Structural Monitoring and Maintenance, *Vol. 8*, *No. 4* (*2021*) *309-328*
https://doi.org/10.12989/smm.2021.8.4.309

Geodetic monitoring on onshore wind towers: Analysis of vertical and horizontal movements and tower tilt

Luiz Filipe C. Canto* and Andréa de Seixas [a]

Departament of Cartographic Engineering, *Federal University of Pernambuco*,
Acadêmico Hélio Ramos Avenue, *n/a*, *2º floor*, *50740-467*, *Brazil*

(*Received May 23*, *2021*, *Revised August 25*, *2021*, *Accepted September 21*, *2021*)

Abstract. The objective of this work was to develop a methodology for geodetic monitoring on onshore wind towers, to ascertain the existence of displacements from object points located in the tower and at the foundation's base. The geodesic auscultation was carried out in the Gravatá 01 and 02 wind towers of the Eólica Gravatá wind farm, located in the Brazilian municipality of Gravatá-PE, using a stable Measurement Reference System. To verify the existence of displacements, pins were implanted, with semi-spherical surfaces, at the bases of the towers being monitored, measured by means of high-precision geometric leveling and around the Gravatá 02 tower, concrete landmarks, iron rods and reflective sheets were implanted, observed using geodetic/topographic methods: GNSS survey, transverse with forced centering, three-dimensional irradiation, edge measurement method and trigonometric leveling of unilateral views. It was found that in the Gravatá 02 tower the average rays of the circular sections of the transverse welds (ST) were 1.8431 m ± 0.0005 m (ST01) and 1.6994 m ± 0.0268 m of ST22, where, 01 and 22 represent the serial number of the transverse welds along the tower. The average calculation of the deflection between the coordinates of the center of the circular section of the ST22 and the vertical reference alignment of the ST1 was 0°2'39.22" ± 2.83" in the Northwest direction and an average linear difference of 0.0878 m ± 0.0078 m. The top deflection angle was 0°8'44.88" and a linear difference of ± 0.2590 m, defined from a non-linear function adjusted by Least Squares Method (LSM).

Keywords: geodetic monitoring; geodetic/topographic methods; onshore wind towers; reference/object points; vertical/horizontal movements

1. Introduction

Onshore wind towers have become frequent as an element of the terrestrial landscape, due to the worldwide growth of their installations in the last decade. Rapid development and technological evolution have forced the need for even taller, grouped towers in wind farms to expand energy production capacity. These structures often operate in harsh environments. Therefore, they can be damaged by several environmental factors and subject to static and dynamic loads, which result in the displacement of individual elements and the entire structure. Structures with significant displacements can result in permanent changes and need periodic

*Corresponding author, Ph.D. Student, E-mail: luiz.canto@unesp.br
[a] Associate Professor, E-mail: aseixas@ufpe.br

http://www.techno-press.org/?journal=smm&subpage=7 ISSN: 2288-6605 (Print), 2288-6613 (Online)

inspections of their geometric operating condition. The need for such inquiries is related to safety requirements, where disturbance of geometry can result in untimely and catastrophic consequences.

Worldwide research undertaken in the methods, techniques, and technologies of monitoring wind towers and their components is scarce, mainly involving the use of geodetic methods. Research involving location, dimensional control (positional control) and monitoring of these towers is required. With geodetic auscultation, it is possible to determine the position of structural elements of the wind towers, through geodesic Cartesian coordinates, by means of geodetic survey techniques, with the purpose of determining the position of structural elements of the wind towers, also enabling the multitemporal analysis of their possible displacements and/or deformities (Canto and Seixas 2020). As a consequence of this, research is required involving the survey, location and monitoring of these towers, with the purpose of determining the position of structural elements of the wind towers, also enabling the multitemporal analysis of the displacements and/or deformities.

Due to the fact that a large number of wind energy towers have been built, monitoring techniques are necessary to guarantee the stability and longevity of these objects (Hesse *et al*. 2006). Worldwide research on methods, techniques and technologies for monitoring wind towers and their components is scarce compared to the growth in wind generation capacity. The more towers are built, the more accidents occur. According to data from Caithness Wind Farm (2021), the number of recorded accidents had an average of 57 accidents per year from 2000-2005 and 184 accidents per year from 2016-2020.

Research involving the use of geodetic methods in wind towers is sparse. The works of Dragomir *et al*. (2014), Rezo *et al*. (2016) and Negrilă (2020) can be highlighted. Therefore, specific research in the control and geodetic monitoring of wind towers is of substantial importance. With the lack of monitoring of the behavior of these structures, there is a need to apply procedures to monitor the verticality and stability of the wind towers. The purpose of this work was to develop a methodology using geodetic/topographic techniques to detect vertical and horizontal movements from object points located at the base of the foundation and in the tower, from a stable Measurement Reference System (MRS). In addition, a methodology for determining the virtual center of the tower will be presented, with the purpose of studying its behavior along the tower and adapting models of adjustments for determining the coordinates of the object points to the methods employed.

2. Methodology for geodetic monitoring on wind towers

Wind energy is currently generated in two forms: onshore wind farms which are large installations of wind turbines located on land, and offshore wind farms which are installations located in bodies of water. In this work, techniques and equipment with geodesic/topographic purposes were used to monitor the vertical and horizontal displacement of onshore wind towers.

The methods of geodetic monitoring aim to find changes in coordinates (planimetric and/or altimetric), of a series of readings, of object points, in a given period. The values found indicate if there were any changes in the coordinate values. Geodetic techniques for the purpose of monitoring must be carried out both horizontally and vertically, with the aim of determining over time the coordinates of the object points under observation and their respective behaviors.

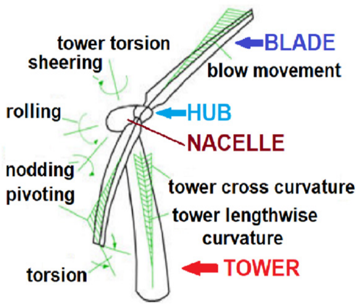
2.1 Object discretization and measurement - Wind Tower

The wind tower is composed of nacelle, the blades, the rotor hub and the tower. The tower is the support structure of the wind turbine installed at the appropriate height for its operation, the nacelle is the housing mounted on the tower, where the generator and the entire control system are located, the blades are aerodynamic profiles responsible for interacting with the wind, converting part of its kinetic energy into mechanical work at the center of the rotor, where the rotor hub is responsible for fixing of the blades (CEPEL/CRESESB 2008). The foundation can be characterized as an important part of the wind tower and it is responsible for its fixation. This foundation supports the entire structure and needs specific solutions.

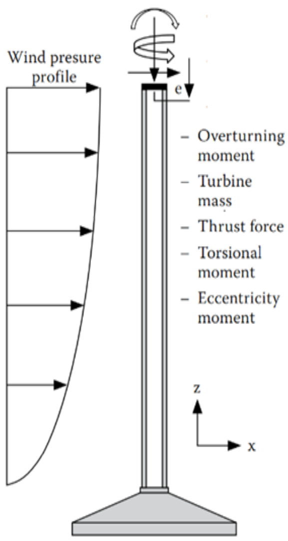
The various forms of steel structures for the construction of the towers are subjected to various internal and external agents that provide malfunction due to wear, either by incorrect construction methods, environmental actions, gradual wear, among others. Monitoring the particularities and geometric properties of these structures requires the implementation of more efficient actions to identify malfunctions in the structural behavior in a timely manner. According to Netto et al. (2002), the transmission of these efforts is done through the structure, changing the relative position of its molecules, generating a displacement.

Numerous efforts, such as horizontal forces, rotor resistance, torsional forces of the tower itself with the force of the wind, among others, generate vibrations and cause a functional imbalance of the turbine and air flows (Widerski and Kurałowicz 2009). Among these efforts mentioned, natural wind should be considered as one of the most important loads for the verification of steel wind towers. The wind action in the structure generates moments that tend to tip the tower, generating traction efforts in the foundations. Fig. 1(a) illustrates the degrees of freedom in wind blades (torsion, pivoting and blow movement), tower (torsion, cross curvature and lengthwise curvature) and nacelle (rolling, sheering and nodding). For further specifications of the degrees of freedom illustrated, see Hau (2007). The loads acting on a wind tower are summarized in Fig. 1(b).

The researched wind towers belong to the Eólica Gravatá wind farm, located in the state of Pernambuco, Brazil. The research object consists of Towers of the Vestas model V82, formed of



(a) Degrees of freedom (Adapted from Hau 2007)



(b) Loads acting on wind tower structure (Way and Van Zijl 2015)

Fig. 1 Efforts in the wind tower and components

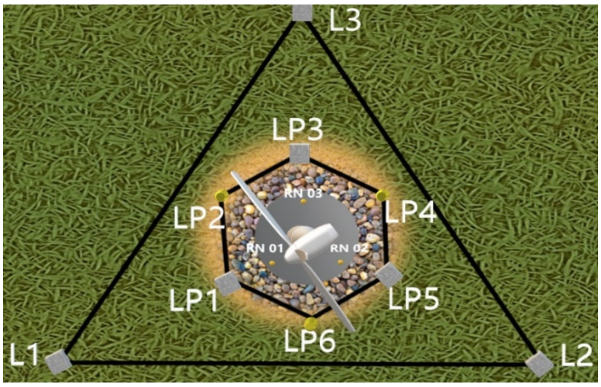


Fig. 2 Integral parts of the wind tower and acting efforts

conical tubular steel made up of a number of prefabricated sections. According to Vestas (2018), the tower in the research area is 70 m high from the base to the rotor hub, with a linear diameter varying along its length, and blades with a length of 40 m.

2.2 Geospatial analysis of the area and definition of the reference points

In order to carry out the monitoring, it is necessary to plan a geodetic network according to the specific requirement and precision to monitor a wind structure. Seixas and Burity (2005) and Krelling (2006) inform that for the determination of a monitoring network, as a reference system, for the geometric control of the test object, knowledge of the magnitude of the displacements and condition is necessary for the establishment of the equipment used and their respective accuracies and conception of the best configuration of the observation control stations.

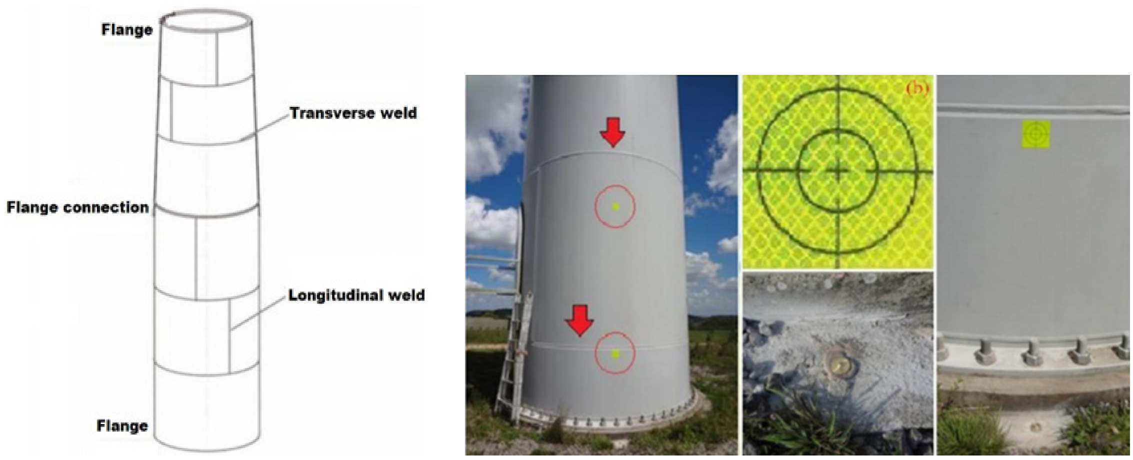
The general procedures for monitoring a structure involve the measurement of spatial displacements, from reference points, which have their positions controlled (Department of Army 1994). In order to have views with a minimum of three directions from the tower, two configurations were designed for the distribution of the reference points (Fig. 2): Equilateral triangle (L1, L2 and L3) and regular hexagon (LP1, LP2, LP3, LP4, LP5 and LP6). Both configurations have the center of symmetry of the geometry coinciding with the centroid of the wind tower.

The objective of the equilateral triangle is to materialize the reference points at their vertices with a distance that can observe in the same alignment all the object points at the different heights of the tower. In addition, the configuration has 3 alignments that are minimum conditions for determining the intersections, adjusting the mathematical model and determining the positional quality of the virtual center. To determine the minimum distance between the vertices of the equilateral triangle and the possibility of observing the highest point-object of the tower without the use of the elbow eyepiece, the methodology of trigonometric ratios was used, through the height of the tower and the maximum zenith angle observed in the total station with the absence of the elbow eyepiece. For narrow sites, it is necessary to study the best configuration of the vertices with respect to the terrain and the adaptation of methods for measuring the tower structures.

The materialization of the vertices belonging to the positional geometry of the equilateral triangle (L1, L2 and L3) was carried out through concrete landmarks. In the regular hexagon there was the materialization of the reference points close to the tower to ensure observations at the base and the closest object points, avoiding the impediment due to the irregular relief; positional coverage for the wind tower monitoring with the aid of the elbow eyepiece; vertices in the same alignment as the regular triangle providing intervisibility between the tower and the profiled reference points of the triangle (L1, L2, and L3); added feasibility for monitoring the nacelle and components at different times according to rotor orientation in relation to the wind; more observations around the tower; as well as showing how high points could be determined with the elbow eyepiece. The vertices of the regular hexagon (LP1, LP3 and LP5) had the same alignment with the vertices of the equilateral triangle and the virtual center of the tower (Fig. 2). These were also materialized with concrete marks, while the others (LP2, LP4 and LP6) by means of iron rods. The materialization of the hexagon vertices was defined with 3 vertices with the same constructive pattern as the vertices of the equilateral triangle and the other 3 vertices of the hexagon were materialized with iron rods, for economic reasons and demonstrate more than one form of stable materialization at the time of implementation of the vertices.

The wind tower of the study, named Gravatá 02, consists of a structure of steel monopolies, where the object points defined to assess the verticality of the tower were through the connections between the tower segments (transverse welds (ST)) Fig. 3(a). Other object points defined to assess the verticality of the tower were through reflective targets aligned with the reference points of the regular triangle. The initial proposal was to place reflective target stickers in the 3 alignments defined in the tower at different heights, in order to serve as targets for measurements in the vertical plane at different times. Due to the unfeasibility of stopping the operation of the wind tower and fixing the reflective targets with the help of the rappelling team, only two sets of three reflective targets were fixed in each alignment, serving for measurements in the lower segments and reference alignment in the upper transverse welds. Fig. 3(b) demonstrate the transversal welds and the object points.

Three pins were implanted with semi-spherical surfaces (RN01, RN02 and RN03, respectively, in the Gravatá 02 wind tower and another 03 pins (RN04, RN05 and RN06) with equal configurations at the base of the Gravatá 01 wind tower, which is located approximately 450



(a) Wind speed profile (Engström *et al*. 2010)

(b) Wind direction profile

Fig. 3 Sections of a steel tubular tower and object points materialized by pins with semi-spherical head and reflective targets meters distance from the Gravatá 02 wind tower, perforated and fixed with high-adhesion epoxy adhesive, in the same alignment as the reference points L1, L2 and L3, serving as a reference for performing high precision geometric double leveling, using barcode staffs, provided with spherical plumbs, equidistant sighting to evaluate possible displacements and changes in relative positions. For more information regarding the definition of the reference and measurement system for the monitoring of the wind tower, see Canto (2018) and Canto and Seixas (2020).

2.3 Materials and methods

In accordance with the justifications and needs for the monitoring of the wind tower, a flowchart was developed with the steps taken in the procedures with the proposed methodology for the survey of the object points located in the bases and towers, ending with the processing and adjustment of the data by the Least Squares Method and its respective analysis. Fig. 4 shows the flowchart of the methodology used.

The measurements were performed with the Topcon Total station model GPT 3200 N/NW (measurement accuracy of one direction in the forward and reverse positions of the telescope ±5” and linear accuracy ±(5 mm + 5 ppm) classified by NBR 13133 (ABNT 1994) as medium accuracy, Topcon GNSS HIPER V receivers: Dual frequency (L1/L2), with horizontal accuracy of 3 mm + 0.5 ppm and vertical accuracy of 5 mm + 0.5 ppm for static surveys and Leica DNA - 03 digital level (accuracy ±0.3 mm/km, 1 km double leveled) classified as very high accuracy level by ISO 17123-part 2 (ISO, 2001) and Leica brand, 2 m long and bar-coded engraved invar staff.

Tests were carried out to verify the digital level and total stations used in the field measurements, aiming to check if the mentioned instruments are within the precision value established by the manufacturers. The digital level check was performed using the Kukkamäki method to check the instrument’s collimation error. The total stations had the verification of the horizontal and the vertical limbus through the method of reiteration. The GNSS survey in the georeferencing of the Reference Points had the antennas horizontal and oriented approximately towards the Geographic North in order to reduce the orientation error.

2.4 Analysis of vertical and horizontal movements

For the monitoring and evaluation of possible displacements of the wind tower in the horizontal

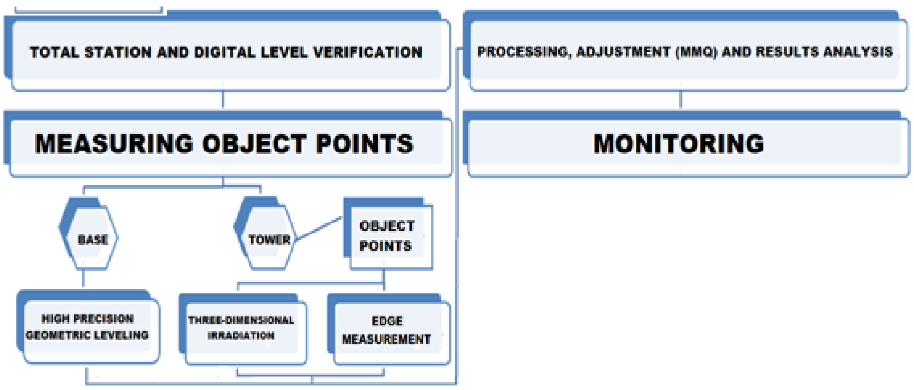


Fig. 4 Serial flowchart developed in the research

and vertical planes, planialtimetric geodetic methods were employed with the use of a total station and the altimetric geodetic method using the digital level. In the study of the variation, mainly regarding the geometry of the tower, and determination of the coordinates of the center (x, y) of each transversal weld, the Adjustment by the Least Squares Method (LSM) was performed, using the combined and parametric models.

2.4.1 Vertical movements in the tower

The proposal for monitoring the vertical displacement of the bases of the wind towers consists of performing the geometric leveling with a very high precision double path, that is, simultaneously leveling two paths with the aid of four change plates, two for reverse reading and two for forward reading, between the points implanted at the bases of the Gravata 01 and 02 wind towers. The altimetric reference system of the Level References - RRNN (level references that materialize an altimetric component of the Brazilian geodesic system) implanted is attached to the Level Reference - RN02 located in the Gravatá 02 wind tower. An arbitrated quota of 1000.00000 m was fixed for this RN, since the nearest RAAP (high precision altimetric network of the Brazilian geodesic system) RN is located 5.52 km away.

The geometric leveling involved an altimetric network composed of 6 RRNN, 3 of which were fixed around the Gravatá 02 wind tower (RN02, RN01 and RN03) and 3 fixed around the Gravatá 01 wind tower (RN04, RN05 and RN06). The geometric leveling of the points fixed in the bases of the towers was carried out starting from the altimetric reference defined by RN02, making a total six leveled and counter-leveled circuits. Fig. 5 illustrates the circuits described.

The geometrical leveling with double walk covered the described circuits using the method of equal views and auxiliary points with support of change plates. The level was programmed to read a series of 4 observations. The mean value of the series was accepted when the amplitude between the 4 observations obtained a value less than or equal to 0.06 mm. For each reverse and forward sight, at least two series of observations were performed. All closing errors resulting from leveling and counter-leveling in the surroundings and between the towers reached the allowable tolerance (better than 1 mm√k), with k being the circuit perimeter during the measurement, in km, for first order survey. In this work, the tolerance of the error of closing of the geometric leveling of 0.3 mm√k was adopted, admitting the fifth classification of levels of ISO 17123-part 2 (ISO, 2001)

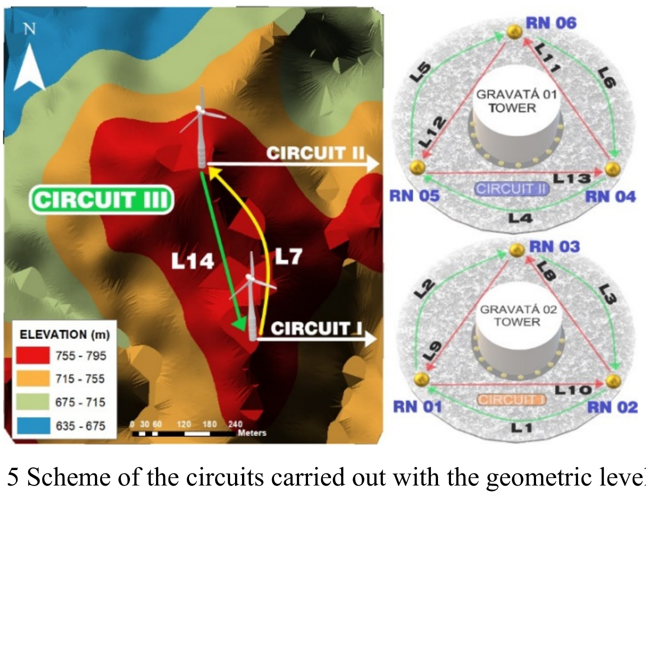


Fig. 5 Scheme of the circuits carried out with the geometric leveling

and precision (Eq. (1)).

$$S = \sqrt{E^2/_{2k}} \tag{1}$$

Being S (leveling accuracy in mm/km), E is the difference between the sum of the reverse readings and the sum of the forward readings (closure error) in mm, and k is the perimeter in kilometers.

In the configuration presented and taking RN02 as an altimetric reference, it is possible to evaluate relative movements, presented in this work. For the analysis of absolute movement, the altimetric geodetic network was expanded with the implantation of Level References implanted in superficial soils and in rocky outcrops in the Santos (2020), close to the structures being monitored.

2.4.2 Horizontal movements in the tower

In the horizontal plane, indirect measurements are oriented with the use of total stations installed over all reference points of the Measurement Reference System. All vertices started to measure the transverse welds (ST) at different arbitrated heights, except for the vertices that had aimed at the implanted reflective targets, in which the measurements were made on the transversal welds and on the reflective targets. The reference points of the regular hexagon were responsible for measuring the section of the tower closest to the base. In the equilateral triangle, they have the possibility of observing in the same alignment all the object points at the different heights of the tower. Eight transversal welds were chosen to carry out the measurements, numbered in ascending order from the closest to the base to the top, with the transversal welds ST2, ST5, ST9, ST11, ST14, ST18, ST20 and ST22 being adopted. For example, in Fig. 6 the transverse welds ST1 and ST2 are shown.

For object point measurements along the tower, three-dimensional irradiation and edge measurement methods are proposed (Fig. 6). Through the three-dimensional irradiation method, the three-dimensional coordinates were determined through measurements on the reference points, vertical angles, inclined distances and horizontal directions. The procedures for indirect measurements of each object point using the three-dimensional irradiation method are carried out by opening the horizontal angle up to the measurement reference alignment, with vertical movement of the telescope to the object point. As there was no possibility of deploying targets over the entire tower, consequently, there was no precise way to carry out measurements in the direct (PD) and in the reverse (PI) position of the telescope of the same object points observed for use at different times of measurement to monitor the structure. With the definition of transverse welds, as object points, it was necessary to measure the lower segments of each transverse weld from the reference points that had a view of the tower.

The edge measurement method (Eq. (2)) consists of determining the central horizontal direction of a given structure, through the definition of the average value of the observations of horizontal directions $Hz_{average}$, from the measurement of horizontal directions at the edges of the structure (Hz_{left} and Hz_{right}). Fig. 6 illustrates the three-dimensional irradiation measurement procedures, edges in a wind tower.

$$Hz_{average} = \frac{Hz_{left} + Hz_{right}}{2} \tag{2}$$

For the analysis of the tower verticality, it is proposed in this paper to calculate the deflection angle (Eq. (3)), defined as the plane angle formed between the projection of an origin alignment

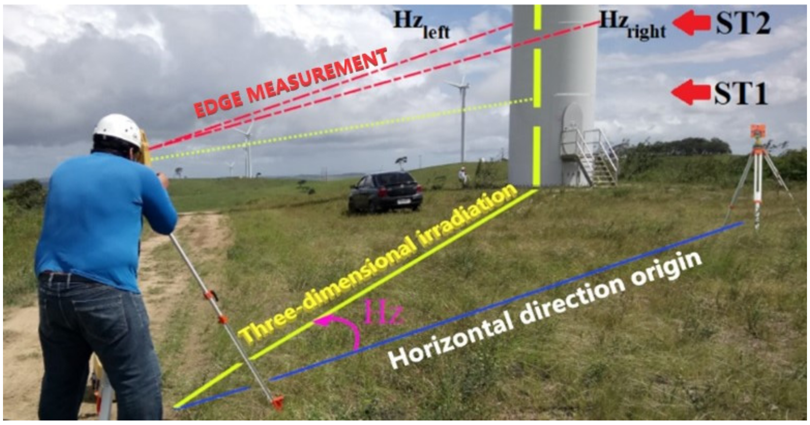


Fig. 6 Procedures for measuring transverse welds

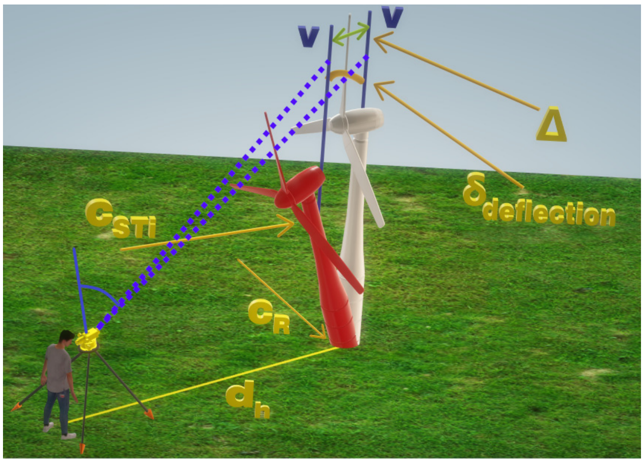


Fig. 7 Example of deflection angle in a wind tower

and a given pointed alignment, i.e., the angle measured between the displacement of any point and the vertical reference alignment. In an ideal tower (not subject to efforts) with circular sections, the planimetric positions of the centers of each cross weld are in the same planimetric position. Fig. 7 describes the angle of deflection in a wind tower.

$$\delta_{deflection} = tg^{-1}\left({}^{\Delta}/_{d_h}\right) \tag{3}$$

In which $\delta_{deflection}$ = Deflection angle; V = Vertical reference alignment; d_h= Horizontal distance; Δ = Linear difference between the respective geometric centers; C_R = Adjusted origin of the vertical reference alignment and C_{STi}= Adjusted geometric center of a transversal weld i.

The Eq. (3) was applied to determine deflections of the specific centers of each transverse weld along the point defined as the origin of the reference alignment. In this paper, the geometric center of the circular section of the bottom transverse weld is defined as the reference alignment.

2.4.3 Quality assessment

For the determination of the radius of the virtual center of each circular transversal section it is proposed in this paper to use the adjustment by the LSM - combined model. To determine the coordinates of the center of each circular transversal section it is proposed in this paper to use the LSM - parametric model.

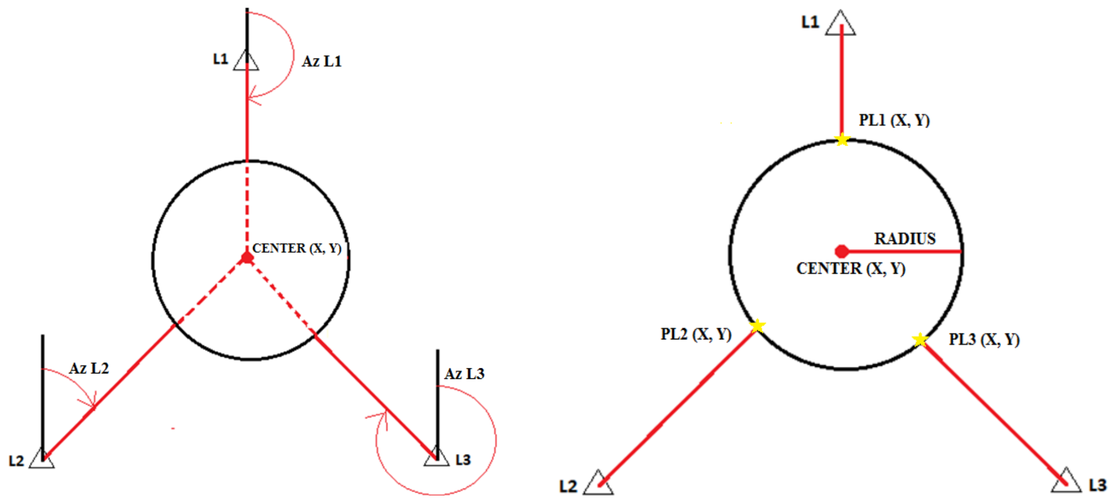
In the adjustment by the LSM - combined model, the mathematical model used for the calculation of the radius is expressed by the equation of the circumference (Eq. 4), which involves the coordinates measured at each circular transversal section between the reference points and the tower, the coordinates of the center and the radius of the circumference. Adjusting the circumference of the circular transversal section requires optimization techniques by means of iterative numerical processes to achieve the solution, as it is a non-linear model. For more details on adjusting observations using the Least Squares Method via the combined model, see Gemael *et al*. (2015).

$$(x_1 - x_C)^2 + (y_1 - y_C)^2 - R^2 = 0 \tag{4}$$

Where: x_1, y_1= Measured coordinates x_C, y_c = Center coordinates; R² = Radius of the transverse weld.

Fig. 8(a) exemplifies the method. The coordinates of the center (x, y) and radius of the circular section are determined from the measurements of the coordinates (x, y) of the circle on the alignment of the reference points. This model has three unknowns and a minimum of four equations, which allows the adjustment to be made. For more details, see Canto and Seixas (2018).

The coordinates (x, y) of the center of the circular sections can be determined using the LSM adjustment - parametric model and based on the forward intersection method, which according to Kahmen and Faig (1988) and Kahmen (2006), consists of determining the coordinates of a given point on an object over two or more known coordinate stations. See Ghilani (2018) for information regarding the adjustment of LSM observations - parametric model. To check an example of the



(a) Parametric method (b) LSM combined model

Fig. 8 Example of determining the coordinates of the center (x, y) of the circular section of the transversal weld methodology, see Canto (2018). In Fig. 8(b) illustrates the data acquisition methodology and application of the forward intersection method. In this case, x, y = coordinates of the circular center of the transverse weld and A_zL1, A_zL2 e A_zL3 = azimuths.

3. Results and discussions

After designing the methodology for monitoring onshore wind towers described in item 2, experiments were carried out to determine the reference points and the surveys of the object points with total station and digital level. In items 3.1. to 3.4 are presented the results achieved and the respective analysis of the measurements.

3.1 Determination of reference points

The reference points L1, L2, L3 and LP3 were georeferenced through the GNSS survey using the static relative positioning method (Table 1) and the other reference points using the 3D transverse method with forced centering. Then the coordinates were transformed from geocentric geodetic coordinates to topocentric coordinates in the Local Geodetic System (LGS).

The measurement data were processed, adjusted by the Least Squares Method using the parametric model and then the quality was analyzed (Table 2). The angular standard deviations of the adjusted coordinates of the quality control of the adjustment with 1σ, using the Global Chi-Square Test (χ2), using the bilateral test and at the level of significance of 5%, with a degree of freedom equal to 3 with hypotheses not rejected in the interval $0.22 < \chi 2 < 9.35$.

3.2 Analysis of vertical tower movements

The geometric leveling occurred between the pins with semispherical surface located at the bases of the wind towers, with the use of equal views and simultaneously two paths between two points with the aid of four change plates. The route remained as detailed in item 2.4.1. After

Table 1 Coordinate values in the LGS in SIRGAS2000

Vertex	X (m)	σx (m)	Y (m)	σy (m)	h (m)	σh (m)
L1	150000.000	0.006	250000.000	0.007	775.428	0.017
L2	149987.395	0.006	250168.124	0.007	777.962	0.017
L3	149881.512	0.006	250130.916	0.007	777.120	0.017
LP3	149938.576	0.006	250112.529	0.007	783.463	0.017

Table 2 Coordinates of the vertices of the polygonal adjusted by LSM - Parametric Model

Station	X (m)	σx (m)	Y (m)	σy (m)
LP1	149987.4068	0.0116	250058.6964	0.0131
LP2	149947.4277	0.0099	250071.5283	0.0132
LP4	149969.7266	0.0110	250140.8003	0.0123
LP5	150009.6450	0.0121	250127.9101	0.0126
LP6	150018.5052	0.0121	250086.8342	0.0135

Table 3 Results of the lines, gross unevenness and leveling and counter-leveling distances

Line	Exit	Arrival	Gross unevenness (m)	Adjusted unevenness (m)	Distance (m)
L1	RN02	RN01	0.01303	0.01301	8.820
L2	RN01	RN03	-0.00245	-0.00247	9.260
L3	RN03	RN02	0.01055	0.01054	15.120
L8	RN02	RN03	-0.01050	-0.01056	15.090
L9	RN03	RN01	0.00247	0.00253	10.090
L10	RN01	RN02	-0.01314	-0.01309	9.740
L4	RN04	RN05	0.00269	0.00269	10.970
L5	RN05	RN06	-0.00023	-0.00023	12.980
L6	RN06	RN04	-0.00249	-0.00246	9.980
L11	RN04	RN06	0.00248	0.00249	10.060
L12	RN06	RN05	0.00026	0.00028	12.200
L13	RN05	RN04	-0.00278	-0.00277	9.280
L7	RN02	RN04	12.66673	12.66673	451.860
L14	RN04	RN02	-12.66730	-12.66730	452.340

Table 4 Closing errors, perimeters, circuit tolerances and leveling accuracy

Circuit	Closing error (m)	Perimeter (m)	Tolerance (m)	Leveling accuracy (mm/km)
I	-0.00008	33.200	0.00005	±0.31046
I	-0.00012	34.920	0.00006	±0.45408
II	-0.00001	33.930	0.00005	±0.03839
II	-0.00005	31.540	0.00005	±0.19908
III	-0.00053	904.200	0.00028	±0.39412

carrying out the survey, the perimeter, closing error and tolerance of the leveled circuits were calculated based on the unevenness and distances measured in the field, according to item 2.4.1. The distances, gross unevenness and the unevenness adjusted through the LSM - parametric model of the leveling and counter-leveling lines of the circuits carried out on the Gravatá 01, Gravatá 02 towers and between the Gravatá 02 and Gravatá 01 towers, are shown in Table 3.

The results regarding the closing error, the perimeter and the tolerance performed between the circuits are shown in Table 4.

The general results of the geometric leveling circuits described in Table 3 and 4 show closing errors and tolerance in hundredths of a millimeter, with the exception for circuit III (closing error and tolerance) and counter-leveling of circuit I (closing error) in tenths of a millimeter. The leveling accuracy was less than ± 1 mm/km, being classified, according to ISO 17123-1 (2001), as very high precision.

3.3 Analysis of horizontal movements of the tower

Through the three-dimensional irradiation method, the three-dimensional coordinates were determined through measurements on the reference points, vertical angles, inclined distances and horizontal directions. Quotas (the term quota means altitude with respect to an arbitrary altimetric reference surface) were defined that served to assess whether the measurements on the reference points made were on the same transversal weld and to perform a quantitative assessment of the quality of the results, through amplitude, average, variance, standard deviation and coefficient of variation. Table 5 shows the measures of dispersion of the quotas.

Fig. 9 illustrates the quotas and average x and y coordinates of the transverse welds measured from measurements at the equilateral triangle (L1, L2 and L3) and regular hexagon (LP1, LP2, LP3, LP4, LP5 and LP6) reference points using the three-dimensional irradiation method.

According to Fig. 9, the results of the x coordinates measured on the L1 reference point show

Table 5 Average quotas of the transverse weld coordinates and dispersion measurements from the reference points

ST	Amplitude (m)	Average quota (m)	σ^2(m)	σ(m)	CV (%)
ST2	0.02748	1004.10222	0.0004	±0.0200	0.0020
ST5	0.02354	1012.52412	0.0004	±0.0193	0.0019
ST9	0.03111	1022.45812	0.0005	±0.0232	0.0023
ST11	0.01740	1027.51289	0.0004	±0.0200	0.0019
ST14	0.02057	1034.95430	0.0003	±0.0174	0.0017
ST18	0.03511	1044.86330	0.0004	±0.0207	0.0020
ST20	0.02529	1049.49784	0.0004	±0.0187	0.0018
ST22	0.05859	1054.06651	0.0009	±0.0304	0.0029

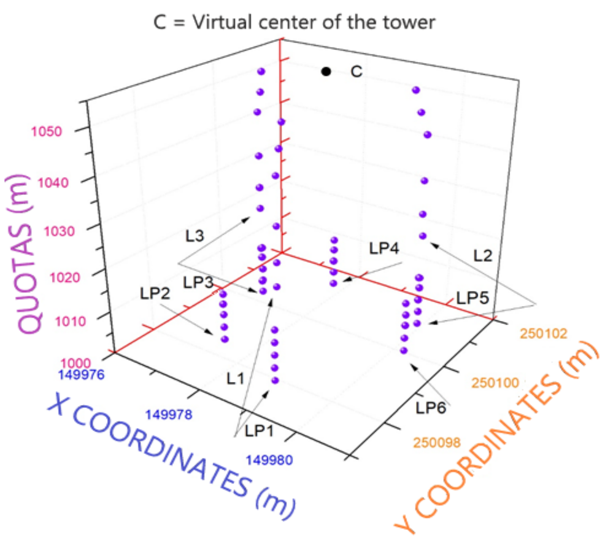


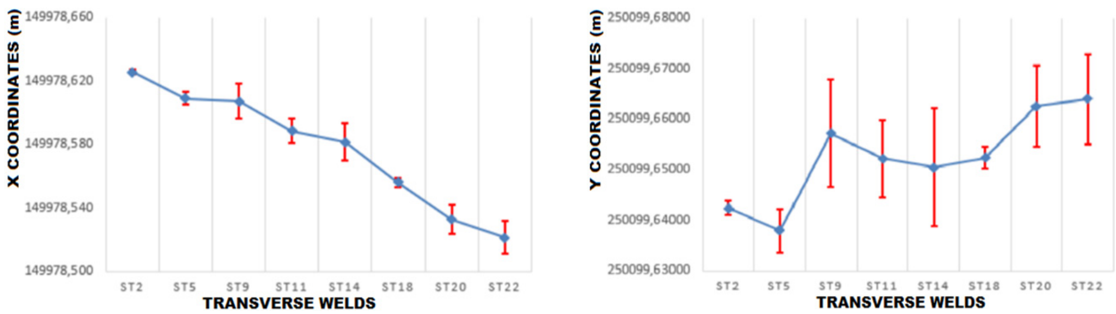
Fig. 9 result of the quotas and coordinates (x,y) of the transverse welds from the reference points a millimetric decrease from ST2 to ST14 and in centimeters from ST18 to ST22, in the same way as the results obtained on the reference point in L2. However, on the L3 reference point, the results of the x coordinates have a growth in centimeters from ST18 to ST22. The y coordinates measured over the reference point L1 and L3 have an increase in millimeters from ST2 to ST18, but with a decrease in the coordinates of ST20 and ST22, obtained in L3, and an increase in the coordinates measured over the reference point L1. At the reference point L2 the results of the y coordinates have a decrease. The reference points of the regular hexagon have an average constant value between the transversal welds, with the standard discrepancy in the x coordinates in ST2 and ST5 over the LP1 reference point.

The behavior of the coordinates of the measurements on the transverse welds gradually decreases with the increase in quota due to the geometry of the tower, but there were discrepant points in this trend, possibly caused by the difficulty of visibility of the object points, due to fog, oscillations, and vibrations of the tower at the time of the measurements.

The coordinates of the center of each circular section of the transversal weld through adjustment by the combined LSM-model, were defined with approximate parameters of the coordinates of the central point and matrix of the weights formed by the inverse of the variance obtained through the propagations acquired in the measurements. Tests were carried out to identify observations with gross errors and hypothesis tests, through the Global Chi-Square Test ($\chi 2$), using the bilateral test with the following degrees of freedom (GL) in the following transversal welds: GL = 1, with hypotheses not rejected in the range $0.001 < \chi 2 < 5.024$ in ST18, ST20 and ST22; and GL = 2, with hypotheses not rejected in the range $0.051 < \chi 2$ 7,378 in ST2, ST5, ST9, ST11 and ST14. Results are illustrated in Figs. 10(a) and 10(b), respectively, of the x and y coordinates with their standard deviations.

According to Fig. 10, the x coordinates show a reduction with the elevation of the quota, with a higher value of 149978.62545 ± 0.00146 m of ST2 and the lower value of 149978.52136 ± 0.01032 m for ST22. The largest standard deviations presented are from the ST9 and ST20 with ± 0.01092 m and ± 0.00930 m, respectively. The y coordinates have an increase with the increase of the quota, with a higher value of 250099.64242 ± 0.00142 m from ST2 and the lower value of 250099.66409 ± 0.00896 m for ST22, with results deviating from the trend in ST9 and ST11. The largest standard deviations presented are of ST14 and ST18 with ± 0.01167 m and ± 0.00224 m, respectively.

The radii of the concentric circular sections and the respective standard deviations obtained from the reference points located in the hexagon and triangle, are shown in Fig. 11. The general



(a) X coordinates (b) Y coordinates

Fig. 10 Combined model: x and y coordinates of the transverse welds

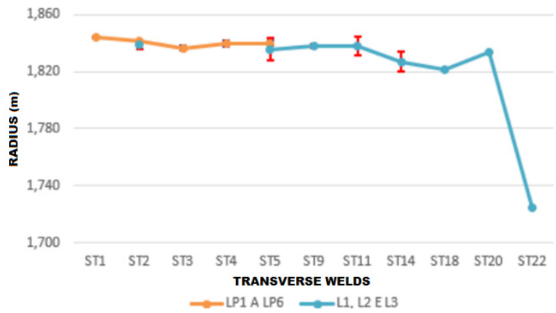
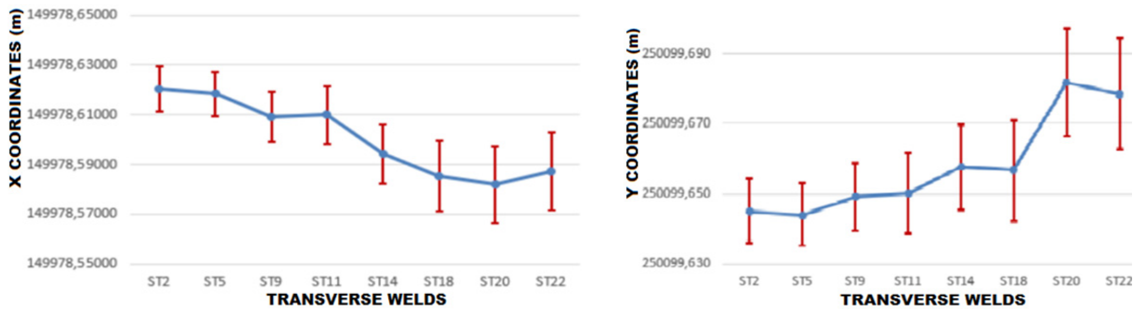


Fig. 11 Radii of circular sections from hexagon and triangle reference points



(a) X coordinates (b) Y coordinates

Fig. 12 Parametric model: x and y coordinates of transverse welds

tendency of the radii of the transversal welds is coherent and coincident between the results obtained in the circular sections observed in common (ST1, ST2, ST3, ST4 and ST5) from the reference points. The radius with the highest value is 1.8473 ± 0.00049 m of ST1 and with the lower value of 1.72453 ± 0.00687 m for ST22.

With the measurements made with the edge measurement method (item 2.4.2), the azimuths regarding the horizontal direction of each transverse weld are obtained from the reference points. Thus, the center coordinates (Fig. 12) of the transverse welds are determined by the LSM using the parametric model and based on the forward intersection method. The following degrees of freedom (GL) were used in the Chi-Square test ($\chi 2$): GL = 2, with hypotheses not rejected in the range $0.051 < \chi 2 < 7{,}378$ in ST1, ST10 to ST13, ST15 and ST22; GL = 4, with hypotheses not rejected in the range $0.484 < \chi 2 < 11.143$ for the other transverse welds.

According to Fig. 12, the x coordinates show a reduction with the increase of the quota, with the higher value of 149978.62040 ± 0.00906 m in ST2 and the lower value of 149978.58747 ± 0.01564 m for ST22. The greater standard deviations presented are of the ST20 and ST22 with ± 0.1535 m and ± 0.1564 m, respectively. The y coordinates are directly proportional with increase of the quota, with discrepant results on the ST18 and ST22 transverse welds, where the highest value is 250099.64513 ± 0.00908 m on ST2 and the lowest value 250099.67834 ± 0.01567 m for ST22. The greater standard deviations presented are of the ST20 with ± 0.01538 and ± 0.01567 m of ST22 m.

The adjustment of observations of the collected data, using the combined model and through the parametric model, respectively, of the measurements with the method of three-dimensional irradiation and edge measurement, proved the possibility of determining the geometry and coordinates of the center of each tower section. The results of the coordinates (x, y) closest to the base, of the highest and respective standard deviations of the circular sections using the three-dimensional irradiation method and adjustment by the combined model was (XST1 = 149978.61090 ± 0.00074 m, YST1 = 250099.64793 ± 0.00065 m) from ST1 and to ST22 (XST22 = 149978.52136 ± 0.01032 m, YST22 = 250099.66409 ± 0.00896 m). The result of the edge measurement method and adjustment by the parametric model were (XST1 = 149978.61214 ± 0.00292 m, YST1 = 250099.64399 ± 0.00369 m) for ST1 and ST22 (XST22 = 149978.58747 ± 0.01564 m, YST22 = 250099.67834 ± 0.01567 m).

The x and y coordinates indicate the position of the center of the circular welds sections of the tower with respect to the local geodetic system. In ideal conditions these centers would be superimposed. However, due to the operation of the tower, the incidence mainly of winds and the inclination of the tower cause the coordinates to vary from welds section to another (Fig. 10 and 12).

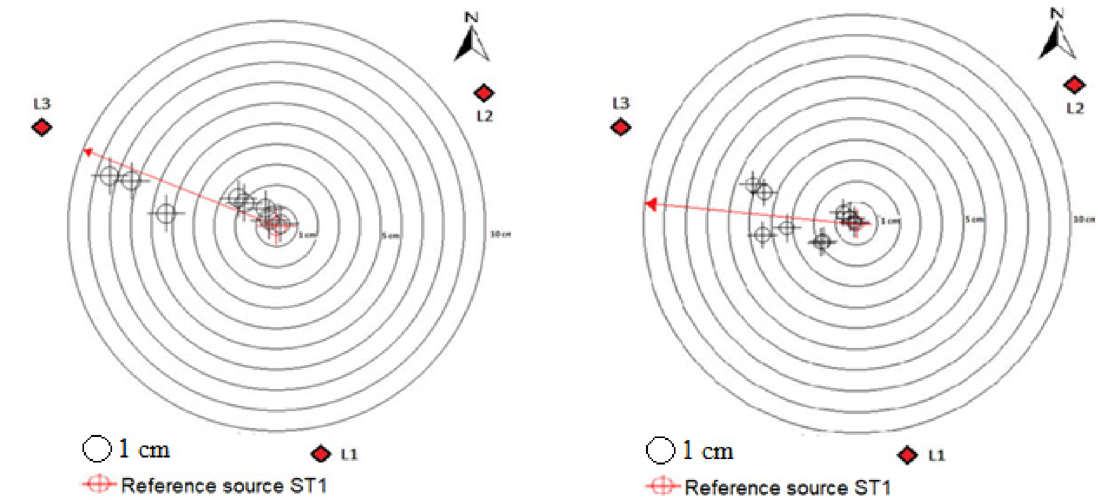
3.4 Tower tilt analysis

The calculation of the deflection angles and the evaluation of the tower tilt direction had the origin of the vertical reference alignment as the center of ST1 for both methods, from the center of the transverse weld obtained from the hexagon reference points. The result of the deflection angles is shown in Table 6 and the result of the evaluations of the tilt direction of the tower are illustrated in Fig. 13.

The behavior of the deflection angle in increasing gradually with the increase in quotas was maintained in the transversal welds, the result of the ST22 being discrepant through the measurement of edges. In Table 6 the difference of the deflection angle in the two methods is gradually increasing with the increase in quotas, because the incidence of wind exerts a greater effort on the tallest structural components of the tower and less on the regions lower, where the tower structures are embedded in the base of its foundation. The analyzes of Fig. 13 illustrate the direction of the tower at the times that the three-dimensional irradiation measurements and the

Table 6 Average quotas of the transverse welds and dispersion measurements from the reference points

Transverse weld (ST)	Deflection angle ($\boldsymbol{\delta}$)	
	Three-dimensional irradiation	Edge measurement
ST2	0°0’3.56”	0°0’2.18”
ST3	0°0’4.70”	0°0’2.28”
ST4	0°0’7.21”	0°0’6.26”
ST5	0°0’14.16”	0°0’12.66”
ST9	0°0’31.07”	0°0’31.91”
ST11	0°0’31.51”	0°0’33.77”
ST14	0°0’37.23”	0°1’6.03”
ST18	0°1’47.29”	0°1’29.37”
ST20	0°2’20.90”	0°1’38.18”
ST22	0°2’42.05”	0°1’27.60”



(a) Three-dimensional irradiation measurement method

(b) Edge measurement method

Fig. 13 Direction of movement of the tower

edge measurement took place, where both are in the north-west direction.

According to item 2.1, the monitored wind tower is 70 meters high. However, it was impossible to carry out measurements of the top of the tower on all reference points from the equilateral triangle. To define the linear displacement and top deflection angle, there was a need to determine a mathematical relationship y = f(x) by adjusting a curve to the measured points of the geometric center of the lower transverse welds. As a result of the points being obtained through measurements, there are errors in the data, and it is unlikely to find a curve of the desired shape that passes through all points. Therefore, it was necessary to determine the coefficients of the function that best fit the data. The Least Squares Method was used to adjust the curve based on the pattern presented by the points.

The results of the three-dimensional irradiation method of the measurements of the second campaign were used because they had results with greater precision and quality. The function used

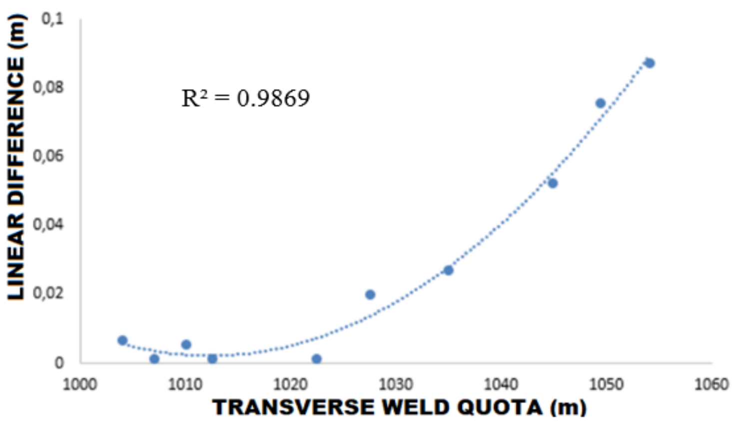


Fig. 14 Polynomial adjustment of the linear displacement function in relation to the quota

used was the linear displacement in relation to its quota. The result based on the presented pattern is a 2nd degree polynomial function. Eq. (4) represents the adjusted function, shown in Fig. 14.

$$\Delta = 10^{-5}c^2 - 0.1011c + 51.191 \tag{5}$$

In which: Δ = Linear difference between the respective geometric centers and c = Quotas of the transversal welds.

The linear displacement between the reference and top alignment was 0.2590 m and the result was 0°8’44.88” for a quota of 70 meters.

4. Conclusions

The purpose of this work is to disseminate the importance and the need for appropriate monitoring in onshore wind towers. This research presents the possibility and effectiveness in the application of geodetic/topographic methods, from the Measurement Reference System, to evaluate the verticality and geometry of the tower by means of reflective targets aligned with the reference points of the triangle, transverse welds between the tower segments and respective edges. The proposed methodology, using geodetic methods and appropriate precision instruments, proved to be adequate and can be used. The results express that the standards likely to be reached for the survey methods used were achieved.

The methodology proposed to evaluate the possible foundation settlements, through the pins implanted in the tower bases to be monitored, by means of high precision geometric leveling, served to demonstrate the possibility and necessity for the auscultation of the vertical movement of the onshore wind tower. Three-dimensional irradiation methods and the edge measurement method were used to determine the coordinates of the center of the transverse welds. In general, the results were compliant across the length of the tower, being more discrepant in the transverse welds starting at ST14 due to the larger movements closer to the top of the tower.

Using the combined method, it was possible to determine the radii with their respective standard deviations from the circular sections formed by the transversal welds. The results are consistent and analogous in most transverse welds, exhibiting the tendency for the radii to be equal or less with increasing tower height. The radii with the greatest discrepancies are those obtained with higher quotas than the ST14. The results of the measured cohesive radii closest to the base (ST3) and the highest (ST22) in addition to the respective standard deviations of the circular sections were RST1 = 1.84373 ± 0.00049 m for ST1 and RST22 = 1.72453 ± 0.00687 m.

The general analysis of the tower’s verticality from the deflection angle of the vertical reference alignment and the geometric center of the ST22, was performed by calculating the average deflections of the results obtained through the three-dimensional irradiation method, due to the results of the edge measurement have been impaired due to the oscillations and vibrations of the tower. The result of the deflection between the coordinates of the center of the circular section of the ST22 and the vertical reference alignment was 0°2’39.22”± 2.83” in the Northwest direction and average linear difference of 0.0878 ± 0.0078 m. A curve was adjusted to the measured points of the geometric center of the transverse welds to determine the deflection angle of the transverse weld at the top of the tower, defined from a non-linear function adjusted by LSM. The result was 0°8’44.88” and a linear difference of 0.2590 m. It can be concluded that the consideration of the angle at which the wind hits the structure is of fundamental importance to assess the behavior of the wind tower, since it can directly interfere in the structural security of the tower.

Depending on the results obtained and the analyzes carried out, it is recommended to analyze the stability of the reference points in each measurement campaign to check for possible differences between the coordinates of the same point for the measurement times; employment of total stations with higher precision or robotic stations than those used in this research, implantation of reflective target stickers on the tower at different heights, in order to serve as targets for measurements at different times; carrying out the measurements with the turbine turned off, in order to suppress the propagations of the vibrations generated and caution during the measurements using the edge measurement method, because of the oscillations and vibrations of the tower, especially in the higher parcels.

Currently there are robotic and multifunctional total stations, which allow measuring and identifying object points in extreme measurement conditions. In addition to the advantage of automation of measurement procedures. In the dynamic monitoring system, it is possible to introduce other observation variables such as temperature, pressure, air humidity, wind, in order to study and correlate the different variables to the vertical and horizontal movement of the wind tower. These different effects have not been considered so far, which is recommended for future research.

Acknowledgments

The authors are grateful to Eólica Tecnologia for authorizing research on the towers of the wind farm in Gravatá-PE and for offering technical support. The Federal University of Pernambuco (UFPE), through the Postgraduate Program in Geodetic Sciences and Geoinformation Technologies (PPGCGTG), for making available the Geodesy Laboratory (LAGEO) and Topography Laboratory (LATOP), as well as the concession of equipment and accessories. To Professor Dr. Sílvio Jacks dos Anjos Garnés for providing the use of AstGeoTop software and students of the Postgraduate Program in Geodetic Sciences and Geoinformation Technologies (PPGCGTG), Leonardo Carlos Barbosa, Priscilla Heliênay Oliveira do Nascimento Pestana and Welisson José dos Santos, and the student in Electronic Engineering at the University of Pernambuco, Italo Garcia Campos do Canto, who contributed to the geodetic surveys.

To the Coordination for the Improvement of Higher Education Personnel - Brazil (CAPES) - Financing Code 001, for the financial support. To the Control and Monitoring of Settlements Research Project - Building under Construction of the Integrated Laboratory for Technology in Oil, Gas and Biofuels - LITPEG/CTG/UFPE processes no. 3076.040512/2015-15 and no. 23076.016133/2018-57.

References

ABNT (1994), NBR 13133 – Normas Técnicas para a Execução de levantamento topográfico, Rio de Janeiro, RJ, Brazil.

Caithness Wind Farm (2021), Annual wind generation newsletter: Summary of Wind Turbine Accident. Available in: http://www.caithnesswindfarms.co.uk/AccidentStatistics.htm. Accessed on: 12 may 2021.

Canto, L.F.C. (2018), "Metodologia para o Monitoramento Geodésico em Torres Eólicas Onshore", Dissertation, Universidade Federal de Pernambuco – Programa de Pós-Graduação em Ciências Geodésicas e Tecnologias da Geoinformação, Recife, Brazil.

Canto, L.F.C. and Seixas, A, (2018), "Geodésia aplicada para o estudo de verticalidade em torres eólicas onshore", *Simpósio Brasileiro de Ciências Geodésicas e Tecnologias da Geoinformação* (*SIMGEO*), Recife, Brazil, November.

Canto, L.F.C. and Seixas, A. (2020), "Auscultação Geodésica em Torres Eólicas Onshore: Definição do Sistema de Referência e de Medição para o Monitoramento", *Revista Brasileira de Cartografia*, **72**(2), 294-311. https://doi.org/10.14393/rbcv72n2-50539

CEPEL, CRESESB (2008), Tipos de Aerogeradores para Geração de Energia Elétrica. Available in: http://www.cresesb.cepel.br/index.php?section=com_content&lang=pt&cid=231. Accessed on: 04 Apr. 2020.

Department of Army – U.S. (1994), Deformation monitoring and control surveying, Washington, DC, USA.

Dragomir, P.I., Negrilă, A.F.C. and Sărăcin, A. (2014), "Geodesic techniques used to monitoring the wind turbines towers". *RevCAD*, Alba Iulia, Romania, December.

Engström, S., Lyrner, T., Hassanzadeh, M., Stalin, T. and Johansson, J. (2010), "Tall towers for large wind turbines", *Report from Vindforsk project V-342 Höga torn för vindkraftverk*. *Elforsk rapport*, 10-48.

Gemael, C., Machado, A.M.L. and Wandresen, R. (2015), *Introdução ao ajustamento de observações*: *aplicações geodésicas*, (2th Edition), Editora UFPR, Curitiba, PR, Brazil.

Hau, E. (2007), *Wind Turbines Fundamentals*, *Technologies*, *Application*, *Economics*, Springer Verlag, Heidelberg, Berlin, Germany.

Hesse, C., Heer, R., Horst, S. and Neuner, H. (2006), "A concept for monitoring wind energy turbines with geodetic techniques", *3rd IAG / 12th FIG Symposium*, Baden, Austria, May.

International Organization for Standardization (ISO) (2001), 17123-1: Optics and optical instruments – Field procedures for testing geodetic and surveying instruments – Part 2: Levels, International Organization for Standardization. Switzerland.

Kahmen, H. (2006), *Angewandte Geodäsie*: *Vermessungskunde*, (20th Edition), De Gruyter, Einbeck, Northeim, Germany.

Kahmen, H. and Faig, W. (1988), Surveying, De Gruyter, Berlin, Germany.

Krelling, P.C.L. (2006), "Concepção de um inclinômetro foto mecânico para controle geodésico de estruturas", Ph.D. Dissertation; Universidade Federal do Paraná, Curitiba, Brazil.

Negrilă, A.F.C. (2020), "Methods for Calculating the Inclination of the Round Section Towers", *FIG Working Week 2020*, Amsterdam, Netherlands, May.

Netto, N.P., Blitzkow, D., Bueno, R.F., Fonseca, E.S., Mazzilli, C.E.N. and Lachapelle G. (2002), "Structural Monitoring Using GPS Receivers", *3ª Assembléia Luso-espanhola de Geodésia e Geofísica*, Valência, Spain, February.

Rezo, A., Branimir, M. and Slavica, B. (2016), "Geodetic works during the establishment of. wind power plants", *SIG 2016 – International Symposium on Engineering Geodesy*, Varaždin, Croatia, May.

Santos, W.J. (2020), "Sistemas de medição geodésica e detecção de movimentos 3D em terrenos inclinados susceptíveis a recalques e deslizamentos", Dissertation; Universidade Federal de Pernambuco – Programa de Pós-Graduação em Ciências Geodésicas e Tecnologias da Geoinformação, Recife, Brazil.

Seixas, A. and Burity, E.F. (2005), "Geodésia aplicada à medição e ao monitoramento de áreas de risco em sítios industrializados", *IV CBCG*, Curitiba, Brazil, May.

Way, A.C. and Van Zijl, G.P.A.G. (2015), "A study on the design and material costs of tall wind turbine towers in South Africa", *J. South Afr. Inst. Civil Eng.*, **57**(4), 45-54. https://doi.org/10.17159/2309-8775/2015/v57n4a6

Widerski, T. and Kurałowicz, Z. (2009), "Geodesic monitoring of tower and mast structures", *Reports on Geodesy*, 411-417.

HL