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Measurements of Displacements and Deformations and Reliability Analysis of Base Transceiver Station (BTS) Made of Steel

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Abstract. Safety and reliability of BaseTransceiver Station (BTS) in Global System for Mobile Communications (GSM) should be provided not only at the design stage and construction work, but also during the service. The technical conditions and safety of building structures is also dependent on the determination of geometric deviation of the entire structure and its individual components. This should be referred to the recommendations of code limits. The geodetic measurements of displacements and deformations of objects are extremely important to evaluate the stability and security of the structure and its maintenance. Steel trusses or concrete columns must meet the requirements of building standards and instructions as well as the standard requirements for the deviation limits during the construction phase and operational work. The primary and overarching objective of inventory of BTS is to ensure that the safety of the service and the users is fulfilled. The investigation of the reliability of BTS towers by determining the reliability index value using First Order Reliability Method (FORM) recommended in Eurocode 0 will be perfomed. The values of reliability index will be defined for the serviceability limit.

Keywords: serviceability limit, reliability of structure, inventory surveys of BTS.

Conference topic: Technologies of geodesy and cadastre.

Introduction

The safety and reliability of tower buildings should be provided not only at the design stage and manufacturing, but mainly at the stage of use. The technical condition and safety of tower depends inter alia on determining the geometric deviation of the whole structure and its individual components and comparing them to the limit states defined by the standards recommendations. Measurements of displacements and deformations of objects are extremely important to determine the durability and technical safety of engineering structures. The steel towers and masts must meet not only the requirements and recommendations of the ER-01 "Exploitation of towers and masts" manual (Instrukcja ER-01 1994), but also because of its design should be done in accordance with the provisions and recommendations of relevant industry standards (PN-ISO 2364:2000; PN-B-03204:2002; PN-EN 1990:2004; PN-EN 1993-3-1:2008) and their deviation should not exceed the limits specified in these standards.

The primary and overarching objective of inventory surveys of telecommunications towers and masts is to ensure the safety of both the usage and users, because telecommunications infrastructure is one of the critical infrastructure providing for the security of the state. By contrast, the minor (secondary) objective is striving to reduce the cost of inventory surveys, thus increasing the economic efficiency of surveys.

The main aim of monitoring of slender structures is determination of its verticality. The height of such object is several times higher than the maximum width of the structure. The most advantageous method of measurement may be a photogrammetric method (Maas, Hampel 2006) or a terrestrial laser scanning (Dumalski *et al*. 2013). This methods are unbiased against observer errors and allows to determine the spatial position of large sets of points on the object surface. Also methods based on GNSS technology (Cazzaniga *et al*. 2006) are often used. Despite of the development of the innovative techniques, in practice, traditional measurement methods are still used, especially in cases of periodic measurements. This paper presents the classical polar method of measurements with usin of refrectorless distance measurements to determine the reliability index value using FORM method.

Normative requirements for serviceability limit states

Essential technical requirements for the terms and situations in which you must make the diagnostic examinations and the scope of required calculations and analyzes are specified in the ER-01 "Exploitation of towers and masts" manual (Instrukcja ER-01 1994). According to this instruction the following steps should be carried out:

- basic and periodic inspections,
- the main and current repairs,
- measurements and adjustments and periodic maintenance.

The basic inspection is an internal control performed once or twice a year or ad hoc in the event of hurricane wind. While periodic inspection is an external audit, the frequency of which depends on the category of the tower. According to the guidelines of ER-01 manual deviation of the axis of the tower from the vertical line greater than H/750 is one of the defects that threaten the safety of the structure and requires immediate repair. The deviations greater than H/1000 are classified as defects deteriorating condition of the structure, which repairs must be done within a year. Where H is the total height of the constructions (Instrukcja ER-01 1994).

Recommended by the PN-B-03204:2002 standard limit values of deformations should be limited to the values given by the users of the tower depending on its purpose. Unless otherwise agreed, the following limits should be taken:

- horizontal displacement of the tower or mast not greater than 1/100 of the total height,
- mast nodes horizontal displacement not greater than 1/100 of the distance of the node from the base of the mast,
- the maximum deflection of spans of the mast on a line between nodes not greater than 1/250 of span length,
- deflection of the truss not greater than 1/200 of the length of the rod.

The EN 1993-3-1:2008 standard in its Annex B provides that the criteria for serviceability that is displacements and rotations are defined in the design specification by the customer and does not provide the reference limits.

Geodetic measurements of displacements should be carried out in accordance with industry requirements in relation to surveying (Ustawa1994; Rozporządzenie 1995; Rozporządzenie 2011; Obwieszczenie 2016).

The BTS tower geodetic survey

The inventory surveys of telecommunication masts and towers can be accomplished using a variety of measurement techniques, from classic to modern, advanced measurement techniques. In case of the analyzed BTS tower reflectorless measurements with total station instrument was used.

A brief description of research object

Tested steel truss tower has a cross-section in the shape of a triangle. Vertical curbs of tower are uniformly convergent, not refracted along its length. The bottom of the BTS tower is firmly established with additional props (Fig. 1a and 1b). Total height of examined structure is about 40 m (Kwiecień 2016).

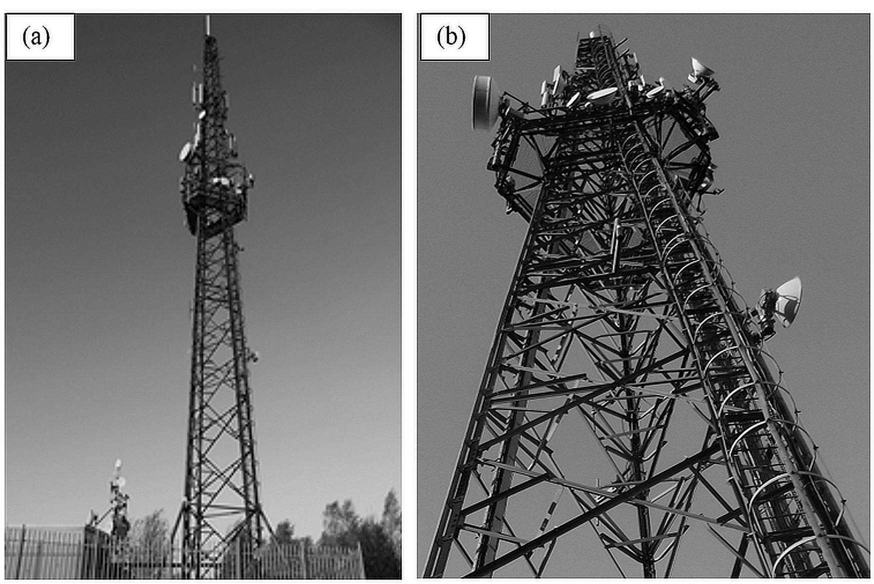


Fig. 1. The object of research: a) – general view; b) – close view

Method of measurement

To measure the tower's vertical axis deflections in horizotal plane the Total Station instrument (South NTS-362R) with reflectorless mode of distance measurements was used. Basic specification of the instrument are listed in Table 1. Reflectorless mode has enabled quick measurements with no need of access to highly-placed measured points. The measurement was carried out from one position to five horizontal cross-sections of the tower structure (Fig. 2).

Table 1. Basic specification of the South NTS-362R

Feature	South NTS-362R
Accuracy of angle measurement	2"
Accuracy of reflectorless distance measurement	±(5 + 2ppm ×D) mm
Range of reflectorless distance measurement	300 m
Plate vial	30" / 2mm
Circular vial	8' / 2mm
Minimal Focus dictance	1 m
Auto compensator	Dual axis, Liquid-electric
Working range of compensator	±3'
Accuracy of compensator	3"

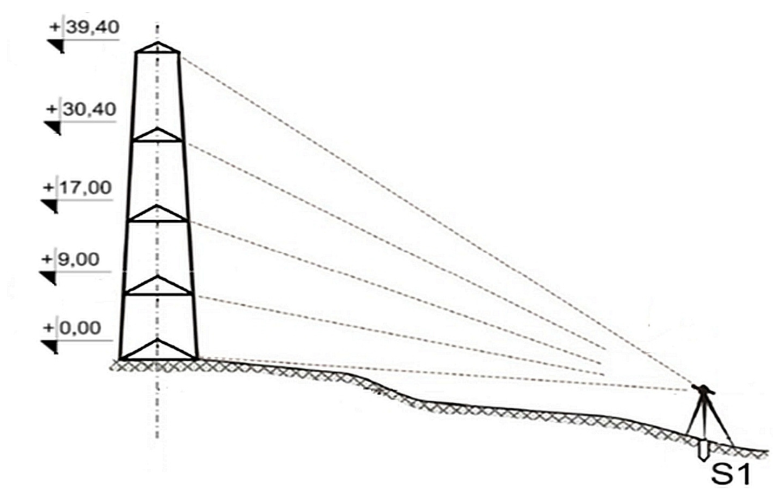


Fig. 2. Schematic drawing of measured cross-sections of BTS tower

The measurements took place in the early hours, in calm weather. The same points of aiming were selected by analogy at subsequent cross-sections at each of outher vertical curbs of tower (Fig. 3).

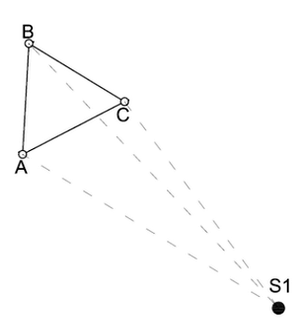


Fig. 3. Schematic drawing of measurement of one cross-sections of BTS tower

On the basis of the observations the coordinates of all points in a local reference system according to well known formula (1; 2) were determined. The beginning of the reference system was the point of geometric intersection of the vertical rotation axis of the instrument, the horizontal axis of telescope rotation and the line of sight of the telescope. Coordinates of reference system beginning point were arbitrarily adopted (Kwiecień 2016).

$$X_i = X_{S1} + S \cdot \sin V \cdot \cos\alpha; \tag{1}$$

$$Y_i = Y_{S1} + S \cdot \sin V \cdot \sin\alpha, \tag{2}$$

where: X_i, Y_i – coordinates of measured points; X_{S1}, Y_{S1} – coordinates of reference system beginning point; S – slope distance; V – zenith angle; α – horizontal bearing.

With the law of propagation of measurements formulas (3; 4) for the coordinates of the points uncertainty can be derived (Baran 1987; Preweda 2013):

$$m_{Xi} = \sqrt{\left(sinV \cdot cos\alpha \cdot m_S\right)^2 + \left(S \cdot cosV \cdot cos\alpha \cdot m_V\right)^2 + \left(S \cdot sinV \cdot sin\alpha \cdot m_\alpha\right)^2}\ ; \tag{3}$$

$$m_{Yi} = \sqrt{\left(sinV \cdot sin\alpha \cdot m_S\right)^2 + \left(S \cdot cosV \cdot sin\alpha \cdot m_V\right)^2 + \left(S \cdot sinV \cdot cos\alpha \cdot m_\alpha\right)^2}\ , \tag{4}$$

where: m_{Xi}, m_{Yi} – coordinates of the point uncertainty; m_S – accuracy of reflectorless distance measurement; m_V – accuracy of vertical angle measurement; m_α – accuracy of horizontal angle measurement.

While uncertainty of coordinates of the center of gravity for individual cross-section will be presented as follows (5; 6):

$$m_X = \frac{m_{Xi} \cdot \sqrt{3}}{3}\ ; \tag{5}$$

$$m_Y = \frac{m_{Yi} \cdot \sqrt{3}}{3}\ , \tag{6}$$

where: m_X, m_Y – uncertainty of coordinates of the center of gravity of cross-section.

The axis of the tower tilt from vertical line in two perpendicular vertical planes are the difference of coordinates of the centers of gravity of particular sections with respect to the lowest cross-section, thus (7; 8):

$$m_{WX} = m_X \cdot \sqrt{2} = \frac{m_{Xi} \cdot \sqrt{6}}{3}\ ; \tag{7}$$

$$m_{WY} = m_Y \cdot \sqrt{2} = \frac{m_{Yi} \cdot \sqrt{6}}{3}\ , \tag{8}$$

where: m_{WX} – uncertainty of horizontal displacement in ZX plane; m_{WY} – uncertainty of horizontal displacement in ZY plane.

On assumption of average measurement conditions for the points determination and taking into account the accuracy of the observations, which are compatible with the specifications of the instrument, uncertainties of the horizontal displacements in ZX and ZY planes will be 2.5 mm. The final displacements of BTS tower axis obtained on the basis of discussed measurements are summarized in Table 2 (Kwiecień 2016).

Table 2. Displacement values of each cross-sections

Height of cross-section [m]	horizontal displacement in ZX plane – WX [mm]	horizontal displacement in ZY plane – WY [mm]	$W = \sqrt{W_X^2 + W_Y^2}$ [mm]
39.4	10	60	61
30.4	13	60	61
17.0	30	13	33
9.0	23	20	30

Measured tilt of the top of the tower exceeds the limit values recommended by the ER-01 manual: H/1000 = 39.4 mm < 61 mm. Boundary displacement value recommended by the PN-B-03204 standard is satisfied (H/100 = 394 mm > 61 mm), and therefore analyzed telecommunication tower in accordance with this recommendation is safe. Currently, the recommended Eurocode 3 standard does not specify limit displacements of the towers, making them user of the tower requirements dependent. Figure 4a and 4b graphically shows obtained displacements.

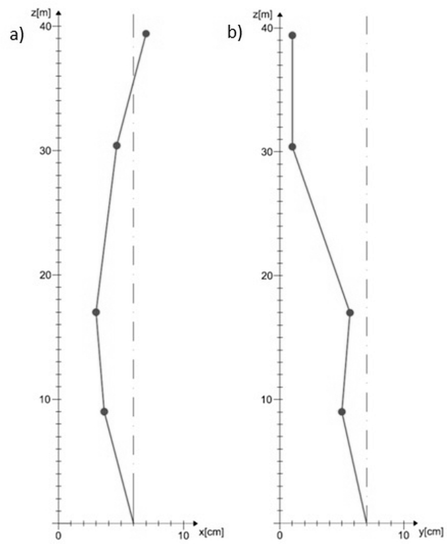


Fig. 4. Graph of displacements: a) – in ZX plane; b) – in ZY plane

As the divergence of both recommendations is very high (one order of magnitude), the following diagram shows the different variants of the H/M ratio as permissible horizontal displacement, assuming M from 100 to 1000 (a jump of 100). The resulting deviation value W = 61 mm is acceptable assuming permissible horizontal displacement of H/600 (Fig. 5).

EN 1993-3-1	No recommendations									
PN-B-03204	$W = 61$ mm < $W_{lim} = 1/100 \cdot H = 394$ mm – construction of safe / reliability									
ER-01	$W_{lim} =$ **1/750**$\cdot H = 53$ mm									
	defects endanger the safety construction and require immediate repair								defects deteriorating condition of the construction, repair must be done within the year	
W_{dop}=H/M [mm]	394	197	131	99	79	66	56	49	44	39
1/M	**1/100**	1/200	1/300	1/400	1/500	1/600	1/700	1/800	1/900	**1/1000**

Fig. 5. Different variants of permissible horizontal displacement related to examined object

The criteria for the serviceability limit states formulated in (Instrukcja ER-01 1994) are very conservative, and therefore the reliability analyzes were performed in order to verify whether the methods of higher order meet the requirements for reliable and safe operation of tower construction for a defined boundary condition at H/750.

Safety and reliability

Safety in telecommunication is defined by (Ustawa 2004). Due to the fact that telecommunication structures are a component of critical infrastructure and are used to ensure the security of the entire country enormous weight on the reliability of these structures is taken. In the case of telecommunication network systems information security is largely determined by the reliability of that system.

Reliability assessment may relate to the past or the future. In both cases the appropriate reliability measures – indicators of reliability are determined. Indicators based on data from the past include: unavailability of the system, the number of adverse events, the duration of interruptions, etc. In turn, the indicators calculated for the future are forecasted on the basis of the results of analyzes using appropriate models and mathematical methods and computer programs.

Due to the safety and reliability telecommunications masts, as objects of ground infrastructure, must meet the requirements defined in the standards for building construction.

Reliability of structures

In the PN-EN 1990:2004 standard reliability of structures is defined as the ability of a structure or its component to meet the specific requirements of the resistance, and durability during the planned service life, which is usually expressed in probabilistic measure. Therefore reliability is called the probability that the construction will not fail in assumed time of her life. Failure is a term related to situation in which the variables defining the structure exceed certain criteria set up by the designer. For example, exceeding of the assumed limits of displacements may be considered as the failure. Reliability of building structures depends on many factors of which the most important are: quality and characteristics of used materials, manufacturing accuracy of construction and the type and values of influences taken into account. In this study, considerations are limited to recommended in PN-EN 1990:2004 and ISO 2394 (PN-ISO 2364:2000) standards method of reliability index β, which belongs to the analytical FORM - First Order Reliability Method methods of level II (Tichy 1993; Gulvanessian, Holicky 1996; Nowak, Collins 2000; Faber *et al.* 2007). It is assumed that all the random variables of are defined by two parameters (mean value and standard deviation) of the normal or equivalent to normal distribution (Melchers 1987; Woliński, Wróbel 2001). Standardized random variable expressing condition of limit state due to the not exceeding the acceptable horizontal displacement by tower's axis can be described by the following formulas (9; 10):

$$Z = W_{\text{lim}} - W \; ; \tag{9}$$

$$Z = W_{lim} - \sqrt{{W_X}^2 + {W_Y}^2} \; , \tag{10}$$

where: Z – standardized random variable of limit state; W_{lim} – maximum permissible horizontal displacement

The measure of reliability (reliability index β) is defined by (11):

$$\beta = \frac{E(Z)}{\sigma(Z)} \, , \tag{11}$$

where: $E(Z)$ – expected value of Z; $\sigma(Z)$ – standard deviation of Z.

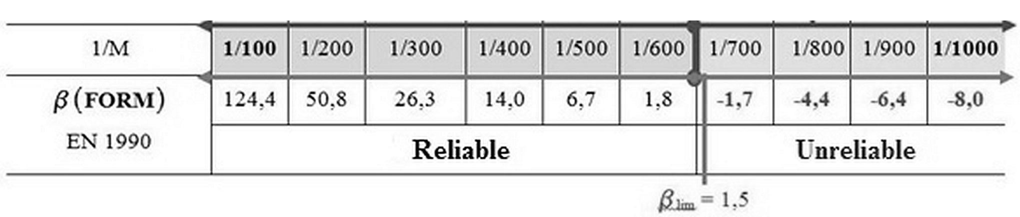
Calculation of reliability

In analyzed example input data, for calculating the reliability index, were adopted in accordance with Table 3.

Table 3. Input data for probabilistic analyze

Feature	W_X	W_Y
Distribution	Normal	Normal
Mean	10 mm	60 mm
Standard deviation	2.5 mm	2.5 mm

The resulting value of the reliability index does not meet the recommendations. The construction should be considered unreliable because the value of the index of reliability is lower than the target value of reliability class RC2: β_{lim} = 1.5 (PN-ISO 2364:2000; PN-EN 1990:2004). If the allowable amount of displacement is defined at the level H/750, the analyzed telecommunication tower does not meet the reliability requirements. On the other hand, when the allowable amount of displacement would be defined at the level of H/600 analyzed tower design would be reliable (Fig. 6).



1/M	1/100	1/200	1/300	1/400	1/500	1/600	1/700	1/800	1/900	1/1000
β (FORM)	124,4	50,8	26,3	14,0	6,7	1,8	-1,7	-4,4	-6,4	-8,0
EN 1990	Reliable						Unreliable			

Fig. 6. Reliability index for different values of the allowable horizontal displacement

The values of reliability index, received above with FORM method, can be helpful in taking appropriate steps regarding the urgency of the work associated with the rectification and repairs of telecommunication tower.

Conclusions

Telecommunication structures are among the objects of particular strategic and economic importance, hence it is very important to ensure trouble-free operation of these structures. In the case of mast and tower design type constructions one of the most important issues is to determine maximum horizontal displacement of the structure. On the basis of the measurements and analyzes of the object of study, which total height is 39.4 m, the following conclusions was found:

– the horizontal displacement, measured for the top section of BTS tower, exceeds the limits recommended by the ER-01,
– the limit value for horizontal displacement proposed in PN-B-03204 for the analyzed case is fulfilled.

In contrast, the currently recommended standard (PN-EN 1993-3-1:2008) does not specify limits of horizontal displacement, making them addicted to user of tower requirements. User is obliged to carry out rectification and meet the requirements of not only the standards recommendation, but also the recommendations of the relevant instructions of industry to ensure safe and reliable operation of the structure.

Application of higher level methods, recommended in PN-EN 1990:2004, to the analysis of reliability and safety of the telecommunication constructions will allow a more accurate assessment of structure condition and effective management of repair work, also more rational economic policies associated with the management of the telecommunications infrastructure.

It should be pointed out that modern telecommunications antenna requires a stable and rigid structures that do not cause disturbances in its work, so conservative criteria (allowable displacements and twisting of structure with respect to the serviceability limit states) did not result from the aspects of constructional requirements.

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