Methods for Calculating the Inclination of the Round Section Towers

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Key words: deformation measurement, engineering survey, GNSS, inclination, risk management

SUMMARY

Determination of the inclination from verticality, using geodetic methods, can be done in more ways, depending on the position of the observation points. The paper will show the most common aproaches for calculating the position for the tower center at each level using measurement made from two observation points or three observation points. The most common way is the determination of the directions toward the center of the tower as the average of horizontal directions tangent to the tower and then of the transverse deviations on each direction through composition of the resulting vectors, determining the inclination at each level of the tower. Another way is by determining the position using forward intersection of the horizontal directions toward the center of the tower and then calculating the deviations for each observed level.

REZUMAT

Determinarea abaterii de la verticalitate, folosind metode geodezice, se poate face în mai multe moduri, în funcție de poziția punctelor de observare. Lucrarea va arăta cele mai frecvente abordări pentru calcularea poziției centrului turnului de la fiecare nivel, folosind măsurători efectuate din două puncte de observație sau trei puncte de observație. Cea mai folosită metodă este măsurarea direcțiilor către centrul turnului ca medie a direcțiilor orizontale tangente la turn și apoi a abaterilor transversale pe fiecare direcție prin compunerea vectorilor rezultați, determinând înclinarea la fiecare nivel al turnului. O altă modalitate este prin determinarea poziției folosind intersecția înainte a direcțiilor orizontale spre centrul turnului și apoi calcularea abaterilor de la verticalitate pentru fiecare nivel observat.

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1. INTRODUCTION

In order to determine the inclination of the constructions by angular measurements, a network of monitoring points must be provided in the area of the monitored object so as to ensure the determination of the displacements from at least two perpendicular directions (Neamtu, 1988), as in the following figure.

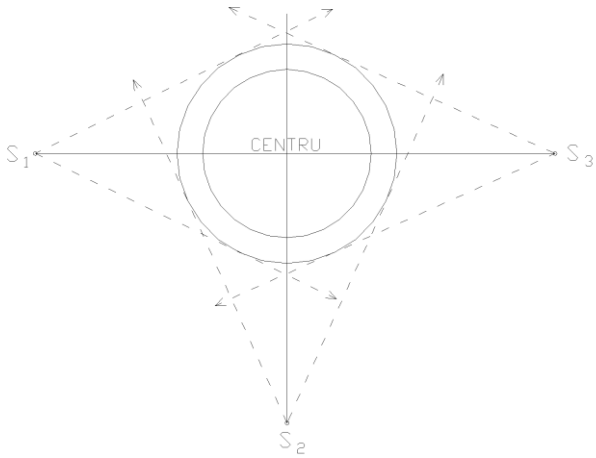

Fig. 1 – Monitoring networks

The observation points S_j must be located at a distance $D \geq H$ (H = construction height), to reduce the influence of the verticality error of the main axis of rotation (VV) of the instrument and not to fall below 2/3 H.

2. DETERMINING THE INCLINATION USING TWO MEASURING POINTS

The most appropriate and often used procedure for such constructions is to measure the horizontal angles, as shown in figure 2.
On the construction axes the observation points 1, 2, 3 and 4, respectively 5, 6, 7 and 8 are set and the orientation points P_i are chosen, which must be distant, stable and clearly visible.
The determination is made by comparing the position of the tower center at different levels with the position of the tower center at the foundation level (Onose, 2003).
From the stations S_j the horizontal angles α_i are measured, and the semisums A, B, C, D are calculated, which gives the directions to the center of the construction at the respective level, with the formulas:

$$A = \frac{\alpha_2+\alpha_3}{2} \qquad B = \frac{\alpha_1+\alpha_4}{2} \quad C = \frac{\alpha_6+\alpha_7}{2} \quad D = \frac{\alpha_5+\alpha_8}{2} \quad (1)$$

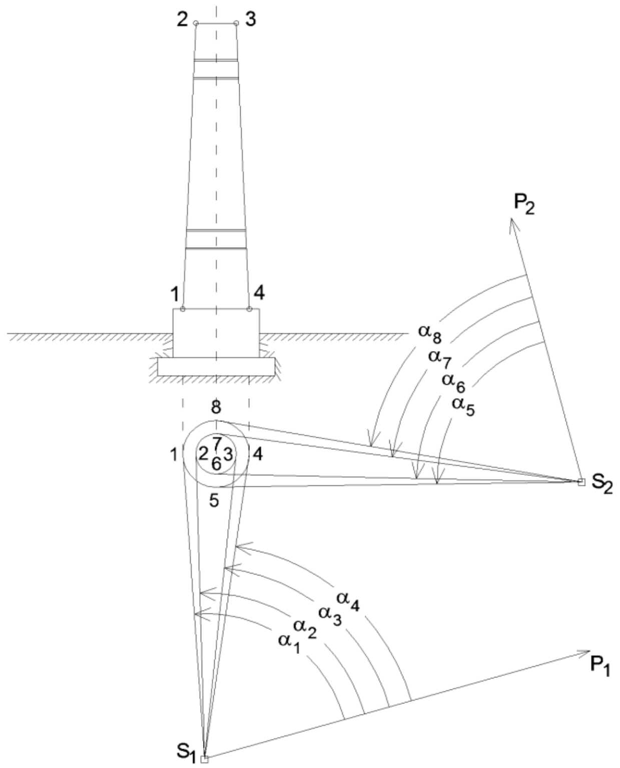

Fig. 2 – Determination of inclination of round section constructions

The distances from the station points S_j to the center of the construction (C) are then determined, measuring the distance to the foundation of the tower (BT) to which is added the radius (R) from the base (the accuracy of determination can be between ± 10 - 20 cm).

$$D_{Sj-C} = D_{Sj-BT} + R \qquad (2)$$

By comparing the averages of the angles at the top A and C with those at the base B and D, the angular deviations Δα of the center of the top from the center of the base are obtained.

$$\Delta\alpha_{S1} = B - A \qquad \Delta\alpha_{S2} = D - C \qquad (3)$$

With the angular deviations and with the measured distances, the linear deviations q_1 and q_2 are calculated according to the relation:

$$q_j = \frac{\Delta\alpha_{Sj}}{\rho} \cdot D_{Sj-C} \qquad (4)$$

The total dimension of the increase of the inclination Q expressed in a linear form is obtained from the composition of the vectors q_1 and q_2 which represent the linear quantities of the transverse inclinations determined from the station S_1 and S_2, according to the relation:

$$Q = \sqrt{q_1^2 + q_2^2} \quad (5)$$

Depending on the signs of the angular deviations $\Delta\alpha$, the sign of the deviations q_1 and q_2 is also established, their vectorial composition offering the inclination direction of the studied objective.
Through the vectorial composition, the size and direction of the inclination result, below being the graphical representation of the linear deviations.

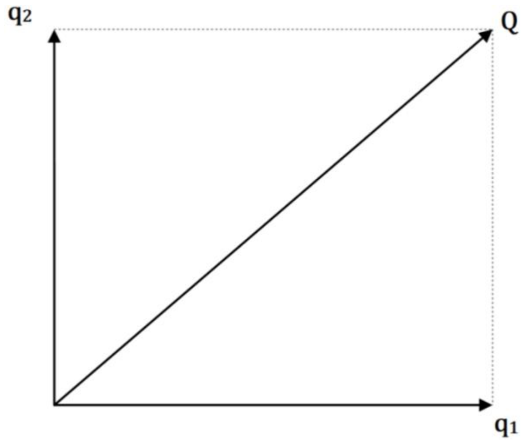

Fig. 3 – Composition of tilt vectors

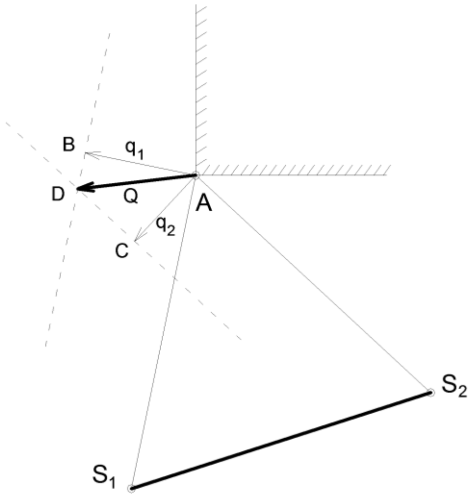

Fig. 4 – Graphical determination of the inclination of the construction

If the conditions in the field do not allow the choice of the stations on two perpendicular directions, and must be chosen arbitrarily, the size and direction of the inclination can be determined graphically (Neamtu, 1988). In the case of lack of a situation plan, a scale drawing shall be drawn up, which shall include the positions of stations S_1 and S_2 and of point A; after which the linear quantities q_1 and q_2 are calculated with the relations (4) and are drawn in natural or reduced value (1:2, 1:5) perpendicular to point A on the corresponding directions, as in the figure 4.
The extremities of these components are noted in the figure with B and C, through them being drawn parallels to the initial directions that will intersect at point D. The inclination size is determined by graphically measuring the AD segment, the direction resulting from the sketch.

This graphic approach is efficient, in case of constructions with round section, of reduced height.
For high constructions (over 50 - 60m) determinations will be made at different levels, which are related to the angular measurements made at the base of the construction.
For the situation in which the points from which the determinations are made are located on perpendicular directions to the construction, the calculation method mentioned first can be applied.
In the situation where the points cannot be placed on perpendicular directions, a method of analytical calculation should be chosen, because the graphical approach for each level would not be efficient.

3. DETERMINING THE INCLINATION USING THREE MEASURING POINTS

In the following will be presented the calculation method for determining the deviation from the verticality of the tower of a wind turbine, which has a height of about 105 m, being constructed of concrete and metal. In this case the project required the placement of three station points from which the tower determinations were made for three different positions of the nacelle.
The design operation was carried out at the office following the observance of the requirements for this type of tower, the points having to form an equilateral triangle that encloses the tower. Starting from the coordinates of the center of the tower, the positions S1, S2, S3 from which the observations will be made are established at approximately 105 m from the center of the tower.
The layout of these points (S1, S2, S3) is represented in the figure below, in which the elements of the created equilateral triangle are also indicated.

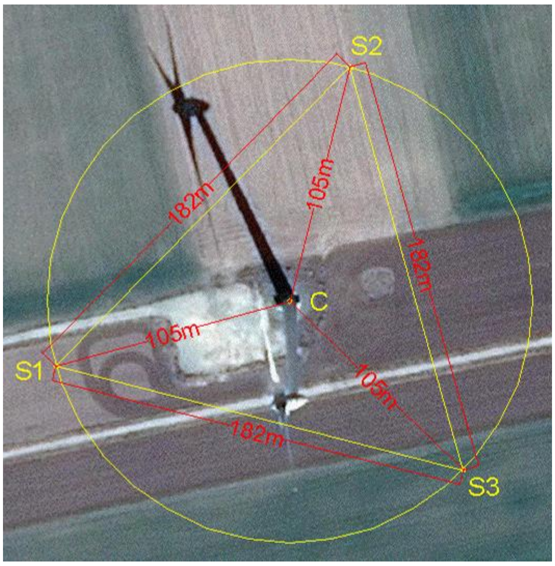

Fig. 5 – Layout of projected points

GNSS technology can be used to perform the stakeout operation, allowing the positioning of points S1, S2, S3 to be done with centimeter accuracy, using the RTK method (Dragomir, 2014).

The marking is generally done with wooden pickets or with anchor type markers, as these points can be easily destroyed by agricultural works (the position of the points is usually in agricultural land).

High precision determination of the positions of points S1, S2, S3 and determination of the positions of the center of the wind power tower at the required levels was performed using instruments that have the standard deviation of 2” for the determination of angles and of 2mm + 2ppm for distances. From each point observations were made in both positions of the telescope, for the inclined visas using the diagonal eyepiece. Aspects during the measurements can be seen in the following pictures.

Fig. 6 – Aspects during the measurements

The observations to the tower were made according to the following sketch.

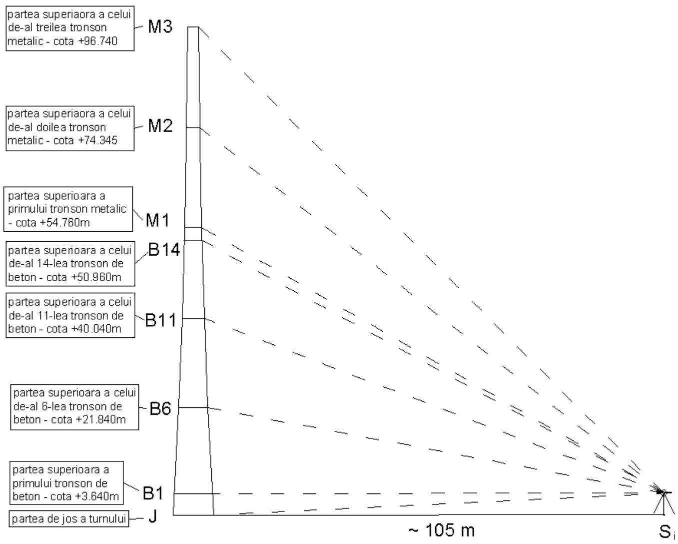

Fig. 7 – Measuring sketch

The distances from the station points to the center of the tower were determined by forward intersection and verified by direct measurement to the base of the tower, to which was added the radius from the base.
For each position of the nacelle there were made three stations, with the corresponding observations.
Using the aforementioned measurements, the coordinates in the local system were determined for the points from which the observations were made. The measurements were rigorously processed at each stage (Negrila, 2013), using least square method, obtaining the average standard deviation of the network composed of all points and the individual standard deviations for each point separately (between 1.1 mm and 1.7 mm).
The coordinates obtained for each level (B1, B6, B11, B14, M1, M2, M3) were used to determine the displacements from the center of the tower base (J) in the local cartesian coordinate system, obtaining the displacement in the direction x (q_x), displacement in the direction y (q_y) and total displacement - deviation from the vertical (Q), corresponding to each position of the nacelle. The results can be found in table 1, 2 and 3.
Deviations of the tower from verticality (Q_M), for each level, can be determined as an average of the deviations determined for each position of the nacelle, thus eliminating the influence of the nacelle on the tower. The averages can be found in table 4.

Tab. 1 – Deviations of the tower from verticality in position 1 of the nacelle

Position 1 of the nacelle			
Level	**q_X (m)**	**q_Y (m)**	**Q (m)**
B1	-0.002	0.001	0.002
B6	-0.009	-0.002	0.009
B11	0.000	-0.020	0.020
B14	-0.005	-0.032	0.032
M1	-0.004	-0.042	0.042
M2	-0.003	-0.105	0.105
M3	0.016	-0.234	0.235

Tab. 2 – Deviations of the tower from verticality in position 2 of the nacelle

Position 2 of the nacelle			
Level	**q_X (m)**	**q_Y (m)**	**Q (m)**
B1	-0.001	0.000	0.001
B6	-0.009	0.002	0.009
B11	-0.003	-0.005	0.006
B14	-0.010	-0.008	0.013
M1	-0.013	-0.012	0.018
M2	-0.032	-0.025	0.041
M3	-0.065	-0.030	0.072

Tab. 3 – Deviations of the tower from verticality in position 3 of the nacelle

Position 3 of the nacelle

Level	q_X (m)	q_Y (m)	Q (m)
B1	-0.001	0.001	0.001
B6	-0.005	0.001	0.005
B11	0.011	-0.008	0.014
B14	0.016	-0.010	0.019
M1	0.019	-0.014	0.024
M2	0.053	-0.033	0.062
M3	0.149	-0.052	0.158

Tab. 4 – Deviations of the tower from verticality without influence of the nacelle

Without influence of the nacelle			
Level	**q_{XM} (m)**	**q_{YM} (m)**	**Q_M (m)**
B1	-0.001	0.001	0.001
B6	-0.008	0.000	0.008
B11	0.003	-0.011	0.011
B14	0.000	-0.017	0.017
M1	0.001	-0.023	0.023
M2	0.006	-0.054	0.055
M3	0.033	-0.105	0.110

In the table below the deviations related to the tower height in mm/m were calculated for each observed level, depending on the position of the nacelle and in case of elimination of the influence of the nacelle.

Target level	Target level height (m)	Position 1 of the nacelle	Position 2 of the nacelle	Position 3 of the nacelle	Without influence of the nacelle
		Deviation (mm/m)	Deviation (mm/m)	Deviation (mm/m)	Deviation (mm/m)
B1	+3.64	0.6	0.3	0.4	0.4
B6	+21.84	0.4	0.4	0.2	0.4
B11	+40.04	0.5	0.1	0.3	0.3
B14	+50.96	0.6	0.3	0.4	0.3
M1	+54.76	0.8	0.3	0.4	0.4
M2	+74.345	1.4	0.5	0.8	0.7
M3	+96.74	2.4	0.7	1.6	1.1

Similar results are obtained using only the linear deviations (q) determined from each measuring station, using formulas (4), based on the angular deviation from the target level towards the base of the tower (Negrila, 2019). The following calculation algorithm is used, developed for the case where the points from which the determinations are made are located so as to form an equilateral triangle, with the tower located in the center of weight, as can be seen in the following figure.

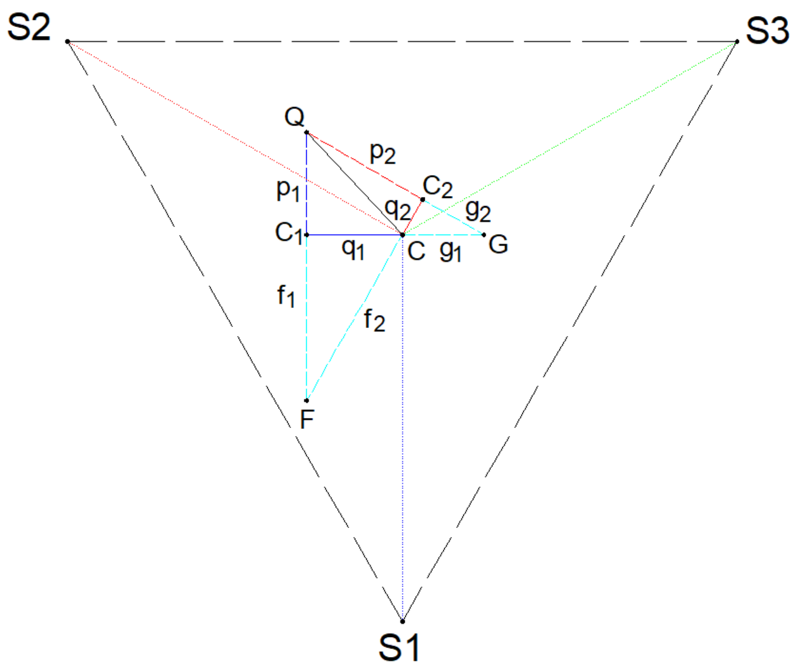

Fig. 8 – Calculation algorithm sketch

The first step is to define a local cartesian coordinate system (for each station point) with the center at point C, the positive direction being up for the *x* axis and to the right for the *y* axis. Thus we will have the displacement in the direction *x* noted $\mathbf{q_x^{Si}}$ and the displacement in the direction *y* noted $\mathbf{q_y^{Si}}$, the total displacement – the deviation from the vertical being noted Q. In figure 8 were made the notations $\boldsymbol{q_x^{S1}} = -\boldsymbol{p_1}$ and $\boldsymbol{q_y^{S1}} = \boldsymbol{q_1}$, corresponding to the determinations made from the S1 station, and $\boldsymbol{q_x^{S2}} = \boldsymbol{p_2}$ and $\boldsymbol{q_y^{S2}} = \boldsymbol{q_2}$, corresponding to the determinations made from the S2 station, similarly being able to make the notations for station S3, the problem being the determination of $\mathbf{p_i}$. For the determination of $\mathbf{p_i}$ we will use pairs of values $\mathbf{q_i}$ ($q_1 - q_2$ / $q_2 - q_3$ / $q_3 - q_1$), determined from each station S_i, using formulas (6) and (7).

$$p_1 = \frac{q_1 \cdot sin\widehat{QGC_1} + q_2}{sin\widehat{C_1QG}} \qquad (6)$$

$$p_2 = \frac{q_1 + q_2 \cdot sin\widehat{C_2FQ}}{sin\widehat{FQC_2}} \qquad (7)$$

In order to be able to use the results from all the combinations, we will have to maintain a single cartesian coordinate system, for example the one created for the S_1 station. Thus through the geometric transcalculation (Onose, 2004), using the formulas (8) and (9) will be found the reduced values at station S_1, from the values determined in station S_2. Similarly it works for all combinations.

$$(q_x^{S1})' = q_y^{S2} \cdot \sin\left(-\widehat{S_2CS_1}\right) + q_x^{S2} \cdot cos(-\widehat{S_2CS_1}) \qquad (8)$$

$$\left(q_y^{S1}\right)' = q_y^{S2} \cdot \cos\left(-\widehat{S_2CS_1}\right) - q_x^{S2} \cdot sin(-\widehat{S_2CS_1}) \qquad (9)$$

The final result, $\mathbf{q_x}$ and $\mathbf{q_y}$, for each target level, will be obtained as an arithmetic average of the three combinations.

4. CONCLUSIONS

Depending on the position of the observation points, the determination of the deviation from the verticality, using geodetic methods, can be done in several ways.

The most used method is using measurements made from two observation points, obtaining the transverse deviations in each direction, and by composing the resultant vectors, determining the inclination at each level of the tower.

If the measurements are made from three observation points, which are not located on directions perpendicular to the tower, the position determination is made using the forward intersection of the horizontal directions determined towards the center of the tower and then calculating the deviations from verticality for each observed level.

If the position of the tower and the points from which the observations are made are known, in the same coordinate system, if only the tower can be targeted, then the final results will be obtained using the calculation method presented in the last part of the paper.

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