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Application of GPS technology in surface subsidence monitoring of water extraction

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ABSTRACT

In order to improve the precision and improve the monitoring system of surface subsidence, the monitoring results are more accurate. Using GPS (Global Positioning System) technology and traditional leveling method, combined with the characteristics of surface subsidence monitoring, GPS leveling is carried out. According to the principles of various fitting models and the characteristics of different fitting models, a step-by-step hybrid model is proposed, and its practicability is verified. The results show that the fitting precision of the step-by-step hybrid model improved by GPS technology is higher than that of the traditional method. It provides a new idea for the application of GPS technology in the monitoring of surface subsidence, and has a reference value for the research and design of fitting model.

Keywords: GPS technology; Surface subsidence of water extraction; Monitoring method; Elevation measurement; GPS elevation fitting

1. Introduction

Land subsidence is an environmental geological disaster that leads to the decrease of regional ground elevation [1]. It often occurs in densely populated and industrial urban areas [2]. In particular, common problems in areas that are located in vast plain areas and rely on extracted groundwater as the main source of water supply. It is of great theoretical and practical significance to study the temporal and spatial variation law of land subsidence during water harvesting to provide a scientific basis for groundwater resource planning, management and rational exploitation as well as the maintenance and improvement of ecological environment [3]. With the continuous improvement of various measuring instruments, relevant monitoring methods and technologies for water extraction and ground subsidence, the monitoring of water extraction and ground subsidence has made great progress [4]. The existing monitoring methods mainly include leveling, trigonometric elevation, digital photogrammetry, GPS (Global Positioning system) and INSAR (Interferometric synthetic aperture radar). The traditional leveling operation has low efficiency and high intensity. The technical cost of digital measurement technology is too high and the equipment is relatively expensive. In GPS measurements, the elevation reference is the elevation of the earth, which cannot be directly used in engineering. The measurement technique, known as synthetic aperture radar interferometry, is highly susceptible to atmospheric errors, ground conditions and satellite orbit parameters in terms of accuracy, which in turn affects its accuracy and reliability. Due to the limitations of technology and cost, GPS and INSAR fusion technology cannot be widely promoted [5].

Numerous GPS elevation transformation models are roughly divided into two categories. One is a single model, that is, only one model is used when performing elevation transformation, such as a conventional geometric fitting model [6,7]. The other is a hybrid model, that is, a comprehensive model [8,9]. Hybrid models are used for elevation conversion, including a mixture of models with the same property and a mixture of models with different properties [10,11]. Today, geological disaster monitoring is

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increasingly dependent on automation and high-precision measurement methods, and traditional measurement methods cannot meet this demand. All-weather real-time measurement will play an important role, in view of this, the elevation conversion processing becomes more and more important. How to use corresponding methods to find the elevation abnormalities in various places, and then transform this pure geometric quantity into the normal height used in engineering are the main problems to be solved.

GPS survey technology and traditional leveling survey method are used in the study, and combined with the characteristics of surface subsidence monitoring. The experiment of leveling technique is carried out, that is, the normal height of the earth is higher than the level of fitting transformation by using GPS, and then the normal height of the required points is obtained. This paper introduces the principle of several fitting models and the characteristics of different fitting models, considers the advantages of each model completely, and proposes a step-by-step mixed model to achieve higher fitting precision. Therefore, the step-by-step mixed model has better practicability.

2. Contents and methods of monitoring of water mining surface settlement

2.1. Geological conditions of the area to be studied

The area to be studied is located in a plain area, with a typical warm-temperate semi-humid and semi-arid continental monsoon climate. The area to be studied is located on the Yanshan subsidence zone, where folds and faults are extensively developed, and underground rock activities are gradually becoming frequent. The surface lithology of the area to be studied is relatively complex, with various rocks and soils partially exposed, and the thickness of the stratum is very uneven, ranging from tens of meters to hundreds of meters. Hydrological conditions: The water flow of the rivers in the area to be studied is declining year by year, and the rivers in some areas are disappearing year by year over time. About two-thirds of drinking water comes from groundwater. The main method of groundwater replenishment is rainfall, and the distribution of precipitation is uneven. From the northern end to the southern end of the area to be studied, there is a general declining trend. The average annual rainfall is about 600 mm, which is difficult to meet the average level of per capita consumption. Excessive exploitation of groundwater in this area is one of the main factors leading to land subsidence. With the development of modern industries, the global warming trend is becoming more and more serious, which in turn has a serious impact on areas where precipitation is the main source of water. In terms of geological structure, the area to be studied is mainly loose deposits. Due to the excessive exploitation of groundwater, the stratum is compressed, which eventually leads to land subsidence.

2.2. Surface subsidence of water extraction method

Leveling measurement is a traditional means of settlement monitoring, and it has greater advantages in terms of operation technology, cost, accuracy, and reliability. The electronic level has improved the accuracy of leveling measurement, the labor intensity has been greatly reduced, and the data collection and processing have become more automated [12]. Although there is great progress, it is still difficult to meet the development requirements of modern surveying and mapping [13]. The biggest advantage of the triangulation method is that it is not restricted by the terrain and the measurement is faster. The triangulation method has certain advantages compared with traditional leveling in places that are difficult to reach or where the elevation difference is large. Therefore, in modern automation and in the monitoring with high precision requirements, its own shortcomings are also exposed [14,15]. GPS elevation measurement has the characteristics of all-weather, easy to realize the automation of measurement. At present, the price of GPS equipment has dropped significantly, and the cost of using deformation monitoring has been greatly reduced [16]. The measurement method uses artificial earth satellites for spatial positioning, and obtains the coordinate information of the measurement points by means of distance rendezvous [17]. When GPS uses satellites for measurement, the three-dimensional spatial coordinates of the receiver's position are calculated through distance rendezvous. Fig. 1 shows the basic principle of GPS measurement.

In the figure, A, B, C, represent three satellites, and P represents a GPS receiver set up at the coordinate point to be determined. The instantaneous distances between the receiver and the three satellites at time t are Sa, Sb, and Sc, respectively. Through the navigation message in the receiver, A, B, C, and the instantaneous spatial coordinates at that moment are interpreted. Then through the method of distance intersection, the three-dimensional coordinates of the P point are calculated, and then the required WGS-84 geodetic elevation of the antenna phase center is obtained. The observation equation is as follows.

$$\left.\begin{aligned}\left(X_P-X_A\right)^2+\left(Y_P-Y_A\right)^2+\left(Z_P-Z_A\right)^2=S_a^2\\ \left(X_P-X_B\right)^2+\left(Y_P-Y_B\right)^2+\left(Z_P-Z_B\right)^2=S_b^2\\ \left(X_P-X_C\right)^2+\left(Y_P-Y_C\right)^2+\left(Z_P-Z_C\right)^2=S_c^2\end{aligned}\right\} \quad (1)$$

Compared with leveling and triangulation, the biggest advantage of elevation measurement is that the error accumulation during long-distance measurement is small, and the measurement can be automated, and it needs to be transformed into a three-dimensional coordinate system. Among them, the GPS geodetic elevation H based on the WGS-84 reference ellipsoid is transformed into the normal elevation Hr based on the similarly large low-level.

2.3. Features of GPS elevation measurement

The GPS system simultaneously receives the ranging information and navigation messages of three or more GPS satellites at a certain time through the GPS receiver, using the coordinate information in the navigation messages and the calculated distance information. And by means of distance rendezvous, the receiver antenna phase center, the spatial three-dimensional coordinates of the location are calculated. The elevation datum is the starting surface

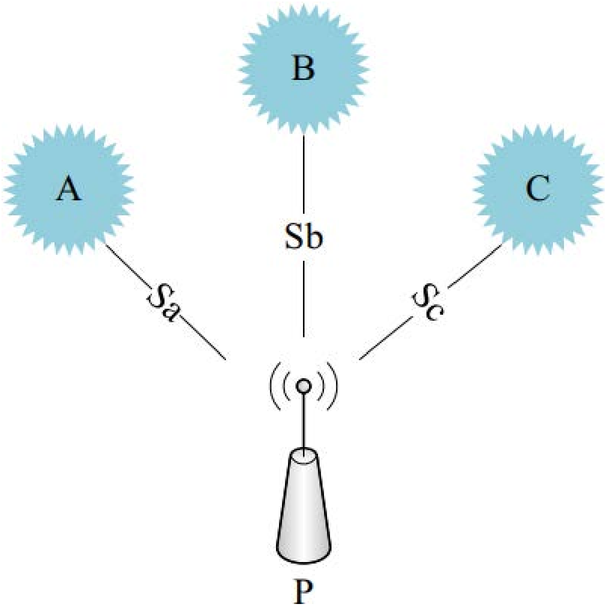

Fig. 1. GPS testing principle.

of the elevation datum. The mass of the earth is unevenly distributed. The horizontal surface is an irregular curved surface, and the adjacent horizontal surfaces are not parallel. There are three main types of elevation systems commonly used in surveying at present.

2.3.1. Orthogonal height system

The distance from a point on the ground along the plumb line to the geoid is called orthometric height, and the elevation system determined by orthometric height is orthometric height system. The following is the calculation formula of the positive elevation system.

$$H_M^B = \frac{1}{g_m^B} \int_{\text{AOB}} g dh \tag{2}$$

AOB is the measured leveling route, which is the average value of gravitational acceleration from the vertical line of point B to the leveling plane where point A is located. The average value is related to the material density and depth at the location of the point, so it is impossible to obtain an accurate normal high value through actual measurement. Generally, the normal gravity value r is used to replace all the g values in the above formula, and the following approximate value equation of the positive height is obtained.

$$H_M^B = \frac{1}{r_m^B} \int_{\text{AOB}} g dh \tag{3}$$

The numerical values of the parameters in the formula are given by Liang and Dong in the literature as follows.

$$r_m = \frac{(r_m + r_m)}{2} - 0.1543 H_m \tag{4}$$

2.3.2. Normal height system

Since it cannot be accurately measured, the normal height system is proposed. The elevation system is defined as the distance from a point on the ground to the geoid along the direction of the normal gravity line. That is, the constant gravity value r_m replaces the g_m in Eq. (2), and the normal height is calculated as follows.

$$H_N^B = \frac{1}{r_m^B} \int_{\text{AOB}} g dh \tag{5}$$

The following is the formula for the difference between the elevation value of the elevation system and the approximate positive elevation value.

$$H_N^B - H_M^B = \frac{1}{r_m^B} \int_{\text{AOB}} (g - r) dh \tag{6}$$

In the formula (g–r) is the gravity anomaly value on the leveling route. The normal height system uses the artificially prescribed quasi-geoid as the reference surface, which can accurately obtain the elevation value of the point.

2.3.3. Geodetic elevation system

The geodetic elevation system is mainly used in space geodetic surveying. Among them, the elevation value measured by GPS is based on the ground height of the WGS-84 ellipsoid. When the reference system and the reference surface are determined, the position on the ground can be calculated to find the ground height value. The following formula shows the elevation system corresponding to different datums and the relationship between different elevation systems.

$$H = H_g + N = H_r + \xi \tag{7}$$

In the formula, H_r is the normal height, H_g is the positive height, N is the geoid gap, H is the geoid height, and ξ is the height abnormality. The elevation system studied is a kind of geodetic elevation system, and the datum plane is the WGS-84 reference ellipsoid.

The GPS survey station is fixed on the natural surface of the earth, and its position in space observation is related to the rotation of the earth. In space, the GPS satellite constellation is rotating around the center of mass of the earth, which has nothing to do with the rotation of the earth. So before using the GPS measurement results, it is necessary to transform the satellite motion coordinate system and the ground coordinate system.

In the conversion process, the origin of the Cartesian coordinate system coincides with the origin of the spherical coordinate system. The distance r from the origin O to the ground point P is used as the first parameter, and the angle $\theta(0–\pi)$ between the OP and the OZ axis is used as the second parameter. Generally, for the convenience of calculation, $\delta = 90°–\theta$ is used instead of the second parameter, and the angle α between the plane ZOX and the plane ZOP is used as the third parameter. The conversion equations between X, Y, Z rectangular coordinate system coordinates and spherical coordinates are as follows.

$$\left.\begin{aligned} X &= r\cos\ \alpha\ \cos\delta \\ Y &= r\sin\ \alpha\ \cos\delta \\ Z &= r\sin\ \delta \end{aligned}\right\} \tag{8}$$

$$\left.\begin{aligned} r &= \sqrt{X^2+Y^2+Z^2} \\ \alpha &= \arctan(Y/X) \\ \delta &= \arctan\left(Z/\sqrt{X^2+Y^2}\right) \end{aligned}\right\} \tag{9}$$

The reference surface of the geodetic coordinate system is an ellipsoid, and the long and short semi-axes are respectively a and b. The origin of the coordinate system is the geometric center of the ellipsoid. The geometric center coincides with the origin of the rectangular coordinate system, and the short semi-axis coincides with the Z axis of the coordinate. The angle B between the normal of the ellipsoidal surface passing the point P and the plane XOY is the geodetic latitude parameter, and the angle L between the plane ZOP and ZOX is the geodetic longitude parameter. Taking the plane ZOX to rotate to the right as positive, the distance from point P to the normal line of the ellipsoid that passes through point P is the height of the earth. The conversion equations between X, Y, Z Cartesian coordinates and geodetic coordinates are as follows.

$$\left.\begin{aligned} X &= (N+H)\cos B\cos L \\ Y &= (N+H)\cos B\sin L \\ Z &= \left[N\left(1-e^2\right)+H\right]\sin B \end{aligned}\right\} \tag{10}$$

$$\left.\begin{aligned} L &= \arctan(Y/N) \\ B &= \arctan\left\{Z(N+H)/\left[\sqrt{X^2+Y^2}\left(N\left(1-e^2\right)+H\right)\right]\right\} \\ H &= Z/\sin B - N\left(1-e^2\right) \end{aligned}\right\} \tag{11}$$

In the formula $N = a/\sqrt{1-e^2\sin^2 B}$, N is the radius of curvature of the point, e is the first eccentricity of the geodetic coordinate system, and its value is $e^2 = (a^2 + b^2)/a^2$. The main parameters of the WGS-84 coordinate system now adopt the recommended values of geodetic constants specified by the International Union of Geodesy and Geophysics in the first conference. The details are as follows.

Long semi-shaft:

$$a = 6{,}378{,}137 \pm 2m \tag{12}$$

The gravitational constant of the atmosphere:

$$G_M = \left(39{,}656{,}005\times10^8 \pm 0.6\right)\times10^8\left(\mathrm{m}^3/\mathrm{s}^2\right) \tag{13}$$

Normalized second-order to-be-harmonic coefficient:

$$C_{2.0} = -484.16685\times10^{-6} \pm 1.30\times10^9 \tag{14}$$

Angular velocity of the earth's rotation:

$$\omega = -7292115\times10^{-11} \pm 1.1500\times10^{-11}\left(\mathrm{rad}\cdot\mathrm{s}^{-1}\right) \tag{15}$$

Ellipsoid flatness:

$$f = \frac{1}{298.257553563} \tag{16}$$

Different elevation systems have different elevation values. First, GPS geodetic height and normal height are used to solve the height anomaly, and then the fitting method is used to establish the conversion model of the elevation system to obtain accurate normal height data for the convenience of engineering applications.

2.4. GPS height fitting method

The following formula shows the fitting equation of the plane fitting model.

$$\xi = a_0 + a_1x + a_2y \tag{17}$$

This method takes the quasi-geoid and WGS-84 ellipsoid in the study area as two completely parallel curved surfaces, the distance between the two curved surfaces is a constant, and ξ is the elevation abnormal value of the area. The corresponding relationship among ξ and the earth height H and the normal height H_r is as follows.

$$H = Hr + \xi \tag{18}$$

According to the number of coefficients in the fitting equation, this method is divided into constant fitting and general plane fitting. The constant fitting contains only one unknown number a_0, and the general plane fitting model contains three unknown coefficients. In the two methods of fitting, except for the need for different pairs of known elevation values, the other steps are roughly the same. There are two types of linear fitting, one is the linear interpolation model, and the fitting equation is as follows.

$$\xi = a\Delta s + h \tag{19}$$

The other is a bilinear interpolation model, and the fitting equation is as follows.

$$\xi = a\Delta x + b\Delta y + c\Delta x\Delta y + h \tag{20}$$

Surface fitting models are generally divided into high-order surface fitting and high-order polynomial surface fitting, and the fitting equation is as follows.

$$\xi = a\Delta x + b\Delta y + m\Delta x^2 + n\Delta y^2 + c\Delta x\Delta y + \ldots + h \tag{21}$$

$$\begin{aligned} \xi = {} & \left(a_{00} + a_{01}\Delta x + a_{02}\Delta x^2 + a_{03}\Delta x^3 + \ldots + a_{0n}\Delta x^n\right) \\ & + \left(a_{10} + a_{11}\Delta x + a_{12}\Delta x^2 + a_{13}\Delta x^3 + \ldots + a_{1n}\Delta x^n\right)\Delta y \\ & \ldots \\ & + \left(a_{n0} + a_{n1}\Delta x + a_{n2}\Delta x^2 + a_{n3}\Delta x^3 + \ldots + a_{nn}\Delta x^n\right)\Delta y^n \end{aligned} \tag{22}$$

This method takes the quasi-geoid and WGS-84 reference ellipsoid in the area to be studied as ideal curved surfaces. It is believed that the elevation anomalies in the study area can be expressed by a higher-order surface equation or a higher-order polynomial. This method can play unique accuracy advantages in the process of abnormally uniform elevation changes. The equation for moving the surface model is as follows.

$$\xi = f\left(x_i, y_i, x_j, y_j, R, w_j\right) \tag{23}$$

(x_i, y_i) is the coordinate value of the interpolation fitting point for the known abnormal value, (x_i, y_i) is the coordinate of the fitting point to be found. R is the distance threshold between the known fitting point and the fitting point to be found, and w is the height anomaly weight of the known fitting point to be fitted, that is, the elevation anomaly influence factor.

Kriging surface interpolation, the Kriging technology used in the research is an optimized interpolation algorithm with a random process z attached, and the basic principle is as follows. (x_0, y_0) is set as a specific point, (x_1, y_1), $(x_2, y_2)\ldots$, (x_N, y_N) is the observation point around it, and the corresponding values are $\xi_1, \xi_2, \ldots, \xi_N$ respectively. The value of the point to be estimated is $\bar{\xi}\left(x_0 y_o\right)$, and its value is obtained from the regression function value of the neighboring points and the random function of each point at that point.

$$\bar{\xi}(w) = F(\beta, w) + z(w) \tag{24}$$

In the formula, $F(\beta,w)$ is the regression function of β, w, w is the point (x, y) of the plane, β is the regression coefficient of the regression function of the neighboring points, and z is the random function of x, y. The expression of regression model $F(\beta,w)$ is as follows.

$$\left.\begin{aligned} F(\beta,w) &= \beta_1 f_1(w) + \beta_2 f_2(w) + \ldots + \beta_p f_p(w) \\ &= \left[f_1(w), f_2(w), \ldots f_p(w)\right]\beta \\ &= f(w)^T \beta \end{aligned}\right\} \tag{25}$$

Assuming that the mean value of the random function z is 0, its covariance is as follows.

$$E\left[z\left(w_i\right)z\left(w_j\right)\right] = \sigma^2 R\left(\theta, w_i, w_j\right) \tag{26}$$

In the formula, σ^2 is the elevation abnormal value of w_i, w_j, and $R(\theta, w_i, w_j)$ is the correlation coefficients with respect to the θ parameter. The fitting equation of the mixed model is as follows.

$$\xi = \xi' + \xi_1' + \xi_2' \ldots + \xi_n' \tag{27}$$

ξ' is the first fitting equation, ξ_1' and ξ_2' are the fitting equations for the first fitting residual and the second fitting residual, respectively. The research principle of this method is based on the fact that changes in elevation anomalies generally have a gradual change without sudden changes, so multi-step solution can be performed when modeling elevation anomalies.

3. Analysis of GPS surface subsidence of water extraction data

3.1. Moving surface fitting and analysis of experimental data

Fig. 2 shows the difference between the fitting based on abnormal values and the fitting based on fixed points.

In the figure, FPBIFR is the fixed-point bilinear interpolation fitting result, BIFRAT is the bilinear interpolation fitting result of abnormal terrain, and FPBIFD and BIFDAT are the corresponding differences. The overall experimental

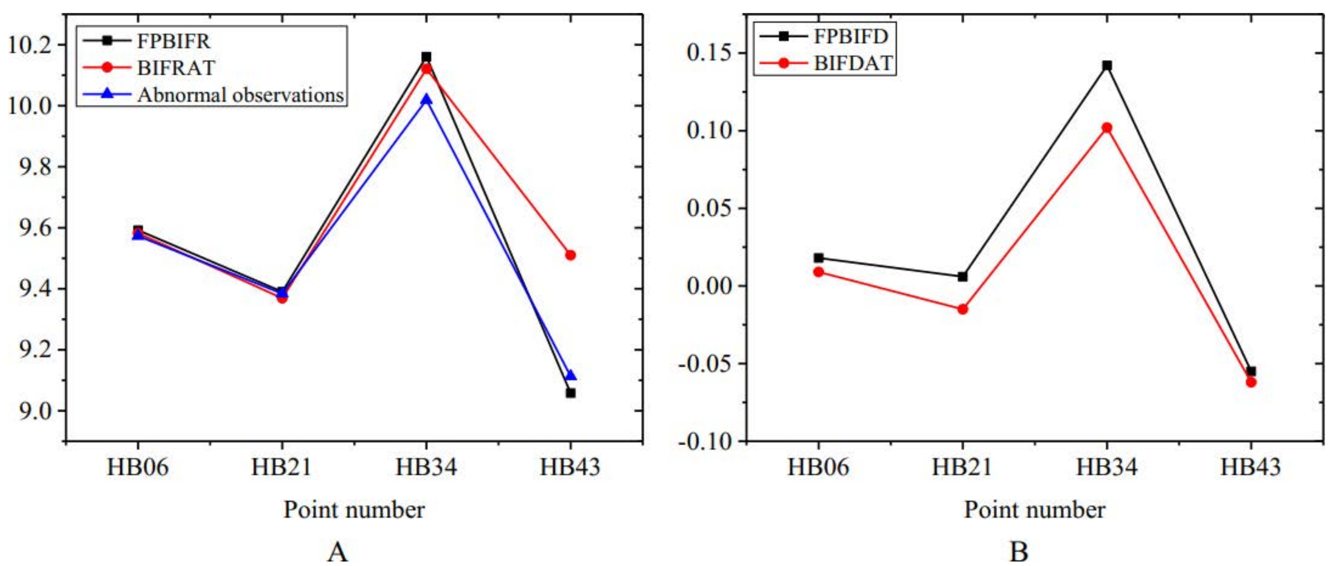

Fig. 2. Fitted values under different methods: (A) fitted values and abnormal observations and (B) differences.

data of the four points are slightly improved. The external coincidence accuracy of the fitting is calculated to be 0.081 and 0.064 m respectively. The external coincidence accuracy of the fitting method based on the abnormal terrain selection method is increased by 21% compared with the external coincidence accuracy of the fixed-point number method fitting. Therefore, it is more intuitive to see the degree of improvement of the fitting accuracy by the fitting method of selecting points.

Fig. 3 shows the difference in stability between parameter changes based on outlier fitting and fixed-point fitting.

When the neighbourhood radius of several fitting models is the same multiple of neighbourhood radius, the experimental data of fixed-point bilinear interpolation

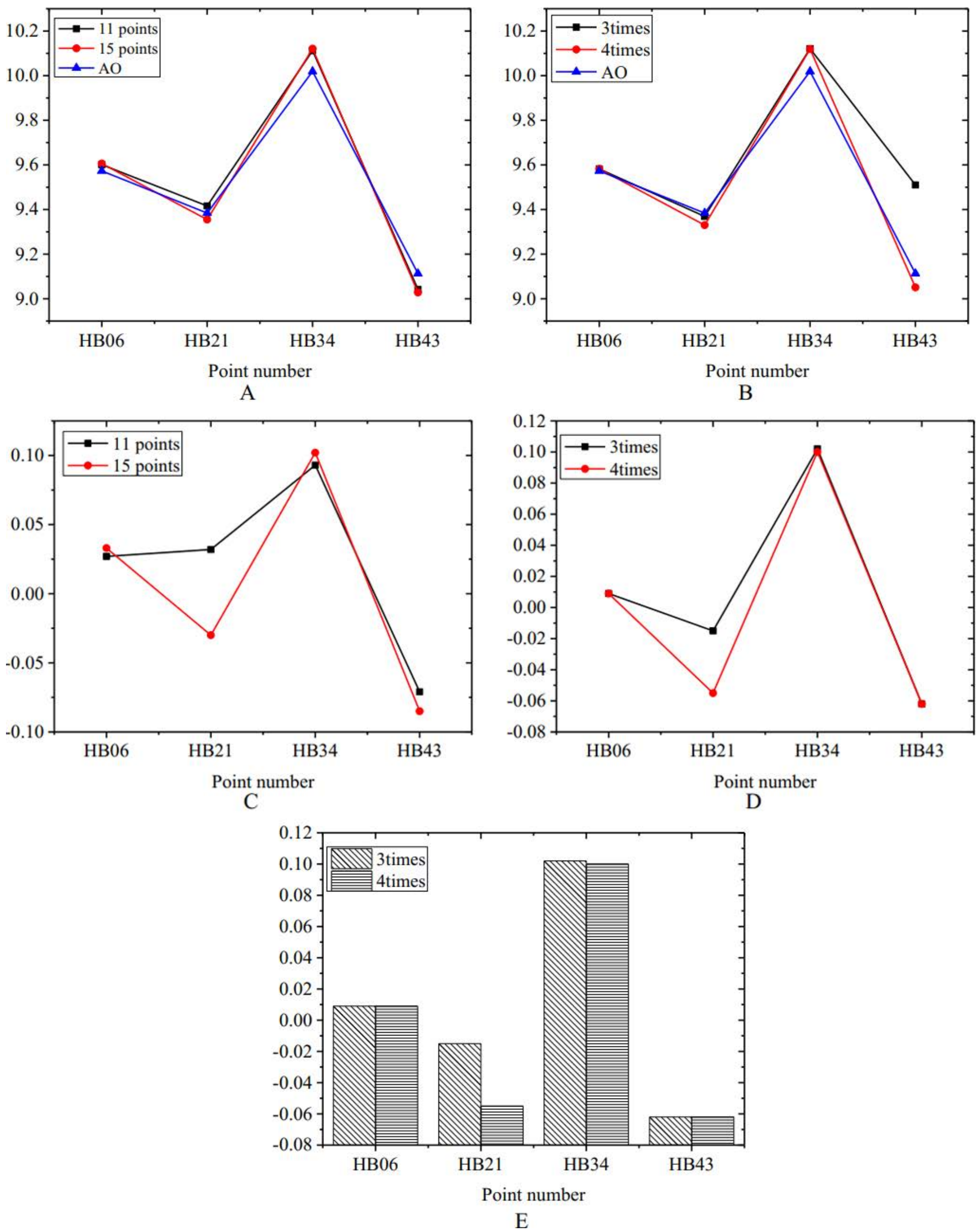

Fig. 3. The fitting value, fitting residual value, and external coincidence accuracy of each fitted model: (A) fixed-point selection bilinear interpolation fitting result, (B) bilinear interpolation fitting result of abnormal terrain, (C) fixed-point double linear interpolation fitting difference, (D) bilinear interpolation fitting difference of abnormal terrain, and (E) external coincidence accuracy.

fitting method is obtained. The number of known fitting points determined is not as many as possible. When the radius of the same neighbourhood is limited, the number of fitting points is increased, and the final fitting accuracy will fluctuate. That is, sometimes increasing the number of points will increase the accuracy of the fitting and sometimes decrease, which indicates that the robustness of the point selection method during fitting is not good.

Fig. 4 shows the fitting accuracy of different points and radii.

The fitting method of selecting different points in the figure is very unstable in fitting. With the increase of the number of points, the fitting accuracy is constantly fluctuating, and the overall accuracy has a trend of sharp decline. When the parameters of the fitting method of selecting points of the elevation abnormal terrain change and the abnormal terrain exerts a limiting effect, the external coincidence accuracy of the fitting model will not change with the change of the parameters.

3.2. Kriging data analysis based on different point selection methods

Fig. 5 shows the difference between Kriging based on elevation abnormal terrain and fixed-point number Kriging.

Fig. 5 shows that the fitting accuracy of HB21 is not as accurate as the fixed-point method. However, the accuracy of points HB34 and HB43 are significantly improved, and HB06 is reduced by 1mm. Through calculation, the external coincidence accuracy of the two methods is

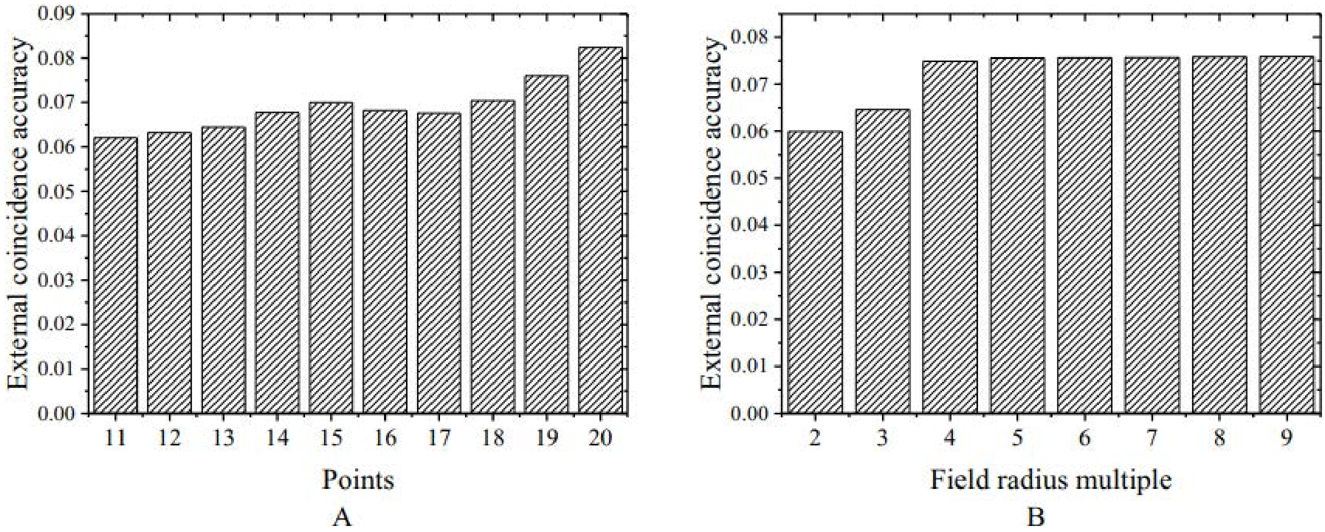

Fig. 4. The fitting accuracy of different points and radii: (A) different points and (B) different radii.

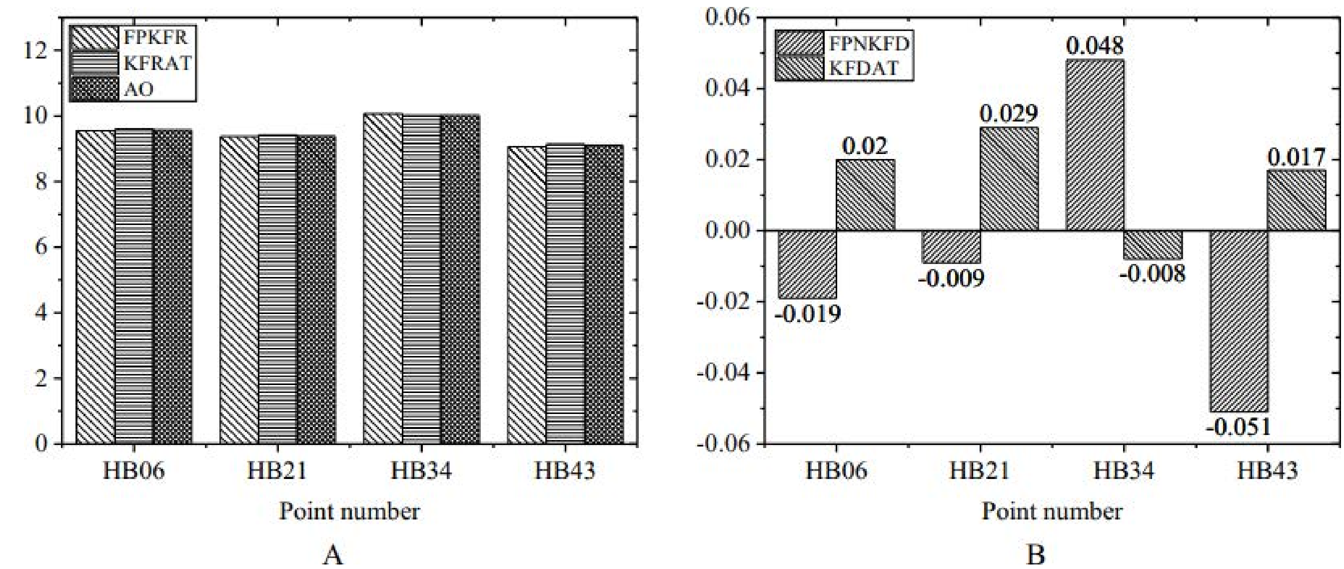

Fig. 5. The difference between kriging based on elevation abnormal terrain and fixed-point number kriging: (A) fitting value and (B) difference value.

higher than that of the bilinear moving surface fitting alone.

Fig. 6 shows the influence of different fitting points and correlation coefficient R on the comprehensive model.

The accuracy of bilinear kriging and combined model fitting is higher than that of bilinear fitting alone. When the number of points is all 8, it is consistent with the accuracy of the Kriging fixed-point number selection point fitting alone. This also shows that for the traditional method of selecting points, the accuracy of Kriging fitting in combination with other models is not significantly improved, or it may be partially reduced.

3.3. Overall data analysis of the experiment

Fig. 7 shows the fitting residuals and external coincidence accuracy of various experimental fitting models.

Affected by the constraints of the model, in general, when fitting, at most two mixed models are used for secondary residual processing, and the data processed by the mixed model are generally less accurate than the single model.

4. Conclusions

GPS measurement technology and traditional leveling measurement methods are mainly used for research. The characteristics of surface subsidence of water extraction are combined with GPS leveling technology measurement experiments. The normal height of the earth higher than the standard is used for fitting conversion, and then the normal height value of the demand point that meets the accuracy requirements is obtained. The principles of multiple fitting models and the respective characteristics of different fitting models are referenced, the advantages of each model

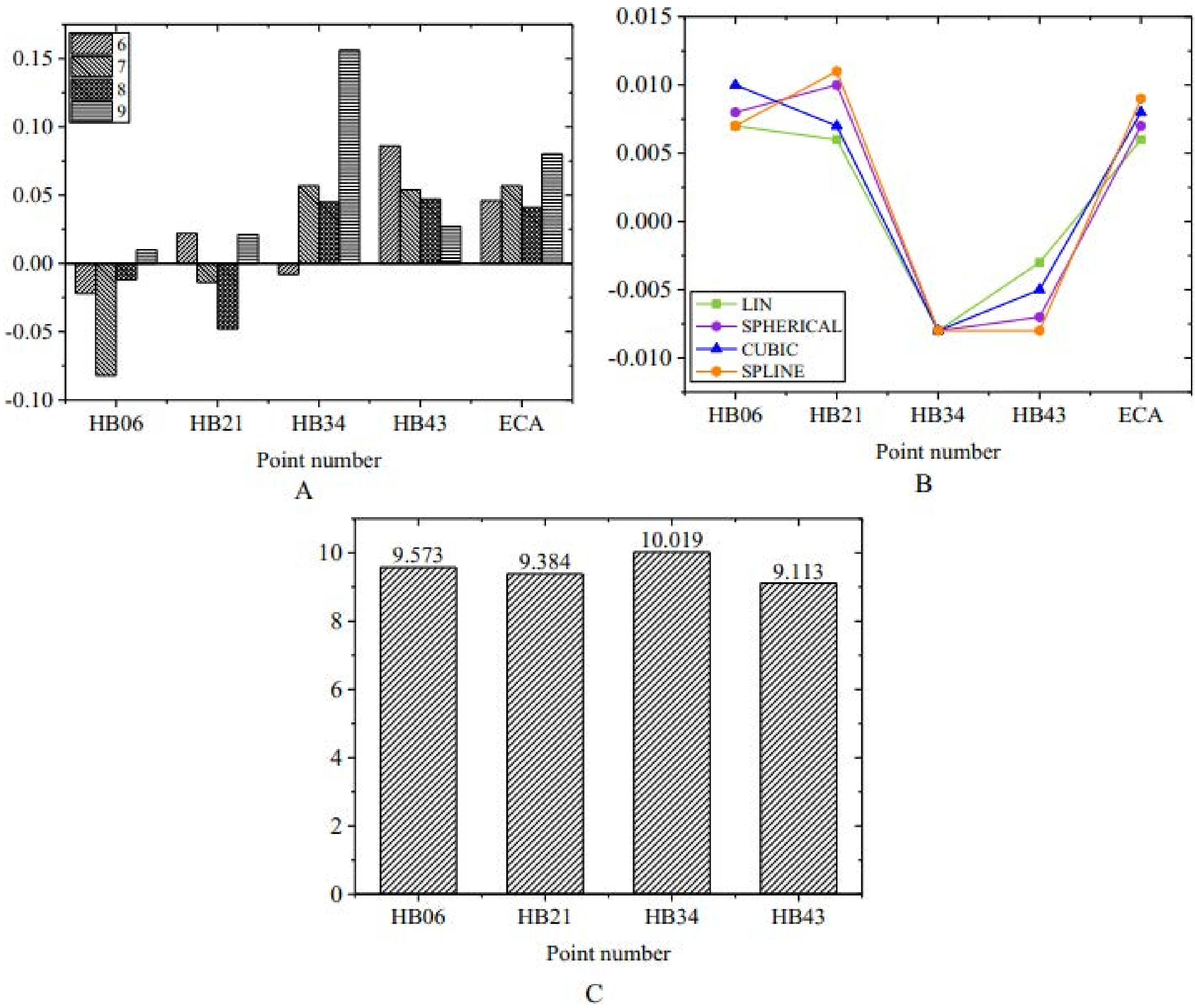

Fig. 6. The influence of different fitting points and correlation coefficient R on the comprehensive model: (A) different points, (B) different forms R, and (C) outer compliance accuracy.

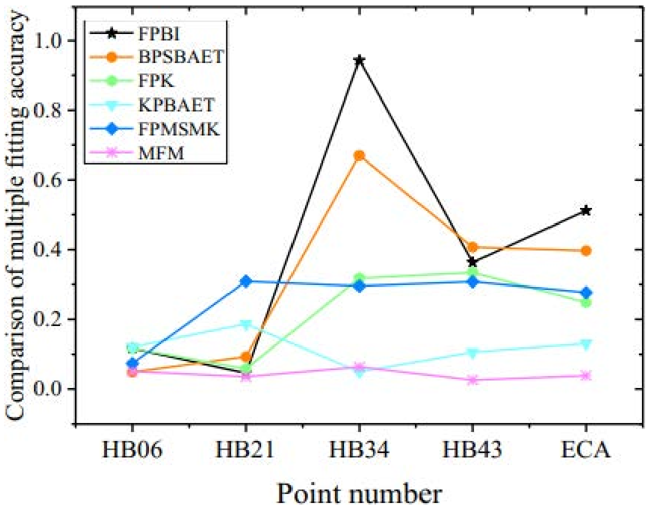

Fig. 7. The overall data analysis of the experiment.

are fully considered, and a stepwise mixed model is proposed, which have better practicability. Through the analysis of data processing in a certain area, the fitting accuracy of the step-by-step hybrid model based on the application of GPS technology to improve the point selection method is higher than that of the conventional point selection method. There are still shortcomings in the research. Some data are slightly different from the fitted values. After analysis, it is possible that the specific conditions of the original data collection at some points are not clear and cannot be screened in advance. In the future, the data will be further studied in a more accurate direction. Subsequent GPS technology has been provided as a technical reference in surface subsidence of water extraction.

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