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Advanced GNSS technology of mining deformation monitoring

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Abstract

Innovation of the mining deformation monitoring technology has been aroused with the development of GNSS technology. This paper probe into the feature of mine Continuously Operating Reference Station (CORS) and precise height difference model was constructed in Yanzhou and inner Mongolia to practise the technology. Based on the technology of mining CORS, we proposed the mining 3D deformation monitoring technology of large area. Based on the technology of RTK, we proposed the mining subsidence monitoring technology of small area. Based on the construction of the model of height difference, GNSS-RTK technology was proposed to be used in subsidence monitoring. This paper provides specific ways to the modernization GNSS monitoring technology in mining deformation.

Keywords: mine surveying; GPS/Pseudolites (PLs); empirical mode decomposition (EMD); wavelet

1. Introduction

With the developments of new satellite positioning system, GNSS system (such as GPS, GALLIEO, GLONASS, COMPASS) has been widely used in military, transportation, spatial information science and resource exploration. Mining deformation hazard is always a significant safeguard in mining safety production. And the urge of new GNSS techniques into practical application is of necessity.

GNSS Continuously Operating Reference Station (CORS) not only provides navigation services based on pseudo-range observations, but also offers carrier phase observations to develop realtime and quasi-realtime deformation monitoring techniques. Many countries in the world have established their CORS to improve the development of domestic and local economics, such as American CORS, Canadian CACS, German SAPOS and Japanese COSMOS (Chen, 2005). On the basis of existing CORS of Beijing and Guangdong, a unity Wide Area Differential GPS (WADGPS) and Wide Area Augment System (WAAS) based on dual-satellites have been considered. Local multi-function navigation positioning system was found by Zhou (2005). Four all-day Continuously Operating stations, which were established in 2004, combined with the standard network of surface subsidence monitoring, may get the resolution of 3 mm in continuous monitoring of surface subsidence which can supply the requirements of subsidence monitoring (Xiong, 2006). However, there are almost no research about mining deformation monitoring using CORS and how to establish mining CORS.

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The high cost of CORS technology limits its applications to rapid GPS deformation monitoring in local areas. Precise positioning, with GNSS-RTK of real-time kinematic differential of carrier phase, has been widely applied in various fields including topographic surveying, river surveying (He, 2006, Yang, 2001) and rapid establishment of control network (Hei, 2006, Shi, 2004). The technique has been used for rapid monitoring of mining deformation with the verification of the precision of wide range RTK. It is of great significance of monitoring subsidence with GNSS-RTK, meanwhile, few concrete applications to precise subsidence monitoring are related so far.

2. Particularity of mining CORS

Because the mining area as a whole moves complicatedly, the establishment of continuous observation stations of the mining area are vulnerable to the impact of mining under the ground floor. As a result, the stability of monitoring mine CORS stations and its technical correction become an important issue. The main issues to be considered are as follows: (1) reference station location and their correction of the deformation technology. Reference station location should be selected in the higher stability of the bedrock or mobile deformation of the smaller areas. Due to references also in the mining area, there is deformation when providing the base of their own. The acquiring technology of the deformation value of station's own reference is vital to decide the positioning accuracy of mine CORS; (2) data access and data integration processing technology. The particularity of mine reference stations require to integrate the observations of global IGS stations to identify the stability of basic stations and to control data quality; (3) deformation disaster in mine is an important issue. Besides finishing the normal requirements of surveying and mapping, an important task is to achieve real-time (quasi-real-time) to monitor deformation of the mine and it is necessary to develop a software and hardware system aiming at special mining application.

3. Establishment of GNSS geoid model

Precise geoid model is basic component in mining subsidence monitoring with the GNSS technology. The different precision of geoid can be obtained by the interpolation model with the combination of GNSS and leveling conjunction according to conjunction accuracy and the number of common points.

There is a difference, named height anomaly ζ , between the normal height and geodetic height H_{GPS} observed by GPS static positioning. According to the height of standard points, the normal height H_{normal} of GPS points can be got with the conjunction of level points in the surveying area. Finally, the height anomaly of GPS points is given by

$$\zeta_i = H_{GPS} - H_{\text{normal}} \tag{1}$$

When deformation monitoring in the mine carry on, height anomaly is essential in the whole surveying area which can be solved by the gravitational field and analytical geometry such as EGM96 direct interpolation of gravitational field model and covered surface fitting.

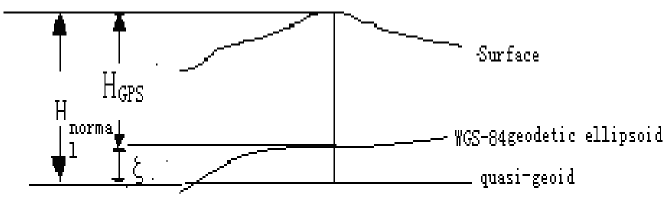

Fig. 1. GPS height anomaly

EGM96 gravity model is a world scale gravity model with the absolute precision of meter and with the relative precision of decimeter. A new EGM96 model has a better precise within 50 kilometers. If the requirement of precision is not very high or difficult to survey with traditional level in the unreachable area, EGM96 model can be applied to obtain the height with the interpolation. However, in order to satisfy the requirement of subsidence monitoring, it is necessary to refine quasi-geoid through the height anomaly with the junction of the level of GPS observations. A case study is carried on to explain the establishment of geoid taking the mine of Yanzhou and Suancigou.

3.1. Establishment of quasi-geoid in Yanzhou mine

Yanzhou mine located on the southwest plains of Shandong province, including Jijing city, Yanzhou, Qufu, Zhoucheng and Weishan county. The scope of geometry is the longitude of 116°33′40″~116°58′40″ and the latitude of 35°12′42″~35°32′42″, with the area of 3000 km^2. The area is flat with the highest elevation of 80 m in the east and the lowest of 33 m in the southwest. If it is known of the normal height and geodetic height of GPS in the level conjunction, the height anomaly of conjunction points can be acquired. The change trend of GPS quasi-geoid in the surveying area can be determined through the analysis of height anomaly with the correct fitting model to fit the quasi-geoid. The height anomaly of 28 points of GPS level conjunction are selected (Fig. 2) and then GPS height anomaly model in Yanzhou can be confirmed through the distributed processing (Tables 1-2).

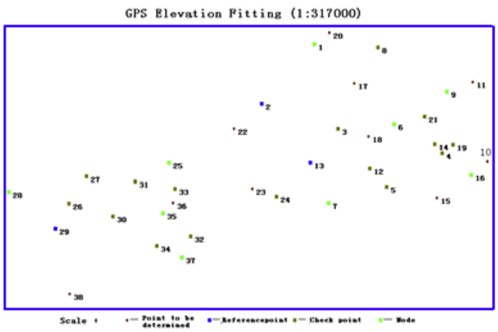

Fig. 2. Distribution of GPS level conjunction in Yanzhou mine

Table 1. Polynomial model and its parameters of height transformation in east GPS network

Model coefficients	a(1)= -673.858 a(4)= -0.061	a(2)= -0.078 a(5)= 0.012	a(3)= 4.973 a(6)= -0.019
Transformation model	h=H-a(1)-a(2)x-a(3)y-a(4)x*x-a(5)y*y-a(6)xy		
Fitting mean square error	2.74 cm	Remarks: h-normal height H-geodetic height a(i)-model coefficients x,y-coordinates	

Table 2. Polyface model and its parameters of height transformation in west GPS network

Model coefficients	a(1)= -1534.398 a(4)= -1742.856	a(2)= -3389.035 a(5)= 12745.749	a(3)= -2254.538 a(6)= -4953.816	
Transformation model	$Z = f(x,y) = \sum_{i=1}^{n} a_i Q(x, y, x_i, y_i)$			
Polyface function	a0=15000.000	b0=1.000	c0=5.000	e0=0.000
Fitting mean square error	5.2 mm	Remarks: aj-unknown coefficients， Q(x, y, xj, yj)-second kernel function of x and y		

3.2. Establishment of local precise geoid model in Suancigou mine

Suancigou mine lies in the central of the Jungar Coal in Inner Mongolian Autonomous Region, which is comprised of two parts with the area of 41.47 square kilometer. Total reserves of coal resources are 11.92 billion kg. 23 points are shown in the GPS network figure above the working face in the mine, including three standard points (G1, G3, G4) and 20 points are used to densify GPS net (Fig. 3).

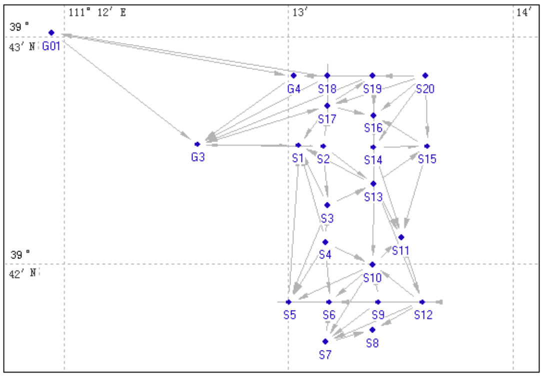

Fig. 3. Distribution of GPS network in GPS-RTK subsidence monitoring area

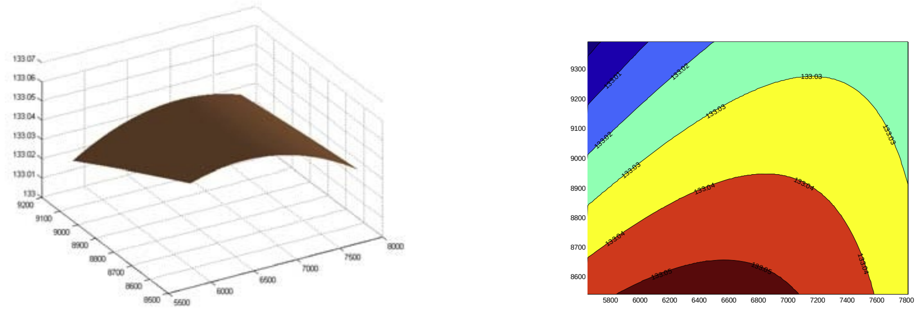

Fig. 4. Second polynomial model: (a) 3Dmodel; (b) plane model

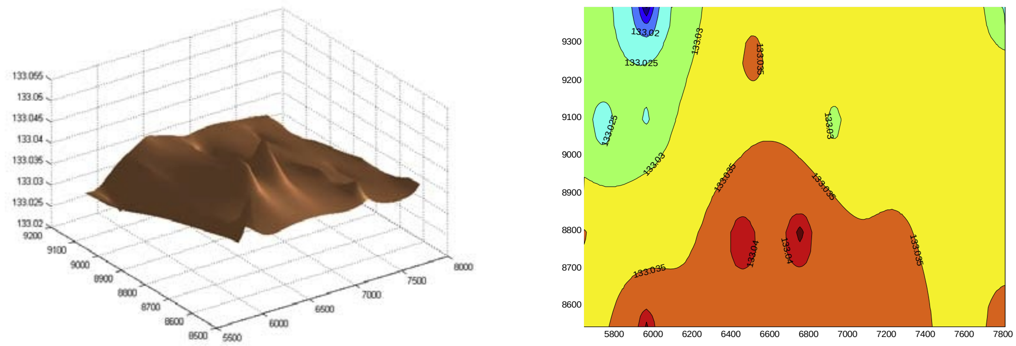

Fig. 5. Anti-distance-weighted model of the height anomaly model: (a) 3Dmodel; (b) plane model

Surface fitting and distance weight are adaptable for fitting geoid (Figs. 4-5). The quasi-geoid can be fitted by the numerical fitting according to the horizontal coordinates(x, y) of known points and its height anomaly value ζ, then interpolating the ζ of unknown points, the normal height of any points can be interpolated. Supposed the relation of ζ and horizontal coordinate(x, y) of the given point:

$$\zeta = f(x, y) + \varepsilon \tag{2}$$

where $f(x, y)$ is the trend value of ζ, ε is the error. Given

$$f(x, y) = a_0 + a_1 x + a_2 y + a_3 x^2 + a_4 y^2 + a_5 xy + \cdots \tag{3}$$

which can be expressed by matrices:

$$\zeta = XB + \varepsilon \tag{4}$$

where,

$$\zeta = \begin{bmatrix} \zeta_1 \\ \zeta_2 \\ \cdots \\ \zeta_n \end{bmatrix}, \; B = \begin{bmatrix} a_1 \\ a_2 \\ \cdots \\ a_n \end{bmatrix}, \; \varepsilon = \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \cdots \\ \varepsilon_n \end{bmatrix} \tag{5}$$

$$X = \begin{bmatrix} 1 & x_1 & y_1 & x_1^2 & \cdots \\ 1 & x_2 & y_2 & x_2^2 & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ 1 & x_n & y_n & x_n^2 & \cdots \end{bmatrix} \tag{6}$$

The former equations can be listed for any given known point and its solution be solved under the condition of $\sum \varepsilon^2 = \min$, and then H_r is gained through ζ of the unknown points. Inversely weighted distance is defined as calculating ζ value through inversely weighted average according to the actual ζ value around the grid points. The equation can be defined as:

$$\zeta^j = \sum_{i=1}^{n} \frac{\zeta^i}{D_{ij}} / \sum_{i=1}^{n} \frac{1}{D_{ij}} \qquad D_{ij} \le DR \tag{7}$$

DR is the threshold of distance, when $D_{ij} > DR$, puncture points can not be used for calculation of weighted average.

The fitting precision index of fitting model can be expresses as

$$m_{fitting} = \sqrt{\frac{[\varepsilon_i \varepsilon_i]}{n}} \qquad (i = 1, 2, \ldots, n) \tag{8}$$

where ε_i is the fitting error of fitting points, m is the number of fitting points. The index was usually used for precision evaluation of geoid model. A geoid model of some area in Suancigou mine is given in Fig. 4 according to the two methods of equations (2)-(8). After substituted the height anomaly of GPS observations and model fitting into the equation (8), the fitting precision of each model can be calculated (Table 1), from which it is clearly seen that the interpolation precision of the inversely weighted distance is the highest. The precision of EGM96 model published by global is the lowest and can not satisfy the subsidence monitoring.

Table 3. The comparison of fitting precision with three models

Model	Maximum error (mm)	Minimum error (mm)	Average error (mm)	Fitting error (mm)
EGM96	42.2	0.3	15.5	19.8
Second surface fitting	11.4	0	0.46	0.56
Inversely weighted distance	0.05	0	0.02	0.01

4. GNSS modern monitoring technique of mine deformation hazard

4.1. Deformation technique based on mine CORS

There are two aspects for based-mine CORS deformation monitoring of 3-D deformation and subsidence monitoring. Aiming at different 3-D deformation monitoring, there are also two ways of whether global IGS are conjunct or not (Fig. 6).

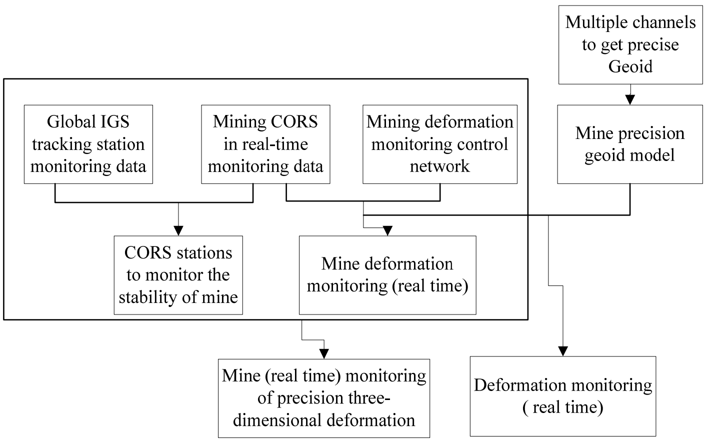

Fig. 6. Flow chart of CORS -based large area of mining subsidence deformation

Mine 3-D deformation can be monitored with the datum of mine CORS real-time monitoring and mine deformation control monitoring and its corresponding soft- and hard-ware equipments. To improve the temporal and spatial precision and reliability of deformation monitoring, if the IGS observations are integrated, 3-D precise deformation monitoring is feasible.

Multi-methods should be used for refining local geoid model to monitor the subsidence, on which multi-periods observations are used for static deformation monitoring and real-time subsidence deformation monitoring.

4.2. Local subsidence monitoring technique based on RTK

It is of importance for temporal and spatial resolution of subsidence monitoring. RTK is possible for rapid monitoring of local subsidence. The local subsidence modern monitoring route in mine based on RTK is given in Fig. 7. The first step is to draft an observation theme, locate the landmark and monument station according to the actual terrain. It is obtainable for the height anomaly of GPS observations by the static positioning and traditional level surveying according to the drafted theme. Under the calculated height anomaly, the model with higher precision is selected to compare the precision of different models with the different mathematic models to refine geoid. The horizontal coordinates of the subsidence control points in the surveying area acquired by RTK are substituted into the GPS height anomaly model and then subtract the GPS height obtained by RTK to achieve the normal height of each observation station. Finally, subsidence deformation value is gained with multi-periods RTK observation and its time-change distribution characteristics can be analyzed. Meanwhile, the multi-scale and periodicity of dynamic deformation are studied by Wavelet transform theory and temporal-frequency analysis to maintain the subsidence deformation essence and provide the foundation for early hazard warning. The research topic group is contributed to impel the technique into the mine deformation monitoring.

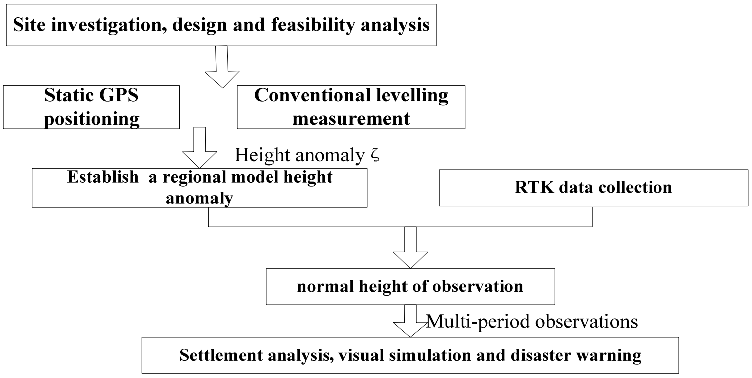

Fig. 7. Low chart of RTK based local area of mining subsidence monitoring

5. Conclusions

The invention of the paper is to research the GNSS modern monitoring technique into the mine deformation and hazard early warning. On the basis of the establishment of GNSS geoid model, the feasibility is demonstrated of the usage of mine CORS into the wide 3-D precise monitoring and subsidence deformation monitoring. For the deformation of local area, GNSS-RTK is proposed to monitor the subsidence and the results show that it can increase the temporal and spatial resolution of mine deformation monitoring.

Acknowledgements

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References

[1] J. Y. Chen, Progress in GPS modernization and the pre-operation of Galileo, Bulletin of Surveying and Mapping. 3 (2005).

[2] L. Zhou, J. N. Liu, and Q. D. Zhang, The progress of GPS around 2000. Geomatics World. 3 (2005).

[3] F. W. Xiong, W. Y Zhu, and J. Q. Li, The application of GPS in Shanghai land subsidence research, Progress in Geophysics. .4 (2006) 1352-1358.

[4] Z. G. He, and D. A.Cai, Discussion on application of GPS-RTK elevation measurement technology in river channel measurement. Yangze River. 12 (2006).

[5] F. Yang, J. Xu, and W. D. Xu, Application of real-time kinematic technology to shipping lane survey. Bulletin of Surveying and Mapping. 2 (2001).

[6] Z. J. Hei, and Q. S. Zhou, Precision estimation of GPS RTK survey production and its application discussion. Journal of Harbin Institute of Technology. 8(2006).f

[7] Z. J. Zhang, Z. H .Xie, and C. Y. Feng, The method study of RTK survey precision assessing. Bulletin of Surveying and Mapping. 1 (2007).

[8] J. F. Shi, and X. H. Li, RTK technology and its application in control surveying. Journal of Liaoning Technical University. 6 (2004).

[9] Y. Q. Shi, and P. Y. Fu, Monitoring system on mine subsidence and deformation. Journal of Taiyuan University of Technology. 2 (2003).

[10] S. J. Miao. and M. F. Cai, Monitoring of high slope deformation in open pit mines. Journal of University of Science and Technology

Beijing. 6 (2006).
[11] S. Q. Xu, Principle and Application of GPS. Wuhan University Press, 2002.
[12] Z. H. Li, and J. S. Huang, GPS Measurements and Data Processing. Wuhan University Press, 2005.