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# DESIGN OF HIGH-SPEED RAILWAY (HSR) LONG-DISTANCE TUNNEL INDEPENDENT CONTROL NETWORK

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## ABSTRACT

Establishing a high-speed railway long-distance tunnel independent control network according to “one point and one direction” will often produce lateral deviation and long and short chains in the joint section. It is necessary to take technical measures such as control network rotation or long and short chain to solve. Combined with the case of a network of independent control network for a long-distance tunnel of a high-speed railway in China, based on the results of the original reference ellipsoid and line control points, the central meridian (L 0) of the tunnel project center with the longitude of the tunnel is plotted, and the average tunnel elevation of the tunnel is Projection earth height (H 0), coordinate transformation calculation and relative stability and reliability analysis of existing line plane control points; select one stable control point of tunnel entrance and exit as starting point, in new projection parameters (L0 Under H0), the overall adjustment is carried out to establish an independent control network for the long tunnel. The results show:

(1) The tunnel independent control network established by the method has high precision and uniform error, which can meet the requirements of network construction precision and improve the tunnel penetration accuracy;

(2) “One point one direction” Compared with this method, the joint segment control point (S = 9.1 km) with the same baseline file, starting point and projection parameters, the maximum coordinate difference Δx is -63.4 mm, Δy is 85.3 mm, requiring technical processing;

(3) The method can solve the problems of large lateral deviation and long and short chain of the connecting section, and ensure the smooth connection between the tunnel and the adjacent structure.

## KEYWORDS

HSR, Control, Tunnels, Network

## INTRODUCTION

According to the length of the Railway Tunnel Design Code (TB10003—2016), the tunnel is divided into: short tunnel (L ≤ 500 m), medium long tunnel (500 m<L≤3 000 m), long tunnel (3 000 m<L) ≤10 000 m) and extra-long tunnel (L>10 000 m) [1]. The "High-speed Railway Engineering Measurement Specification" (TB10601-2009) stipulates that the engineering independent coordinate system is a plane rectangular coordinate system established by projection of arbitrary central meridian and elevation projection surfaces. When the line plane control network (CPI, CPII) at both ends of the tunnel entrance is not in a projection belt, an independent tunnel construction control network can be established. It is advisable to use the tunnel average elevation surface as the reference plane and take the central meridian of the tunnel project center line as the coordinate projection; the construction independent coordinate system with the tunnel long straight line or

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curved tunnel tangent (or common tangent) as the coordinate axis, the selection of the coordinate axis should be Convenient for construction [2].

Yang Liu and Zuo Zhigang explored the method of changing the projection datum and the central sub-line to weaken the deformation length of the control network. The one-to-one direction method was used to establish the tunnel independent control network [3]. Ye Changxuan studied the fixed-width control of the special long-distance tunnel, and used the method of controlling the rotation of the network to solve the lateral deviation of the connecting section [4]. Yang Xuefeng and Liu Chenglong used two methods to check and analyse the direction angle of the independent control network of the long tunnel group, and established the independent control network of the long tunnel group by point-by-point method [5]. Hong Jianghua and Shi Debin et al. studied the layout, observation scheme, accuracy evaluation and penetration error of the planar GPS network of the long tunnel [6]. All these research results have certain practical significance for improving the penetration accuracy of the control network outside the tunnel. However, the tunnel independent control network established by the one point one direction method often leads to large lateral deviation and long and short chains. It is easy to handle in the subgrade, and it is more difficult to eliminate when the bridge is connected with the tunnel.

The research ideas of this paper are: Based on the original reference ellipsoid reference and the results of the existing line control points, the central meridian (L0) projected by the center line of the tunnel engineering center is used to project the earth height (H0) with the tunnel mean rail elevation, and the existing plane control points are respectively switched to the independent control network coordinate system (L0 , H0), analyse the stability and reliability of the starting point, select a stable and reliable control point of the tunnel entrance and exit as the starting point for the overall adjustment, and establish under the new projection parameters (L0 , H0) Tunnel independent control network.

The tunnel's independent control network established by the method can effectively solve the long and short chain and the lateral deviation, and does not need to rotate or set the long-short chain and other post-processing measures to ensure the smooth connection between the tunnel and the adjacent structure.

## THE NECESSITY OF ESTABLISHING AN INDEPENDENT CONTROL NETWORK FOR LONG TUNNELS

### Control projection length deformation value

The projection length deformation value refers to the discrepancy between the measured length and the inversed coordinate value after the correction of the two dimensions [7]. In the construction measurement process, in order to ensure the relative accuracy between adjacent points in the construction control network, it is necessary to control the projection length deformation value within a certain range. The railway engineering control network is a long and narrow strip network, and its projection length deformation value is affected by factors such as the elevation of the point, the elevation of the projection surface and the central meridian [8]. In order to improve the relative accuracy of adjacent points in the railway control network and control the projection length deformation value, the "High-speed Railway Engineering Measurement Specification" (TB10601-2009) stipulates that "the projection length deformation value of the coordinate system on the elevation surface of the corresponding line rail surface design is not more than 10mm /km".

### Tunnel penetration needs

The tunnel penetration error can be divided into vertical, horizontal and elevation penetration errors from the spatial distribution. The elevation penetration error can be controlled by the precision levelling technology. The longitudinal penetration error only affects the distance (or mileage), and the transverse penetration error has a direct impact on the tunnel quality. Once the tunnel penetration surface deviation is too large, it is difficult to correct it by technical means. It is usually necessary to carry out secondary construction of the lined section (or the inverted section), causing huge economic losses. The tunnel independent control network generally builds a network at a time, covering all construction work areas. The control points have high precision, the orientation of the holes is accurate, and the error of the whole network is uniform, which is beneficial to the construction measurement surveys and checks.

### Construction measurement needs

In addition to the main tunnel entrance and exit, the long tunnel often has auxiliary tunnels such as inclined shafts, horizontal tunnels or parallel guide holes. The general terrain is complex and often spans several engineering coordinate systems. For different engineering coordinate systems, control points often need to be swapped for calculations and are prone to errors. Therefore, it is necessary to establish a unified independent coordinate system. The "High-speed Railway Engineering Measurement Specification" (TB10601-2009) stipulates that "when the line plane control network (CPI, CPII) at both ends of the tunnel entrance is not in a projection belt, an independent control network of tunnel construction can be established."

## “TWO-POINTS METHOD” ESTABLISHES AN INDEPENDENT CONTROL NETWORK FOR LONG TUNNELS

Generally, the tunnel meridian is used as the coordinate projection central meridian, and the average elevation of the tunnel rail surface is used to project the earth's height. The existing plane control points are respectively converted into the tunnel independent control network coordinate system to carry out the stability of the existing control points. After the reliability analysis, each control point of the tunnel entrance and exit is selected as the starting point, and the overall adjustment is performed under the coordinate system of the independent control network to establish an independent control network for the long tunnel. The steps of the "two-point method" network construction are as follows:

(1) Selection of points and network design. Combined with the topographical features, geological conditions, traffic conditions and original plane control points of each tunnel construction operation area, the site selection and burial of piles are carried out in each tunnel construction operation area, and each construction area is buried with 3 to 4 plane control piles.

(2) Select the projection parameters. Take the longitude of the tunnel engineering center as the central meridian (L O) of the coordinate projection, and take the average tunnel elevation of the tunnel as the projection height (H 0).

(3) Starting point coordinate conversion calculation. Convert the existing planar control points to the tunnel independent control network coordinate system (L 0 , H 0).

Perform closed loop, repeated baseline test and three-dimensional unconstrained network adjustment on the tunnel GPS network. After meeting the tolerance requirements, perform stability and reliability analysis of the starting point. Then select one control point of the tunnel entrance and exit as the starting point. The overall adjustment is performed under the new projection reference to establish a tunnel independent control network.

The side length and angle detection are performed on the independent control network constructed, and the accuracy of the independent control network is evaluated.

## CONSTRUCTION OF INDEPENDENT CONTROL NETWORK

### Project overview

A railway Wulingshan tunnel (double-line single-hole) is located in Cili County, Zhangjiajie City, Hunan Province. The starting distance is DK234 + 491. 2 ~ DK243+535. 3, which is east-west and 9.044 km long. The tunnel is located in the middle and low mountainous areas of Wuling Mountain, with an altitude of 550 to 800 m. The tunnel is only provided with one construction guide, which is located at the entrance of the tunnel and intersects the tunnel with the DK235+460. The tunnel entrance elevation is 389. 442 m, the exit rail elevation is 458. 9082 m, and the plane position is between 110°45' and 110°51'. The longitudinal slope of the tunnel's body is: 17. 4‰ /8. 8 m, 17. 5‰ /4950 m, 6‰ /600 m, - 6‰ /3485. 3 m. DK240 +365. 634 ~ DK241+562. 069 On the curve of R = 7 000, DK242+754. 763 to the exit on the curve of R = 4 500, the rest are on the straight-line segment.

The Wulingshan Tunnel has 4 plane control points (co-points with elevation), 2 tunnel entrances (CP I163 and CP I164), and 2 tunnel exits (CPI165 and CPI166), both of which are high-speed rail standards. There are no control points around. Obstructed, the soil is hard and well preserved. The tunnel reference ellipsoid is consistent with the entire line, and the basic ellipsoid parameters of the 2000 national geodetic coordinate system (long semi-axis a = 6 378 137 m, flattening α = 1 /298. 257 222 101) are used, crossing two engineering coordinate systems, see Table 1.

*Tab. 1 - Wulingshan Tunnel Construction Coordinate System*

| Coordinate system number | Central meridian | Projection surface height /m | Elevation anomaly /m | Starting mileage | |
|---|---|---|---|---|---|
| | | | | start point | end point |
| CK－12 | 110°45' | 315 | －25 | DK231+000 | DK235+000 |
| CK－13 | 110°50' | 375 | －25 | DK234+700 | DK248+100 |

### Network shape design

The hole's subnet and other subnets are interconnected to form a main network, and the s hole's subnet is arranged in a geodetic quadrilateral. The newly buried control points are placed in places with wide vision, good visibility, solid soil and not easy to damage. Existing control points are included in the tunnel independent control network, as shown in Figure 1.

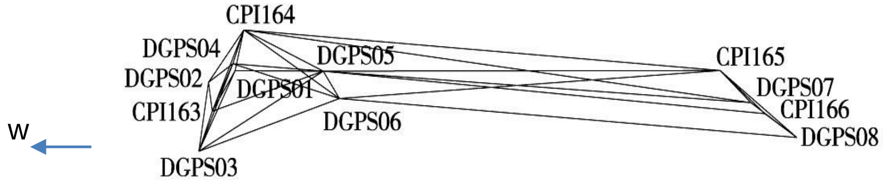


*Fig. 1 - Distribution of control points in Wulingshan tunnel*

### Network construction accuracy level

According to the "High-speed Railway Engineering Measurement Specification" (TB10601-2009), the independent control network of Wulingshan Tunnel is established according to the accuracy of the first-class GPS network of high-speed railway. The specific precision control indicators are shown in Table 2 and Table 3.

*Tab. 2 - Plane control network accuracy requirements*

| grade | Fixed error a /mm | Proportional error coefficient b/ (mm /km) | Error in baseline orientation / (“) | Relative error of side length between constraint points | Relative error of the weakest side length after constraint adjustment |
|---|---|---|---|---|---|
| First Class | 5 | 1 | ≤0.9 | 1/500 000 | 1/250 000 |

*Tab. 3 - Basic technical requirements for GPS surveying operations*

| Type | Project | Precision index |
|---|---|---|
| Static measurement | Satellite altitude angle / (°) | ≥ 15 |
| | Total number of active satellites | ≥ 4 |
| | Effective observation time of any satellite in the time period /min | ≥ 30 |
| | Length of time /min | ≥ 120 |
| | Number of observation periods | ≥ 2 |
| | Data sampling interval /s | 15~ 60 |
| | PDOP or GDOP | ≤ 6 |

## Projection parameter selection

The Wulingshan tunnel is a slope with a plane longitude between 110° 45' and 110°51' and a rail elevation of 389 to 479 m. Take the average meridian 110°48' as the central meridian of the independent coordinate system, and take the average elevation surface 434 m as the projection height.

### Starting point coordinate conversion calculation

Referring to the original reference ellipsoid, the tunnel inlet ends CP I163, CPI164 (110° 45 ', 315 m), the exit end CP I165, CP I166 (110° 5', 375 m) are respectively converted to the Wulingshan tunnel independent coordinate system (L 0 = 110°48', H 0 = 434 m) [9].

### Baseline solution and 3D unconstrained adjustment

Independent control network data processing includes baseline vector solution and network adjustment. The baseline vector solution uses GPS random post-processing commercial software. The satellite ephemeris uses the broadcast ephemeris uniformly [10]. The synchronization observation time is not less than 120 min in any period, and the number of effective satellites in any period is not less than 4, and the observation value of the same period is calculated. The data rejection rate is less than 10% [2], and the asc baseline vector file is exported after the solution is completed. When the network adjustment is performed, the asc baseline vector file is imported into the data post-processing software. First, the independent baseline loop and the repeated baseline are calculated. Check that all independent closed loop closure differences and duplicate baselines are within the specification tolerance, and select the network. The three-dimensional rectangular coordinates of the control point CPI165 are unconstrained adjustments for the starting point, confirming that the three-dimensional baseline vector residual is within the specification tolerance.

## Checking of start point relative stability

In the Wulingshan tunnel, one or two CPI points are selected for entrance and exit. This time, CPI164, CPI165 and CPI166 are selected, of which CPI164 is located at the tunnel entrance and CPI165 and CPI166 are located at the tunnel exit. Considering the distribution of points (see Figure 1), CP I164 and CP I166 are used to analyse the positional mismatch and the relative accuracy of the side length (points spacing 8 518. 550 1 m). CPI165 is close to CPI166 (points spacing 903. 449 1 m), CPI165 as an auxiliary point, only the azimuth analysis. The plane coordinates (L 0=110°48', H 0= 434 m) obtained by three-dimensional unconstrained adjustment of CPI164, CPI165 and CPI166 are compared with the conversion results, and the side length between adjacent points is calculated. Azimuth and angle, and comparative analysis, to determine the relative stability and reliability of the three plane control points.

### "Two-point method" constraint adjustment

Taking CPI164 and CPI166 as the starting point, the constraint is adjusted by the tunnel independent coordinate system L0=110°48' and H 0= 434 m. The error of the baseline side azimuth of the weakest edge DGPS05-DGPS06 after adjustment is MA= 0. 83″, the relative length error of the side length MS= 0. 17 cm, the relative accuracy is 1/259 648 (ie 3. 851 × 10-6, the relative length error of the side length is <1/250 000), which satisfies the accuracy requirements of the high-speed rail first-class GPS network in the specification.

## Independent control network reliability analysis

In order to verify the reliability of the independent control network [11], a triangle is selected for each angle of the construction area (tunnel entrance, exit and route) of the Wulingshan tunnel for angle and distance inspection. The test data is shown in Table 4 and Table 5.

*Tab. 4 - Comparison of measured side length of total station with GPS side length*

| Side name | Total station measurement /m | After the projection is corrected /m | GPS point inverse value /m | Mismatch value / mm | Projection length deformation value / (mm /km) |
|---|---|---|---|---|---|
| DGPS01 ~CPI164 | 528. 669 1 | 528. 668 7 | 528. 664 9 | 3. 8 | 4. 96 |
| DGPS01 ~CPI163 | 628. 680 9 | 628. 680 4 | 628. 676 3 | 4. 1 | 4. 54 |
| DGPS02 ~DGPS04 | 458. 262 6 | 458. 267 4 | 458. 269 3 | - 1. 9 | - 4. 15 |
| DGPS02 ~DGPS03 | 877. 586 7 | 877. 595 9 | 877. 593 8 | 2. 1 | 2. 39 |
| DGPS07 ~CPI165 | 640. 342 3 | 640. 343 2 | 640. 345 6 | - 2. 4 | - 3. 75 |
| DGPS07 ~DGPS08 | 862. 950 3 | 862. 951 6 | 862. 954 5 | - 2. 9 | - 2. 21 |

*Tab. 5 - Total station measured azimuth and GPS comparison*

| Corner name | Total station measurement / (° ' ") | GPS coordinate Back calculation / (° ' ") | Mismatch value / (″) | Back point | Measurement station | Front point |
|---|---|---|---|---|---|---|
| DGPS01 | 200 43 25. 3 | 200 43 25. 6 | - 0. 3 | CPI164 | DGPS01 | CPI163 |
| DGPS02 | 130 36 58. 1 | 130 36 56. 7 | 1. 4 | DGPS04 | DGPS02 | DGPS03 |
| DGPS07 | 171 25 24. 6 | 171 25 25. 3 | - 0. 7 | CPI165 | DGPS07 | DGPS08 |

It can be seen from Table 4 that the maximum projection length deformation value of the independent control network is 4.96 mm /km, which meets the requirements of the high-speed rail specification not to be greater than 10 mm /km. Table 5 shows the maximum difference between the total station measurement azimuth and the GPS back-calculated azimuth is 1.4″, the total station instrument detection data is in good agreement with the GPS data, and the reliability of the Wulingshan tunnel independent control network meets the requirements.

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## COMPARISON AND ANALYSIS OF NETWORK CONSTRUCTION METHODS WITH ONE POINT - ONE DIRECTION

In order to facilitate comparative analysis, the Wulingshan tunnel independent control network was established in one direction using the same baseline file, starting point and projection parameters. Taking CP I164 as the starting point, CP I166 is the direction point, the orientation θ = 125°18'22. 92″, the central meridian L 0=110°48', and the earth height H 0=434 m. After the one point one direction adjustment [12], the error of the baseline side orientation of the weakest edge DGPS05-DGPS06 is MA=0.77″, the relative length error of the side length is MS=0.15 cm, and the relative accuracy is 1/294 772 (the relative error is <1 /250 000), which satisfies the accuracy requirements of the high-speed rail first-class GPS network in the specification, the coordinates are poor. See Table 6.

*Tab. 6 - Control points poor statistics*

| Point No. | One point one direction network construction results | | Two-point method network construction results | | mismatching value | |
|---|---|---|---|---|---|---|
| | X/m | Y/m | North coordinate | East coordinate | dx/mm | dy/mm |
| CPI164 | 3 226 587. 404 8 | 497 361. 112 9 | 3 226 587. 404 8 | 497 361. 112 9 | 0. 0 | 0. 0 |
| DGPS04 | 3 226 298. 375 3 | 497 004. 061 5 | 3 226 298. 379 4 | 497 004. 065 6 | - 4. 1 | - 4. 1 |
| DGPS01 | 3 226 204. 761 4 | 496 996. 314 9 | 3 226 204. 766 4 | 496 996. 319 2 | - 5. 0 | - 4. 3 |
| DGPS02 | 3 226 280. 893 5 | 496 546. 120 3 | 3 226 280. 897 3 | 496 546. 129 9 | - 3. 8 | - 9. 6 |
| CPI163 | 3 225 932. 682 3 | 496 429. 555 6 | 3 225 932. 690 3 | 496 429. 566 6 | - 8. 0 | - 11. 0 |
| DGPS05 | 3 225 522. 743 0 | 498 252. 804 4 | 3 225 522. 755 8 | 498 252. 794 1 | - 12. 8 | 10. 3 |
| DGPS03 | 3 225 593. 401 4 | 496 000. 644 5 | 3 225 593. 413 6 | 496 000. 660 4 | - 12. 2 | - 15. 9 |
| DGPS06 | 3 225 096. 947 1 | 498 321. 623 5 | 3 225 096. 965 0 | 498 321. 612 4 | - 17. 9 | 11. 1 |
| CPI165 | 3 222 482. 730 9 | 503 930. 822 2 | 3 222 482. 779 0 | 503 930. 745 3 | - 48. 1 | 76. 9 |
| DGPS07 | 3 221 892. 425 6 | 504 178. 999 7 | 3 221 892. 480 9 | 504 178. 919 8 | - 55. 3 | 79. 9 |
| CPI166 | 3 221 664. 065 2 | 504 312. 956 3 | 3 221 664. 123 2 | 504 312. 874 8 | - 58. 0 | 81. 5 |
| DGPS08 | 3 221 155. 679 5 | 504 628. 346 3 | 3 221 155. 742 9 | 504 628. 261 0 | - 63. 4 | 85. 3 |

It can be seen from the analysis that the same baseline calculation file and projection parameters, the one-point direction and the "two-point method" can meet the accuracy requirements of the high-speed rail first-class GPS network, and the control point coordinates are different: the reference point difference is small, the direction point difference Large, and increasing with distance, reaching a maximum at the exit end of the tunnel. In combination with Table 6, it can be seen that the DGPS08 (distance from the reference point of about 9.1 km) has a poor coordinate Δx of -63. 4 mm and Δy of 85. 3 mm. The analysis shows that the coordinate is poorly affected by the distance and orientation [13], CPI164 CPI166 coordinate orientation θ = 125°18'22. 92″, located in the second quadrant, see Figure 2, the control point difference Δx is negative, Δy is a positive value and both increase with distance. Combined with the mid-line data of the Wulingshan tunnel line, the angle between the center line point tangent of the DGPS08 corresponding line and the reference direction of the control network is 61°43'08″, and the calculated DGPS08 corresponding center line point is 50.4 mm left, resulting in a long chain 93. 6 mm, the lateral deviation has already affected the tunnel exit connecting section, and needs to be controlled by the control network rotation, otherwise it will cause the structure of the tunnel exit section to be displaced and connected.

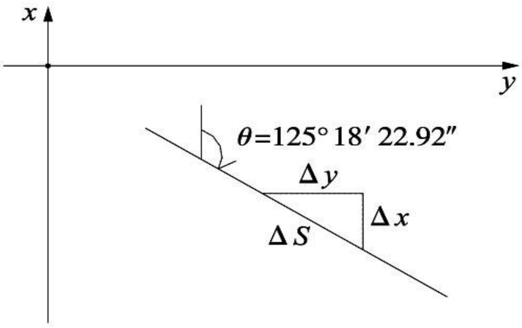


*Fig. 2 - Azimuth versus coordinate influence*

## TRANSVERSE PENETRATION ERROR PREDICTION ANALYSIS

The influence of the control network outside the tunnel on the lateral penetration error is related to the point error of the entry point, the azimuth error of the entry hole, the angle between the entry point and the connection point of the penetration point and the tangent of the penetration point line [14]. After the establishment of the outside control network, the penetration error prediction formula in the "High-speed Railway Engineering Measurement Specification" (TB10601-2009) should be calculated to verify whether the accuracy of the outside control network meets the requirements of the penetration measurement.

$$M^2 = \sigma_{\Delta x}^2 cos^2 \propto_F + \sigma_{\Delta y}^2 sin^2 \propto_{\propto F} + \sigma_{\Delta x \Delta y}^2 sin^2 2 \propto_F$$

Where σΔx、σΔy、σΔxΔy — the variance and covariance of the x, y coordinate deviations derived from the entrance and exit to the point of penetration;

αF — penetration plane orientation.

The Wulingshan Tunnel is 9. 044 km long and is constructed separately from the entrance, levelling and exit planes. The flat guide is located at the entrance of the tunnel and is placed at the entrance of the tunnel at 1 km. Therefore, it is included in the tunnel entrance. It is estimated that the tunnel entrance and exit will be about 4. 5 km, and the middle part of the tunnel will be DK239 + 013 as the pre-measurement. The entrance point of the tunnel entrance is DGPS02 and the direction is DGPS03. The entrance point of the tunnel exit is DGPS07, and the orientation point is CP I165. The tunnel transverse penetration error is expected [15] see Table 7.

The estimated lateral penetration error of the Wulingshan Tunnel is 10.1 mm, which is less than the error value of 45 mm [2] in the case of 7 km ≤ L < 10 km in the High-Speed Railway Engineering Measurement Specification (TB10601-2009), which satisfies the requirements.

*Tab. 7- Estimation of horizontal penetration measurement of Wulingshan tunnel*

| Penetration mileage | Lateral penetration error /mm | Entrance entry point | Entrance orientation point | exit entry point | Exit orientation point | direction |
|---|---|---|---|---|---|---|
| DK239+013 | 10. 1 | DGPS02 | DGPS03 | DGPS07 | CPI165 | 33 01 22. 9 |

## CONCLUSION

The "two-point method" can not only achieve sufficient accuracy, meet the tunnel penetration requirements, but also effectively solve the problems of large lateral deviation and long and short chains. The "two-point method" can not only achieve sufficient accuracy, meet the tunnel penetration requirements, but also effectively solve the problems of large lateral deviation and long and short chains.

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