elements for the wind action definition on monopoles

Monopole	Shaft	Equipments				
		Antennas	Headframes	Feeders	Ladders	Total
M1	55%	8%	6%	11%	21%	45%
M2	40%	9%	9%	12%	30%	60%
M3	46%	19%	5%	13%	17%	54%
M4	47%	10%	13%	18%	13%	53%

4 Conclusions

Mainly for economical and functional reasons, communication structures are relatively lightweight structures with structural characteristics such as high slenderness ratios and varying levels of flexibility. With the desire to install wireless hubs, more specifically in locations with a high population density, new structural forms have arisen, namely monopoles that challenge the limits of conventional pole design. This paper presents and discusses the results obtained in a parametric study to quantify the relative influence of the most important parameters used for wind action definition in telecommunication monopoles.

It is therefore concluded that the location of the monopole, as well as the geometrical characteristics of the structure, are crucial to the wind action definition of these telecommunication structures. The fact that this type of structures is usually placed in higher grounds, with no major obstacles to air flow, highlights the importance of these parameters in wind action definition, so their influence must not be neglected.

In the case of antennas, it has been found that increasing the reference area with the increase of the number of antennas or the increase in height of the antennas placement, has an influence on wind action definition. It was also found that the increase in height of a given quantity of antennas is more onerous than the increase in the number of antennas installed at the same height.

Regarding headframes, a further increase of the overall results was found when compared with the case of antennas; the results for headframes placed at the top of the structure without any installed antenna prove the importance of this type of equipment for wind action definition.

In the case of non-structural elements with linear development, such as feeders and ladders, it was found that their relative influences are still more significant when compared with discrete elements such as antennas and headframes. In fact, these elements present, in general, a large reference area and they are mounted throughout the entire height of the monopole, which explains the results obtained and emphasizes their importance for the wind action definition of such structures.

Finally, a global analysis of the studied monopoles was carried out, taking into account the combined effect of all the studied parameters. This study found that these non-structural elements play a crucial role in wind action and should not be underestimated.

Because of this crucial role and due to the degree of uncertainty associated with some of the aspects discussed in this paper, further studies in some of the issues presented are essential, namely by means of wind tunnel testing, in order to compare the global effects of the wind action on the telecommunication monopoles with the sum of the effects associated to each one of the parameters considered in this work.

References

- [1] Smith, B. W. – “Communication structures”. London. Thomas Telford, 2007, 352 p.
- [2] Støttrup-Andersen, U. – “Mast and towers”, Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium, Valencia, Ed. A. Domingo and C. Lazaro, 2009, p. 127-138.
- [3] Travanca, R.; Varum, H.; Vila Real, P. – “The past 20 years of telecommunication structures in Portugal”, Engineering Structures, 2013, Vol. 48, p. 472-485.
- [4] Filipe, J.; Travanca, R.; Baptista, A. M.; Pipa, M. – “Monopólos auto-suportados para telecomunicações: A influência da localização e da geometria da estrutura na definição da ação do vento”, 5.ª Jornadas Portuguesas de Engenharia de Estruturas, Lisboa, novembro de 2014.
- [5] Filipe, J.; Travanca, R.; Pipa, M.; Baptista, A. M. – “Monopólos auto-suportados para telecomunicações: A influência dos equipamentos na definição da ação do vento”, 5.ª Jornadas Portuguesas de Engenharia de Estruturas, Lisboa, novembro de 2014.
- [6] EN 1991-1-4 – “Eurocode 1 – Actions on structures, Part 1-4: General Actions – Wind Actions”, European Committee for Standardisation (CEN), 2005.
- [7] NP EN 1991-1-4 – “Eurocódigo 1 – Acções em estruturas, Parte 1-4: Acções do vento”, Comité Europeu de Normalização (CEN), 2010.
- [8] EN 1993-3-1 – “Eurocode 3 – Design of steel structures, Part 3-1:

Towers, masts and chimneys - Towers and masts", European Committee for Standardisation (CEN), 2006.

- [9] "SAP2000 version 18: CSI Analysis Reference Manual", CSI: Computers and Structures Inc. Berkeley, California, 2015.
- [10] Antunes, P.; Travanca, R.; Varum, H.; André, P. – "Dynamic monitoring and numerical modelling of communication towers with FBG based accelerometers", Journal of Constructional Steel Research, 2012, Vol. 74, p. 58-62.
- [11] Wood, G. – "Wind loading of telecommunication antennas and head frames", School of Civil Engineering, The University of Sydney, Research Report N.º. R881, 2007, 40 p.
- [12] Carril Jr., C.; Isyumov, N.; Brasil, R. – "Experimental study of the wind forces on rectangular latticed communication towers with antennas", Journal of Wind Engineering and Industrial Aerodynamics, 2003, Vol. 91, p. 1007-1022.

