Geodetic network for the construction of the high-speed railway line

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Abstract. Geodetic support for construction and operation of high-speed railways requires high-precision geodetic work both at the construction stage and during operation of the structure. Geodetic separation network, being the basis of mainline construction, requires special care and accuracy in measurements for its creation. The analysis of studies carried out in this field shows their insufficiency or incorrectness, and the comparison of current rules and regulations documents shows their contradiction. In the article, based on the results of existing scientific works, on the basis of the allowable standard values of outstanding lateral accelerations, the necessary accuracy of building a marking network for the construction of a railway line with speeds up to 400 km/h is calculated. On the basis of the analysis of existing regulatory documents of various countries engaged in high-speed rail traffic, the correctness of the obtained result has been proved. The imperfection of the Russian normative base in the field of construction of such objects is shown. Based on the findings, practical recommendations are given on methods for constructing a planned network for the construction of a high-speed highway and fixing its points, which can significantly reduce the cost and intensity of work on its creation, as well as directions for further necessary research in the field of geodetic support for the construction of high-speed highways.

1 Introduction

High-speed rail service in the Russian Federation, represented by the only line between Moscow, St. Petersburg and Helsinki, is currently under development. According to the program for organizing speed and high-speed rail service in the Russian Federation, approved by a protocol decision of the JSC "Russian Railways" board meeting of 23 November 2015, 20 projects with a total length of 7,000 km are to be implemented. Therefore, there is little experience in developing regulatory requirements for geodetic support for the construction and operation of such lines in our country. Current regulatory documents in this area (e.g., "Special reference system for monitoring the condition of the railroad track in the profile and plan: Technical requirements", code of practice SP 233.1326000.2015 Infrastructure of railway transport. High-precision coordinate system and others) are outdated, in some cases contradict each other and have other drawbacks that

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complicate their practical application in the design and construction of high-speed railroads. Analysis of scientific studies performed in this area [e.g., 1-16 and others] shows that their results do not allow to answer the question of what should be the accuracy of determining the coordinates of layout network points for construction of high-speed railroads and why exactly it is sufficient and not redundant. Therefore, the purpose of this article is to answer this question.

2 Materials and methods

The most complete theoretical basis for calculation of necessary accuracy of geodetic network for high-speed railways is stated by Russian professor Kougia in his work "Geodetic network for high-speed railways", where the research of permissible deviations of track from straight line, having character of long waves, is carried out. Taking into account that such deviations lead to violation of the design geometry of the railroad track at high speeds, and their detection by means of geodetic measurements is one of the main tasks of special reference systems, such criterion, in our opinion, can be considered reasonable.

The base of calculation is train speed 400 km/h (maximum operating speed on modern high-speed lines is 380 km/h), tolerable value of unaccompanied transverse acceleration 0.2 m/s² (on native and foreign high-speed lines for the specified speed it is equal 0.4-0.73 m/s²) and acceleration rate of unaccompanied transverse acceleration 0.3 m/s³ (on native and foreign high-speed lines for the specified speed equals 0.28-0.40 m/s³). Thus, the research results can be considered relevant and corresponding to modern normative requirements, which is confirmed by using the results of this work in developing special technical conditions for the design of the Moscow-Kazan high-speed railway line.

Performed by Professor Kougia calculations have shown that the maximum permissible value of the deviation axis of the railroad track from the design position is 30 mm at a distance between these deviations not less than 300 m. Adopting this value as the limit error of dividing works, the author has calculated their mean square errors of measurement, and on their basis - the mean square errors position items breakdown network (15 mm and 7.5 mm, respectively). Having taken the specified value for limiting error isolation work, the author has calculated their mean square errors of measurement, and on their basis - the mean square errors position items breakdown network (15 mm and 7.5 mm, respectively). Note that the obtained value of 7.5 mm is the mean square error of position of some point of geodetic network M. Consequently, based on the principle of equal influence its coordinates should be determined with mean square errors not exceeding

\[ M = \sqrt{m_x^2 + m_y^2} \]

\[ m_x = m_y = m_x(y) = \frac{M}{\sqrt{2}} = 5.3 \text{ mm}, \]

Where M is the mean square error of the position of the point; mₓ, mᵧ are the root mean square errors of determining its coordinates.

However, in our opinion, the obtained value of the permissible deviation of the track axis from the design position can be considered only as a tolerance for the actual position of the rail strands in the plan (i.e., the tolerance of the installation works). Otherwise, taking the specified value for a limiting error of alignment works, the axis of a track after installation of a rail-tie trellis can be deviated from the design position more than 30 mm as
errors of geodetic measurements will be added to errors of installation works. Thus, it is possible to suppose, that the result received by professor Kougia is incorrect and it is necessary to create an alignment network for construction of the high-speed highway with another accuracy. Let us prove this assumption correct and show what this accuracy should be.

3 Results

According to GOST R58941-2020 System for ensuring the accuracy of geometric parameters in construction. Rules for measurement performance the permissible error $\delta x_{\text{met}}$ of measurement should not exceed

$$\delta x_{\text{met}} \leq 0.2 \cdot \Delta x, \quad (2)$$

Where $\Delta x$ – tolerance of the measured geometric parameter.

Then, based on the permitted deviation of the track axis from the design position equal to 30 mm, the mean square error of the layout works when bringing to the ground axis of the track should not exceed 6 mm. The coordinates of the points of the route network in this case must be determined with an accuracy of 2-3 times greater. Usually, this coefficient is recommended to be equal to 2.5 when solving practical geodesy problems. Based on this value, the mean square error in determining coordinates of breakdown grid points must not exceed 2.4 mm. In this case, the quality of construction of the layout network must ensure the performance of all types of geodetic works with the accuracy specified by regulatory documents. Let's consider what these requirements are in different countries.

Today China has one of the most extensive networks of high-speed railroads, as well as the maximum operating speed of trains and experience in its organization in difficult climatic conditions. The main normative document regulating the order of creation of the division network, as well as the accuracy of some geodetic works on high-speed railways is the standard [17]. A number of works (e.g., [1] and [2]) are also devoted to development of methods of geodetic works and their accuracy on such objects.

The standard [17] defines the geodetic basis for construction and operation of high-speed railroads as a four-level construction - CP0 - CPIII, the points of which, depending on the network class, are located at a distance of 50 km (frame support network CP0) to 50 m (track network CPIII) from each other. The most stringent requirements for the accuracy of the construction are imposed on the network CPIII, intended for the demarcation work of the elements of the track superstructure and serving as a geodetic basis for its further operation. Mean square error of relative position of adjacent points of such network must not exceed 1 mm, but this value implies the mean square error of x, y coordinates components. In addition to the requirements for the accuracy of the layout network, the standard specifies the requirements for the accuracy of certain geodetic works in road construction. The most stringent requirements are set for the axis breakdown of the concrete base of the upper structure of the track (3 mm), breakdown of track switches (5 mm) and axis breakdown of the track (10 mm).

Comparing the obtained by the formula (2) permissible mean square error of determining the coordinates of the layout network points with the given requirements, we see that the accuracy of the layout network determined by the standard [17] is excessive, which forces to use expensive robotic total stations and measuring equipment for its construction. At the same time, the calculated accuracy of the layout network makes it possible to perform the division works with errors not exceeding the set values.
The German railroads use a fully mixed organization of high-speed traffic with a maximum speed of up to 300 km/h, when both high-speed and conventional trains move along the existing railway lines. The same scheme but at lower speeds of 250 km/h is used today in the Russian Federation. Issues of construction and operation of railways with different speeds are discussed in detail in the book "Möser M., Müller G., Shlemmer H., Werner H. Handbuch Ingenieurgeodäsie", where based on the analysis of normative documents used in Deutsche Bahn AG railroad network the requirements to accuracy of determining coordinates of the layout network points and individual geodetic works are defined.

Geodetic network for construction and operation of high-speed railroad is created as a four-level structure - Punktstatus 1 - Punktstatus 4, which points are located at a distance of 1 km (Punktstatus 1) to 40 m (Punktstatus 4) from each other depending on the network class. The Punktstatus 4 network, designed for detail work at sites with high accuracy requirements, has the most stringent requirements to the accuracy of its construction. The error in determining the planned coordinates of such points should not exceed 5 mm, and their relative position - 6 mm. Note that these coordinates must be determined with a probability of 68.26 % (t = 1), ie these errors are equal to their limit values, while the root mean square errors, based on the recommendations of [13] must not exceed 2 mm. When dividing works the highest requirements for the accuracy of laying track switches and track axis (5 mm) when the relative error of removal of the axis not exceeding 1:2500.

Comparing the formula (2) obtained by the allowable root mean square error in determining the coordinates of points of the layout network with the stated tolerances, we see that both values are virtually identical, and obtained by the calculated accuracy of the division network again allows to carry out the divide works with errors not exceeding the specified values.

In the Russian railroads, the main regulatory documents governing the accuracy of the creation of a layout network are the technical requirements "Special reference system for monitoring the condition of the railroad track in the profile and plan" and the Code of Practice SP 233.1326000.2015 Infrastructure of the railway transport. High-precision coordinate system. The latter document establishes a layout network (referred to in the document as "reference geodetic network") as a two-level construction, including the main and intermediate points with distances between them 4-5 km and 250-750 m, respectively. In this case the mean square errors of relative position of adjacent points regardless of their type must not exceed 8 mm. In the Code of Rules, the division network is considered as a four-level construction, including frame, main and intermediate points, as well as working reference points. Mean square errors of relative position of adjacent intermediate points must not exceed 8 mm, while working reference points must not exceed 5 mm. Note that in contrast to equation (1) the documents specify the mean square error of the relative position of adjacent points. In the general case, the value of the indicated parameter will depend on the chosen criterion characterizing its accuracy. When solving applied geodetic tasks as such a criterion is usually used the horizontal distance S between points

\[
S = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} = \sqrt{\Delta x^2 + \Delta y^2},
\]

Where \(x_1, x_2, y_1, y_2\) – flat rectangular coordinates of adjacent points; \(\Delta x, \Delta y\) are coordinate increments.

Then the mean square error of this distance can be calculated by the known formula for assessing the accuracy of functions
where the partial derivatives are

\[
\frac{\partial S}{\partial \Delta x} = \frac{\Delta x}{\sqrt{\Delta x^2 + \Delta y^2}} = \frac{\Delta x}{S},
\]

\[
\frac{\partial S}{\partial \Delta y} = \frac{\Delta y}{\sqrt{\Delta x^2 + \Delta y^2}} = \frac{\Delta y}{S}.
\]

Substituting (5) into (4) and considering the principle of equal influence, we obtain

\[
m_S = \sqrt{\left(\frac{\Delta x}{S}\right)^2 \cdot m_{\Delta x}^2 + \left(\frac{\Delta y}{S}\right)^2 \cdot m_{\Delta y}^2} = \frac{m_{\Delta x} \cdot (\Delta y)}{S} \cdot \sqrt{\Delta x^2 + \Delta y^2} = m_{\Delta x}(\Delta y)
\]

In turn, \(m_{\Delta x(y)}\), taking into account the principle of equal influence, can also be calculated by formula (4). Given that \(\Delta x = x_2 - x_1, \Delta y = y_2 - y_1\), we obtain

\[
m_{\Delta x(y)} = m_x(y) \sqrt{2},
\]

\[
m_x(y) = \frac{m_S}{\sqrt{2}} = \frac{5}{\sqrt{2}} = 3.5 \text{ mm}
\]

I.e., the coordinates of the working reference points should be determined with a root mean square error not exceeding 3.5 mm.

Comparing the obtained by the formula (2) permissible mean square error in determining the coordinates of the breakdown network points with the specified tolerances, we see that the accuracy established by domestic rules and regulations documents is lower than the calculated. Given that Russian railroads do not have train speeds higher than 250 km/h, this is to be expected. At the same time, regulatory documents establishing the accuracy of individual geodetic works on the railroad are also not designed for traffic at speeds above 250 km/h.

Thus, we see that the above theoretical calculations are sufficiently supported by the requirements of regulatory documents, and the layout network created with the accuracy calculated by the formula (2) fully ensures the performance of the entire complex of construction and installation works.

4 Discussion/Analysis of the Results

Analyzing the results obtained as a whole, it is possible to draw several main conclusions:

the mean square errors in determining the planned coordinates of the layout network for the construction of the railway with speeds up to 400 km/h should not exceed 2.4 mm, which is sufficiently confirmed by the requirements of rules and regulations documents;

this accuracy can be achieved by an ordinary electronic tachymeter with angular accuracy 2 "-3" with fixing points of the network plastic reflectors [18], which will
eliminate the use of expensive points of forced centering and prism reflectors, thereby reducing the cost of creating a network;

construction of a layout network with higher accuracy (as required, for example, by the standard [17]) will lead to the need to use expensive robotic total stations and specialized measuring equipment, i.e., will significantly increase the cost of work of its creation. Construction of the network with lower accuracy will not ensure safe train traffic at speeds up to 400 km/h;

for the construction of railroads with speeds up to 400 km/h in the Russian Federation, it is necessary to adjust the existing rules and regulations documents taking into account the above conclusions.

5 Conclusion

It is not very difficult to build a network with the accuracy obtained in this article on relatively small objects. However, a railroad line is a linear structure up to several thousand kilometers long. Under such conditions, the accuracy of the final result can be significantly affected by the cartographic projection adopted to create the coordinate system, so additional research is needed in this area.

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