PRECISE LEVELING OF THE
VERY LONG QINLING MOUNTAIN TUNNEL

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ABSTRACT The Qinling tunnel with length of 18.488km is located on the railway line from Xi'an (Shanxi Province) to Ankan (Sichuan Province) in the middle of Qinling mountain. It is the longest double track railway tunnel in China and takes the third place in the world. According to the design, the breakthrough error in vertical direction caused by the altimetric control surveying is limited to 18mm for the case of one piercing face. Because the leveling route reaches over 120km in length and must go over two mountains in 2800m height, the first-order precise leveling and precise gravity measurement should be carried out in the construction stage. In this paper the field leveling approach, the application of new technology, some experience as well as the office calculation with final results analysis are introduced. By meticulous planning, organization and observation, the final accuracy of vertical difference between two tunnel end points is only 8mm, and it provides reliable surveying guarantee for this great tunnel engineering. Finally it is pointed out that this vertical difference distinguishes obviously from the primary measurement result as high as 114mm. It means that the primary result is not accurate enough.

1 Introduction

1.1 General situation of the project
The tunnel project consists of the major two-lane tunnel and parallel hollows. The height of its entrance is 869m and that of its exit is 1022m, so the height difference between entrance and exit reaches 153m. The height of the mountain ridge exceeds 2800m and the relative height difference within the survey area is about 2000m.

1.2 Presentation of problems
The original vertical control surveying is completed with the second-order leveling; the height of the entrance is inferred from the national third-order leveling point named Chang 13 with the leveling route length of 14.039km and that of the exit is inferred from the national second-order leveling point named Guang 3 with the length of 3.2km; the leveling accident standard error equals to 0.7mm per kilometer; the Chang 13 is not connected by leveling route with the Guang 3 (the distance reaches 109km), thus the height difference between the entrance and the exit is directly gained by their inferred heights.

In addition, the GPS positioning technique is also applied. After correction of GPS heights the normal heights of points at the entrance and exit of the tunnel terminals can be obtained. The height difference gained from GPS data differs from the inferred leveling height difference by 24.2mm. According to the "Technical Specification of Railway Sur-
The "Specification" stipulates that a second-order leveling should be adopted if the leveling route length between two terminals of the tunnel is longer than 36 km, however, it doesn't point out in which case the first-order leveling must be taken. The leveling route length of Qinling tunnel is more than 120 km (it is taken as 130 km for safety). The formula estimating the height difference standard error $M_{\Delta h}$ is:

$$M_{\Delta h} = \pm m \sqrt{S_k} \tag{1}$$

where $m$ is the leveling standard error per kilometer; $S_k$ is the leveling route length in kilometer from the entrance point $j$ to exit point $c$. For the second-order leveling, $m = \pm 2.0$ mm/km; for the first-order leveling $m = \pm 1.0$ mm/km (in mountain area is $\pm 1.2$ mm/km); so we can obtain from Eq. (1):

for the second-order leveling: $M_{\Delta h} = \pm 22.8$ mm for the first-order leveling: $M_{\Delta h} = \pm 11.4$ mm or $M_{\Delta h} = \pm 13.7$ mm in mountain area.

Obviously the second-order leveling survey can not satisfy the requirement ($M_{\Delta h} \leq 18$ mm). From Eq. (1) we know:

$$S_k = \left( \frac{M_{\Delta h}}{m} \right)^2 \tag{2}$$

Suppose $M_{\Delta h} = 18$ mm, $m = \pm 2$ mm/km, we can obtain $S_k = 81$ km. That is to say, if $S_k$ is more than 81 km, the first-order leveling for the altitude control survey outside the tunnel must be applied.

Obviously the accuracy of the results provided originally is not enough. Additionally, there are following problems:

1) The order of the applied national leveling points is too low (one of them is the third-order leveling point);

2) The surveying time, organization and altitude datum of two national leveling points are not known clearly;

3) There is no need checking for the two national leveling points;

4) The two national leveling points are not connected with leveling route;

5) The precision of GPS height is not enough, the geoid differences at the known leveling points are different from that of the two terminals, then the precision of the geoid differences is relative lower, we consider that the GPS height differences can not be used for checking the leveling height difference.

2 Design of the surveying scheme

2.1 Collection of data

While designing the survey scheme, we collected the latest data of the national leveling and gravity survey, which include adjustment values of the first and second-order national leveling network points, as well as the values of the national gravity field in this area. Then we found out that the data of the two leveling points provided originally are not correct because Chang 13 should be the first-order leveling point (it was regarded as the third-order point) and the distinguish of height difference between two known leveling points of two cases reaches 0.101 m. Therefore it is further proved that there is need to make a first-order leveling.

2.2 Design of the leveling lines

The first-order leveling lines consist of one main line and two branch lines (see Fig. 1). The length of the main line from Chang 13 to Guang 3 is 109 km which consists of 38 measurement segments and is divided into three parts: ($\text{a}$) from I Qin 1 to I Qin 15 (43.8 km); ($\text{b}$) from I Qin 15 to I Qin 29 (33.8 km); and ($\text{c}$) from I Qin 29 to I Qin 39 (31.4 km). There are 16 common leveling stakes and 23 rock leveling stakes, which include 18 national leveling point stakes.

In order to connect the leveling points at the tunnel terminals, two branch leveling lines from I Qin 1 and I Qin 38 on the main line to the entrance and the exit are measured respectively. The length of the entrance branch line on which three rock leveling points named Z1, Z2, and Z3 are buried is
14.3 km and that of the exit branch line is only 1.5 km.

3 Field observations

3.1 The leveling

The leveling is completed with two Zeiss precise levelers Nio2. The field work took up about 40 days from early June to middle July, 1995. We strictly abided by the "Specification" and paid particular attention to the following aspects.

1) In order to reduce the effects of refraction and angle, the sight distance is strictly limited and is directly measured with measuring rope, the difference between fore-and-back sight distance is limited to 0.5m, to make the staff image clear and steady while surveying.

2) To pay attention to the reduction of the lateral and terrestrial refraction effects. Considering the characteristic of the mountain area, the sight should avoid close to the hillside. It is prohibited strictly to set the staff in plow groove to improve the reading of the sight.

3) The particular attentions to the stability of the staff bearing are paid. We found out that it is the principal cause why the fore-and-back measurement closure exceeds its tolerance.

4) The circular bubble on the staff should be adjusted every day before the observation. The leveling staffs were calibrated three times by the standard metal meter through the whole time.

5) The operators are technically trained who should be decisive and work quickly; the working group (6 persons) should be in harmony with one another.

6) The best observation time should be selected and strictly abided, the observations of each day should be examined and processed in time. If the results are doubted, it must be measured again.

3.2 Application of the new technology

The field recording and data processing of the first-order leveling are taken by the "Cosa" system (a connected sequence and automatic system in control surveying) developed by the authors. The data are gathered by a hand-computer RD-EBI (Fig. 3.) The "Cosa" system is very suitable to the field recording and data processing (including network adjustment). It can not only save the observation time, reduce the intensity of field and office work, but also realize the automation for full measurement and data processing procedure. The quality of the products will be more reliable.

3.3 Gravity survey

In order to correct the measured height differences caused by abnormal gravity, the gravity of each point was surveyed from three lines using the
relative gravimeter Lacoste. Three known gravity points were applied. The observation time and the counter reading are recorded at each station. There is one or two test points on each line.

The gravity difference between two points measured by Gravimeter Lacoste is:

$$ \Delta g = C(S_2 - S_1) \quad (3) $$

where $S_2$ and $S_1$ are the gravimeter counter readings respectively; $C$ is the grid value of the gravimeters. The absolute gravity of each leveling point can be obtained from the gravity of known point, through correction of the solid tide and the zeroing. As a result the standard error is about 0.1 milligal.

4 Processing and evaluation of the observations

4.1 Quality of the Observations

| line name         | distance/km | segments | $n_1$ | $n_2$ | $\Delta L_{(1/3)}$ | $\Delta L_{(3/4)}$ | $\Delta L_{(2/3)}$ | $\delta_L/mm$ |
|-------------------|-------------|----------|-------|-------|-------------------|-------------------|-------------------|---------------|
| main line         | 109.0       | 38       | 25    | 13    | +10.66            | ±18.79            | ±2.59             | ±6.81         |
| entrance branch   | 14.3        | 7        | 7     | 0     | +2.59             | ±6.81             | ±2.59             | ±6.81         |
| exit branch line  | 1.5         | 4        | 0     | 0     | ±0.39             | ±2.20             | ±1.78             | ±4.32         |
| total             | 124.8       | 50       | 36    | 13    | +12.86            | ±20.11            | ±2.59             | ±6.81         |

Note: Only the numbers of $< (1/3) \delta_L$ or $< (3/4) \delta_L$ for $\Delta L$ are counted.

4.1.2 Calculation of the accident standard error per kilometer

The accident standard error per kilometer of the first-order leveling can be calculated by the following formula:

$$ M_A = \pm \sqrt{\frac{\Delta L}{R}}/(4n) \quad (4) $$

where $\Delta L$ is the fore-and-back height difference closure of each segment (in mm); $n$ is the total numbers of segments; $R$ is the distance of each segment (in km). When $R$ is less than 1 km, it is taken as 1 km. The accident standard error per kilometer of the main line is estimated as 0.33mm, it is better than the "specification" requirement of 0.45mm.

4.2 Office calculation

4.2.1 Altitude datum and initial data

A normal height system and the national altitude datum 1985 were adopted for the first-order leveling of Qinling tunnel. The checking measurements were made on the base lines from I Chang 11 to I Chang 13 and from II Guang 3 to II Guang 4. It shows that the applied known leveling points are stable and reliable, the tested height differences differ from that of the known only by 0.42mm and 0.73mm respectively.

4.2.2 Correction of the height difference

Three corrections of the observed height difference were made according to the accuracy requirement of the project and to the characteristics of the surveying area.

1) correction $\delta$ for the length error of leveling staffs

$$ \delta = f \times h \quad (5) $$

where $f$ is the correction coefficient of the staffs (known as $f = 0.010$ mm); $h$ is the height difference of the measurement segment.

2) correction $\epsilon$ for the unparalleled normal level

$$ \epsilon = -(\gamma_{i+1} - \gamma_i) \times H_m / \gamma_m \quad (6) $$

where $\gamma_{i+1}, \gamma_i$ are the normal gravity of the two terminal leveling points of the measurement seg-
3) Correction for the gravity anomaly

The height difference correction $\lambda$ of one segment can be estimated as

$$\lambda = (g - \gamma)_m \times h / \gamma_m$$

(7)

where $h$ is the height difference (in m); $(g - \gamma)_m$ is the average value of the free-air gravity anomaly of the two leveling points (mm/s$^2$). The free-air gravity anomaly for any point $i$ is:

$$(g_i - \gamma_i)_i = (g_i - \gamma_i) + 0.308 6H_i$$

(8)

where $g_i$, $\gamma_i$ are the measured absolute gravity and normal gravity of point $i$, respectively; $H_i$ is its approximate height.

The ranges of the above three corrections are: (0.01 to 3.09 mm) for $\delta$, (0.13 to 5.18 mm) for $\epsilon$, and (0.01 to 12.9 mm) for $\lambda$, which demonstrate the necessity of the corrections. Corrections 1) and 2) are systematic, and 3) can be counteracted.

4.3 Evaluation of the results

Regarding the I Chang 13 (I QinShui 1) as datum point of the first-order leveling, the normal heights of the known leveling point I Guang 3, the entrance leveling point BM1, the exit leveling point BM5 can be calculated with the corrected height difference of each leveling line, then the height difference $\Delta H_{\text{I II}}$ between the two known leveling points and that $\Delta H_{\text{I e}}$ between the entrance and the exit leveling points can be estimated as:

$$\Delta H_{\text{I II}} = H(\text{II Guang 3}) - H(\text{I Chang 13}) = 430.360 \text{m}$$

$$\Delta H_{\text{I e}} = H(05) - H(JBM1) = 152.650 \text{m}$$

The height difference between the two known leveling points is known as 430.356 m, which differs from this measured value only by 4 mm (its tolerance value is 44.3 mm). Thus it is not only verified that the national leveling data collected this time are reliable, but also concluded that the accuracy of this leveling measurement is very high. The “affected value” error can be converted according to the actual accident standard error per kilometer and estimated as 8.0 mm (or 9.7 mm in mountain area), which is far less than 18 mm.

The height difference between the two known points Chang 13 (be originally taken as the national third-order leveling point) and II Guang 3 is 430.255 m according to the original data, which differs from this measurement by 105 mm; and the original height difference between the entrance and the exit is 152.53 m which differs from this measurement result by 114 mm. It shows that the results provided originally are seriously wrong, it is not only because the initial data do not come from the new results and the leveling order used as the initial datum is too low; but also because the leveling accuracy of the entrance and exit branch line is obviously low.

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