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Research paper

ACCURACY IN BUILDING BRIDGE SUPERSTRUCTURE CONSTRUCTIONS VIA CANTILEVER CONCRETING OR ASSEMBLY METHOD

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Abstract

This article examines the cantilever method for constructing bridge superstructures and highlights the lack of specific accuracy requirements in Bulgarian regulations for this technique. The study defines the necessary accuracy for building bridge superstructures using the cantilever concreting and assembly methods and calculates the precision required for determining the spatial coordinates of observed points on the bridge cantilevers. Through mathematical analysis, permissible deviations in height and plan position are established. The findings emphasize the importance of precise geodetic measurements and high-accuracy instruments to ensure structural integrity and minimize construction errors, ultimately contributing to improved quality control in cantilever bridge construction projects.

Key words: *Bridge superstructure constructions, Cantilever method, Regulations, Accuracy, Spatial coordinates*

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1. INTRODUCTION

Bridges are critical civil engineering structures designed to facilitate the safe passage of vehicles and pedestrians over physical obstacles such as rivers, valleys, roads, or industrial zones. A typical bridge consists of three main components: the substructure (piers and abutments), the superstructure, and the deck (roadway and associated elements). Each of these components requires precise planning, execution, and monitoring to ensure structural stability and long-term functionality.

The superstructure—the focus of this paper—is the primary load-bearing system of the bridge and can be constructed using different methods depending on factors such as terrain constraints, material availability, and construction technology. Two of the most widely adopted methods for constructing bridge superstructures are the cantilever method (using in-situ concreting or segmental assembly) and the segmental construction technique (typically involving precast elements). Both methods present specific challenges with respect to construction accuracy, particularly in terms of segment alignment, geometric control, and deflection management during erection.

The accuracy with which these methods are executed has a direct impact on the bridge's structural performance. Misalignments or positioning errors can accumulate and lead to significant deviations from the design geometry. This is especially critical in long-span or continuous bridges, where even minor angular errors can cause large displacements at the free ends. As such, geodetic surveying plays a vital role at every stage of construction—from the initial layout of foundations to the final positioning of segments.

This paper evaluates and compares the achievable accuracy of bridge superstructures constructed using cantilever concreting and cantilever assembly methods. It investigates the key technical factors that influence construction precision, including support system geometry, bearing alignment, segment fabrication, and real-time monitoring. By analyzing case studies and geodetic data, the study aims to identify best practices that help minimize geometric errors and improve construction accuracy in modern bridge engineering.

2. BUILDING BRIDGE SUPERSTRUCTURE CONSTRUCTIONS VIA CANTILEVER CONCRETING OR ASSEMBLY METHOD

One of the most common, effective and fine technologies for bridge construction is that of cantilever construction. It ensures the bridge construction in difficult-to-access terrains and/or deep valleys and water obstacles. The "cantilever construction" technology was created more than 60 years ago by the Norwegian company "Jacobsen" and is applied in two versions: monolithic (cantilever concreting - with 70 ÷ 330 m spans) and assembly (cantilever with 45 ÷ 135 m spans) [1], [2], [3], [4], [5], [6]. The largest bridge span built using the "cantilever concreting" method is 330 m (cantilever length - 165 m) - Figure 1.

Figure 1. Road bridge “Shibanpo”, China [7]

There are two bridges in Bulgaria built via the "cantilever concreting" technology - the bridge at "Makaza" pass (Figure 2), near the town of Momchilgrad and the viaduct at the 48th kilometer of "Hemus" highway.

Figure 2. Cantilever construction of “Makaza” viaduct [8]

The principle of cantilever construction is shown in Figure 3 [1]. The building of the superstructure construction begins after the construction of the abutments and pillars which are implemented monolithically. The superstructure block “O” (Figure 3) in cantilever concreting is constructed monolithically and in cantilever assembly – either monolithically or as an assembly block on the corresponding pillar.

The supporting structure between each two adjacent piers is built with cantilevers symmetrically from each pier until they meet the opposite cantilevers built from the adjacent piers. When the two adjacent cantilevers meet, a “rigid connection” is formed, known under the term “key segment” - “A” (Figure 3 d) which makes it possible to level out the small spatial discrepancies of the two cantilevers.

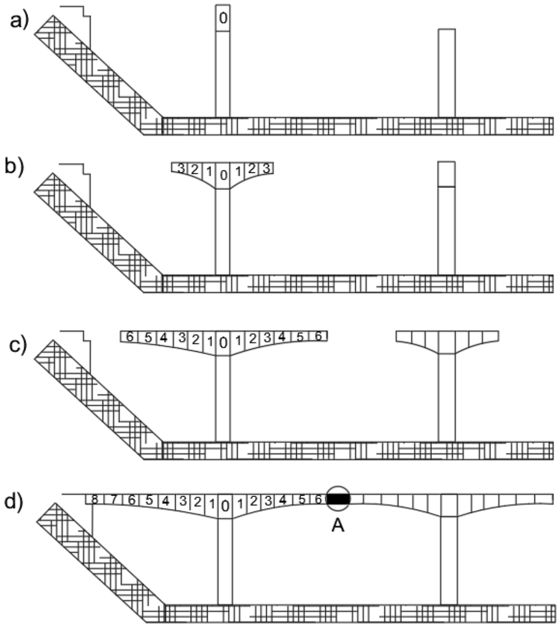

Figure 3. Cantilever construction principle [1]

Throughout the whole construction period, precise geodetic measurements are carried out to determine the spatial position of the frontal cross-section of each constructed segment and its deviations from the design. Based on these results, the necessary corrections are calculated in the position of the next segment and in the deformation, calculation models in order to reconcile the deformation characteristics with the results obtained from the measurement. The described sequence is repeated until the final completion of the bridge.

The scarce literature [6], [9], [10] mentions that measurements are performed with a total station, and for each stage of the implementation of the cantilevers, depending on the project geometry, relevant preparatory calculations are carried out - mainly coordinate transformations and setting out data.

Considering the extreme importance of geodetic measurements in the cantilever bridge construction, reliable control of the computational work and geodetic setting out works for the spatial orientation (so-called navigation) of the cantilevers must be carried out at each stage of the implementation. According to the author, this implies the development of a geodetic control system, including at least a high-precision geodetic device for determining spatial coordinates, a portable field computer with specialized software for calculation setting out data, and means of communication between them.

This idea is the basis of a research project developed at the University of Architecture, Civil Engineering and Geodesy, by means of which a working model of a geodetic control system for cantilever bridge superstructures construction was created. The geodetic control system is described in detail in the author's dissertation [11].

3. ACCURACY IN BUILDING BRIDGE SUPERSTRUCTURE CONSTRUCTIONS VIA CANTILEVER CONCRETING OR ASSEMBLY METHOD

The current regulations in Bulgaria for the implementation and realization of construction and installation works lack specific requirements for accuracy in the bridge superstructure construction using the cantilever concreting method.

In the “Technical Specification” of the Road Infrastructure Agency under the Ministry of Regional Development and Public Works since 2014, part 10200, table 10212.1, only permissible deviations of geometric parameters in the construction of abutments and pillars are given. In parts 10300 “Monolithic superstructure constructions for road bridges” and 10400 “Assembly superstructure constructions for road bridges” similar requirements are also not specified. In [9] there are permissible deviations δH given for the achieved elevation when constructing the supporting structure by cantilever concreting, namely: for the upper slab δH = +/-15 mm, for the lower slab δH = +/- 30 mm. These are accuracy requirements set by the manufacturer of the cantilever installation – “Jacobsen” used in the construction of the viaduct at 48^{+000} km of the “Hemus” highway.

Due to the lack of other information, the smaller of the two tolerances will be used in the following calculations, i.e. this is the one used in the manufacture of the upper slab.

It is known that from a geodetic point of view, the permissible deviation in the geometric parameters (dimensions, elevations, slopes, etc.) of constructed building elements is considered as an allowable error of the corresponding parameter. In this case, the permissible deviation δH is treated as an allowable error m_H in the height of a point on the upper contour of a completely finished cantilever segment. According to Gauss Law of Error Propagation, m_H (1) can be represented as a function of several consisting errors:

$$(m_H)^2 = (m_H)_{GN}^2 + (m_H)_{meas}^2 + (m_H)_{CIW}^2 \qquad (1)$$

where:

- $(m_H)_{GN}$ – allowable error in the height of the initial point from the geodetic network (observation station);
- $(m_H)_{meas}$ – allowable error when defining the height of the observed point from the cantilever due to errors in geodetic measurements;
- $(m_H)_{CIW}$ – allowable error in the height of the point from the cantilever as a result of the implementation of construction and installation works.

The required height accuracy $(m_H)_{meas}$ that must be ensured in geodetic measurements for setting out and control of the implementation of the cantilevers can be established from formula (1) with an assumed influence ratio of the consisting errors on m_H. If the principle of equal influence is accepted, at m_H =15 mm, we get:

$$(m_H)_{meas} = (m_H)_{GN} = (m_H)_{CIW} = \frac{m_H}{\sqrt{3}} = 8.7mm \qquad (2)$$

The corresponding mean square error for the measured height at the confidence interval (-2m, +2m) will be m_H = 4.35 mm. Since there are no requirements for permissible deviations in the plan, we will assume the same for them as for the height, i.e. δP=+/-15 mm. By analogy with the above analysis, the mean square error in the plan position of a measured point with confidence interval (-2m, +2m) is m_p = 4.35 mm.

3.1. Accuracy in determining the spatial coordinates of the observed points from the bridge cantilevers

The plan coordinates and heights of the observed points from the bridge cantilevers can be defined using linear-angular measurements, carried out with a total station providing the necessary accuracy.

The heights H_p are determined by the well-known formula:

$$H_P = H_i + S_{ip} \cos Z_{ip} + J - T + \frac{1-k}{2R} S_{ip}^2, \tag{3}$$

where:

- H_i is the height of the observation station;
- S_{ip} – the inclined distance;
- Z_{ip} – measured zenith angle;
- J, T – instrument and signal heights;
- k – refractive index;
- R – average Earth radius; R= 6371 km.

The accuracy of the measured heights depends mainly on the accuracy of the measured zenith angles, the influence of the Earth curvature and the vertical refraction. The height H_i of the observation station in most cases can be defined with an error of about 1 mm by geometric levelling and the J and T values can be measured without any problem with such accuracy. Therefore, when assessing the accuracy of the measured heights based on formula (3), their respective errors can be neglected.

In such case, after applying Gauss Law of Error Propagation to formula (3) for the arguments S_{ip} , Z_{ip} и $c = \frac{1-k}{2R} S_{ip}^2$ we get:

$$m^2{}_H = \cos^2 Z \ . m^2{}_S + \frac{S^2 m^2{}_Z \sin^2 z}{\rho^2} + m_c^2 = (m_H^{z,s})^2 + (m_H^c)^2 \ , \tag{4}$$

where:

- $m_H^{z,s}$ is the error in the measured height, due to errors in the measured zenith angles and distances;
- m_H^c – the error in measured height, caused by the Earth curvature and the vertical refraction;

In case we can ignore the influence of the Earth curvature and the vertical refraction, it is necessary that $\mathrm{m_H^c} \le m_H /3$ (m_H=4.35 mm), i.e. $\mathrm{m_H^c} \le 1.45$ mm

Based on this value m_H^c and the values for *R = 6371 km* and *k=0.106*, the largest value of the distance S_{max} (i.e., the system range) can be calculated where the error $m_H^c \le$ *1.45 mm*, namely S_{max} *= 144 m*.

Similarly, in case we can ignore the influence of the error in the measured distance, the value of the corresponding term in formula (4) should be $\cos Z . m_S \le m_H/3 \le 1.45mm$. Based on this assumption, at a minimum zenith angle $Z=60^g$ (assumed maximum inclination of the sights) and S_{max}*=144 m*, it follows that the distances must be measured with a mean square error $m_S \le$ *2.5 mm*.

The required accuracy of measuring the zenith angles m_Z is obtained from the equation:

$$m^2{}_H = \frac{S^2 m^2{}_Z \sin^2 z}{\rho^2}. \tag{5}$$

Given that $m_H = 4.35$ mm, $Z=60^g$ and $S_{max}=144$ m it follows that $m_Z = 24^{cc}$.

The scope of the system can be increased if the errors involved in formula (4) are defined using the principle of equal influences, namely:

- the error caused by the Earth curvature and the vertical refraction is $m_H^c = 2.5\,mm$.

With the so defined value of m_H^c, at $R=6371$ km and $k=0.106$, the system range comes to be $S_{max} = 188$ m.

- the required accuracy of the measured distances is defined by the equation $cosZ.m_S = \frac{m_H}{\sqrt{3}} = 2.5\,mm$. Hence, at a minimum zenith angle $Z=60^g$ and a maximum length of the sights $S_{max}=188$ m, it follows that the distances must be measured with a mean square error $m_S=4.2$ mm.
- the required accuracy of measuring zenith angles is derived from:

$$m_Z = \frac{m_H.\rho}{S.\sin Z.\sqrt{3}}. \tag{6}$$

where $m_H = 4.35$ mm, $Z=60^g$ and $S_{max}=188$ m we get $m_Z = 10.5^{cc}$.

As it can be seen from the results, the system range increases by about 40 m, at the expense of double increase of required accuracy of measuring zenith angles.

The preliminary accuracy assessment is based on the assumption that the setting out will be carried out from stations located on the terrain below or above the supporting structure. When constructing bridges over steep or deep gorges as well as over water obstacles, it is better to place the observation stations on the superstructure block ("O" – Figure 3) of the already constructed piers. In this case, the slope of the sight's changes in a relatively small range. For example, with a maximum sight length of 188 m, a maximum slope of the grade line of 5% and a cantilever height of 5 m, the sights will have zenith angles in the intervals of 97-99 ^{g}, respectively 103-105 ^{g}.

When changing the sight inclination in the above mentioned intervals, the system range $S_{max}=144$ m and the assumption that the error in the measured heights caused by the Earth curvature and the vertical refraction and the error in the measured distances are assumed to be insignificantly small (i.e. $m_H^c \leq 1.45\,mm$ и $cosZ\,.m_S \leq 1.45$ mm), it comes that the mean square error in measuring distances for different values of the zenith angles in the specified intervals varies from 18.5 to 92 mm. The zenith angles must be measured with accuracy $m_Z = 19.3^{cc}$.

With a system range of $S_{max}=188$ m, an error caused by the Earth curvature and the vertical refraction $m_H^c = 2.5mm$ and a sight inclination in the intervals 97-99 ^{g}, respectively 103-105 ^{g}, it comes that the average error of the measured distances varies from 32 to 159 mm and the required accuracy of measuring the zenith angles is $m_Z = 8.5^{cc}$.

4. CONCLUSION

A preliminary accuracy assessment in building bridge superstructure constructions via the cantilever concreting or assembly method has been carried out. The permissible deviations in plan and height have been established. The calculated values should be used as a minimum criterion for accuracy when selecting geodetic tools and measurement methods suitable for the construction using the cantilever concreting method.

The accuracy in determining the spatial coordinates of the observed points from the bridge cantilevers has been calculated. The already made calculations confirm once again that the required accuracy in defining the heights of the observed points depends primarily on the accuracy of the measured zenith angles. Therefore, in the bridge construction along with other similar expensive facilities, it is reasonable to purchase precise and high-quality tools with an angular accuracy of 1 " or 2 ". They can ensure the required accuracy of angular measurements when working in two positions of the sighting telescope with appropriate signaling of the observed points - for example, with reflective symbols.

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