Jin Fengxiang, Wang Tongxiao, Xu Ping, Li Yunling, Ji Min[1]

Vertical Shaft Deformation Monitoring and Pattern Analysis*

Der Beitrag beschreibt Deformationsuntersuchungen an Schächten in Kohlenminen. Dazu werden Messeinrichtungen beschrieben und die Deformationsanalysen kritisch betrachtet.

1 Introduction

In China, coal mine industry plays a very important role in the national economy. During the past decades of years it has been well developing on scale and technology. Many big coal mines, more than 3 Mt/year, were built. Most of them are deeply underground. For the transport and ventilation reasons many of large and deep shafts, more than 8 m in diameter and more than 400 m in depth, were constructed. In some areas certain of them have been gravely deformed, some were damaged (broken, cracked and inclined). This has brought a production stop. It not only and has a huge economic damage but also a menace to the mine security.

The shaft deformation monitoring is a very important work in mine engineering. It should be throughout the whole mining procedure. It is necessary in the purpose of not only security, but also shaft dynamic information for their maintenance and reparation. In this field, some people had worked some. In URSS and Poland, the mining engineers had done some experiments and established some methods to measure the internal stress within the shaft's wall in order to understand the stress variation of the shaft wall during its drying procedure [1]. Some geometrical monitoring methods had been also adopted or developed. In China, a big research project has been carried out in Haibei Mine bureau since 1987 by Chinese government. It includes nine aspects: a subsidence leveling over whole area's surface, pit head leveling, water level observation, investigation in alluvium, vertical layer deformation observation, subsidence observation of industrial site, relative displacement observation between the pit head and the near surface, surface deformation observation and the investigation on damage situation. A comprehensive study was realized on the relation between the shaft damage and those nine aspects. Some very important conclusions and valuable information were obtained. But it is pity that the deformation of the shafts damaged had not been measured directly during the procedure due to the technical difficulty. This is why Coal Ministry lanced this project. Shandong University of Science and Technology (SUST) and Yanzhou Coal Group Company collaborated with each other to have studied on this problem. This paper summarizes the research in the group.

It is known that the shaft deformation comes from many factors, for example its type, dimension, construction technology, geology and age. Geologically, The surface in the area studied is quite even. A loose stratum of Cenozoic Era, 100 ~ 200 meters thick and almost horizontal, exists over the coal measures of Carboniferous Period. Within this loose stratum there are several water-bearing layers and water-division layers. The shallow water-bearing layers are supplied with permeating of the raining water on the surface. Their water levels vary with seasons. At the bottom of the loose stratum there is a complex water-bearing layer of 10 ~ 20 meters think and of mixture with putty gravel, sand and clay. It is just directly over the coal measures layer. It is called "bottom water-bearing layer". The water in this water-bearing layer is the pressured water. Over the bottom water-bearing layer there is a water-division layer of 50 meters thick and composed mainly of clay, which can effectively divide the water between the shallow and the bottom.

It has been found that coal mine surface located in this area had subsided all over. The subsidence every year is about 35 mm, in some zones about 60 mm. From experience [3, 4], the main reason for that is the coal exploitation leads to the water loss of the bottom water-bearing layer and then the bottom water-bearing layer becomes dense. The observation on water level indicated that the water level descends in the speed of 8 meters every year. This dense caused the loose layer to subside. It has been verified from the investigation and observation as follows. (1) The surface of subsidence is correspondent to the zone of the bottom water-bearing zones; (2) The value of subsidence is proportional to decrease of the water level; (3) The observation on the layers with the Sondex has shown the vertical compressing deformation come from the bottom water-bearing layer.

The loose layer's subsidence gives the external wall of the shafts an

---

* Project supported by Natural Science Foundation of China (40074001), Education Ministry of China and Coal Industry Ministry of China (97-356)

[1] Geoscience Dept. of Shandong University of Science and Technology
Tai'an, Shandong Province, P.R.China

enormous downward frictional force. The force makes the shaft deform and damage the wall of it finally. Generally, it occurred about 10 years late after its construction. This shaft's deformation is usually during its whole life. Some features on deformation are summarized as follows:

- Damages come from vertical compression. It is a horizontal circle rupture with some cracks and located on the boundary of the loose layer and the bedrock.
- The deformation is well proportional to their external frictional force, speed and the surface subsidence.
- The subsidence and speed present a temperature effect. When the shaft expansion occurs due to temperature increase, the possibility of their damage would increases.
- Mechanically, the damage is caused by their vertical bend, precisely the bend shearing stress and bend tensile stress. They damage the shaft with a shearing rupture and a tensile rupture.

2 Deformation Monitoring Theory and Method

Until now, a whole and systematic theory on the shaft deformation monitoring has not formed yet. The effective and practical monitoring method has not been established. Following the methods used, there are two monitoring methods used often. Based on the rock mechanics a method of observing the mechanical parameters was established. Based on the engineering surveying a method of geometrical deformation survey was found. Those methods could be divided into direct and indirect, manual and automatic.

2.1 Mechanical Monitoring Method

The deformation is well related to the distribution of stress. From the deformation observation of the wall surface and the distribution of the additional stresses, the shaft situation could be well known and the deformation of the whole shaft could be also derived inversely. A practical method is called "hole deformation monitoring method". On the object studied some holes are made following some principles. When the object deforms the holes deforms too. From the deformation observation of the holes, the deformation of the whole object could be derived. Because the deformation of the holes is usually very small, the precise sensors for observation are indispensable. There are also some things should be well considered in order to assure the observation correct. Firstly is the selection of the sensors following the physical and mechanical characteristics of the object studied. Then is the matching problem, disturbing to the original stress field by the installation of the sensors. Third is the type selection and model selection of sensors following the problem. Forth is the coupling problem between the sensors and the object in order to assure the observational correctness and reliability. It mainly deal with the performance of the daub (modulus of elasticity and density) and the installation technology.

2.2 Geometrical Monitoring Method

In addition to the indirect measurements mentioned above, some direct measuring methods are also studied on the shaft deformation monitoring. Those methods could be divided into two groups: partial deformation monitoring and whole deformation monitoring.

For the partial deformation monitoring method, some vertical and horizontal base lines of 10 ~ 20 meters long are installed on the wall of the shaft. Their length could be measured with steel tape and other precise distance instruments. For the whole deformation monitoring method, one or two temporary plumbing lines are hung in the shaft as the base datum lines for distance measurement. The equipment and the points installed on the wall or the equipment could be measured with instruments. The datum lines are served for the whole shaft.

The two methods described above have some virtues and defects in practice. In the first one the observations could be automatically controlled by the computer. It can work with high effect and without any occupation of shaft. This method marks out the developing direction in the future. At present, there are some problems to be solved.

Theoretical Problem: An inverse analysis theory is used to derive the deformation of the whole shaft from the deformation on the holes. The solution of the inverse analysis is very variable from an assumption to another. The determination of the boundary conditions and the selection of the models are very important and difficult.

Technical Problems: The matching and coupling in the installation technology are two very difficult problems. The electronic and magnetic interference of the electrical power cables to the deformation monitoring system (sensors and wires) installed in the shaft should be resisted in order to get a real electronic deformation signal. But it is very difficult. In addition, the system must have a good quality for a long term because the deformation monitoring work should be carried out for a long period (15 years at least). The other important problem is that it could not carried out geometrical deformation measurement, such as inclination and bending of the whole shaft, which are exactly the key factors for shaft damage in the case we face with.

In the second method the geometrical deformation measurement of the whole shaft could be realized, but it should occupy the shaft. The deformation measurement could not be carried out frequently.

Following the author's experience and researches, two methods should be used at the same time in order to complement each other and to perfect the first method, especially in the case that not enough experience could be referred. A part of this paper is to present the monitoring system was developed by our research group.

3 Shaft Deformation Monitoring System

Under the so bad conditions within the shaft, it is very difficult to establish a geometrical deformation monitoring system with good performance, good reliability and convenience of maintaining. This is why there is not any ripped technique yet until present. The system should be able to measure the deformation of the shaft as a whole object. The vertical deformation, inclination deformation and bending deformation should be directly or indirectly measured. It should be served for long-term, and permits to be repaired and replaced without any influence on the measurements. From the limit strength of cement construction, the measurement precision is 1 mm for vertical and 10 mm for horizontal. And also a computing and analysis program should be developed for the deformation data processing and deformation analysis.

3.1 A System with Inverse Plummet

The deformation monitoring system with inverse plummet is presented in Fig. 1. The upper part is a float with a floating force of 45 kg. A stainless invar wire is hung within the shaft along the wall. One end of it is connected with the float located on the top of the shaft and the other end connected with the fixed point in the level of bedrock. Certain special points, a stainless steel plate of a forced centering system for the measuring instruments, are installed near the invar wire along the wall. On the wire some observational marking blocks are fixed near and over the plates. The stainless invar wire is 1 mm in diameter and its the temperature expansion coefficient is 1.2×10^{-6}. One instrument CG-3A is used to measure the horizontal coordinates (x, y) and another SCG-2 is used to measure the vertical coordinate (z). The number of the stainless invar wires in one shaft is about $3 \sim 6$.

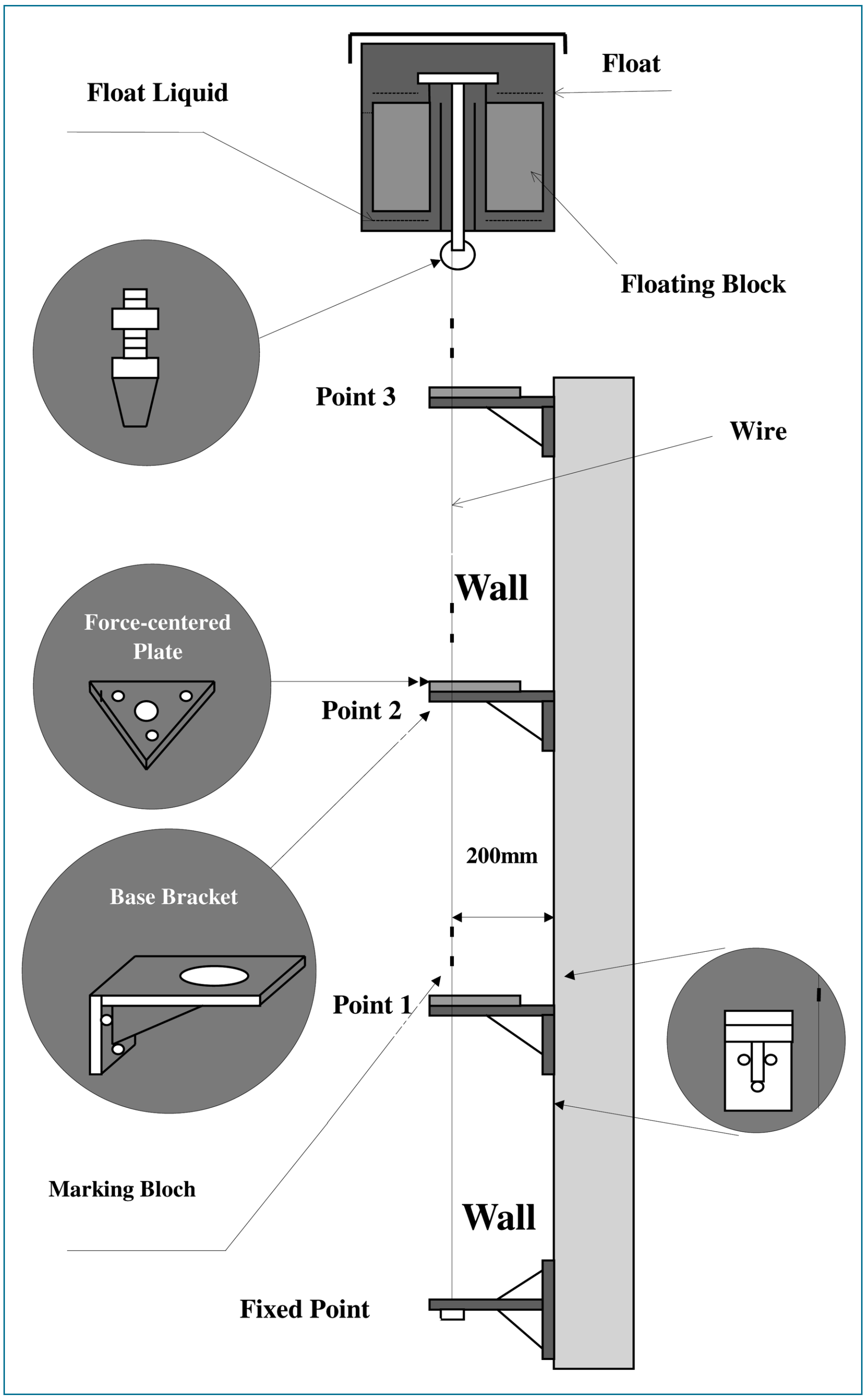

Fig. 1:

3.2 Measurement Realization

In practical observation, two measuring techniques have been used. One is by the instruments CG-3A and SCG-2, another is by a photogrammetric system DCRPS (Digital Close Range Photogrammetry System). For the first the measurements are directly the coordinates of the points. For the second is to take three photos on every point and then restore the model in the computer and measure the model instead of measurement on site. This is a time saving and holographic method. The coordinate of the points could be measured on the restored model by computer. The most important advantage of this technique is that the measurements could be realized in any time and for every point with the photos. And we could remeasure all with the photos from the begin-

Tab. 1: Coordinate Measurements of A Wire

Date	X(mm)	Y(mm)	Z(mm)
97.7.5	25.255	3.180	48.099
97.8.4	25.475	3.305	49.038
97.9.5	24.125	3.330	48.857
97.10.3	26.635	3.370	47.282
97.11.5	25.080	3.450	45.809
97.12.3	25.490	3.610	45.110
98.1.5	25.185	3.160	47.097
98.2.5	25.810	3.785	46.749

Tab. 2:

Date	X(mm)	Y(mm)	Z(mm)
97.7.5	24.245	25.585	46.078
97.8.4	24.760	25.540	47.116
97.9.3	23.960	25.550	46.570
97.10.3	24.290	25.535	46.120
97.11.7	24.730	25.280	45.126
97.12.3	24.260	24.675	45.166
98.1.5	24.310	25.075	45.857
98.2.5	24.745	25.375	45.573

ning to the end if necessary. The measurement should be carried out every month during the first two years, every two months during the second two years. Of cause it also depends how active the shaft is.

4 Deformation Analysis

Two corrections should be taken into account for the measurements, index errors and temperature correction. And then the coordinates obtained should be reduced to the same coordinate system by a coordinate orientation and coordinate transformation. This procedure is very similar to the orientation with double plummets in a shaft. In order to analyze the deformation pattern, the deformation is decomposed into five sub-patterns: horizontal displacement, inclination deformation, vertical deformation, bending deformation and radial deformation. There are some mathematical models being correspondent to those sub-patterns. Based on the pattern recognition theory and method, the shaft's deformation behavior could be characterized through the

Tab. 3: Vertical Stress from A Wire and Other Observations

Date	Stress	A-A_1 (32.6M)	A_1-A_2 (35.9M)	A_2-A_3 (59.5M)	A-A_3 (128.0M)	Temp.	Water Level (M)	Month
97.7.5	ε_z (2-1)	– 9.9	– 6.6	– 4.7	– 6.6	26.1	61.67	1
97.8.4	ε_z (3-1)	– 13.1	– 8.8	– 6.9	– 9.0	30.0	61.68	2
97.9.5	ε_z (4-1)	– 11.4	– 7.3	– 4.3	– 7.0	26.0	61.87	3
97.10.3	ε_z (5-1)	– 10.0	– 4.2	– 3.8	– 5.5	23.5	61.85	4
97.11.5	ε_z (6-1)	– 7.0	– 2.9	– 1.8	– 3.4	16.0	62.00	5
97.12.3	ε_z (7-1)	– 7.1	– 2.9	– 1.8	– 3.4	15.5	62.14	6
98.1.5	ε_z (8-1)	– 9.2	– 4.4	– 4.4	– 5.6	18.8	62.10	7
98.2.5	ε_z (9-1)	– 8.3	– 4.3	– 5.9	– 6.1	18.0	61.68	8

Tab. 4: Plan Coordinate Correlation Coefficients

Point	ρ_{XY}	ρ_{XT}	ρ_{XM}	ρ_{XW}	ρ_{YT}	ρ_{YM}	ρ_{YW}	ρ_{TM}	ρ_{TW}	ρ_{MW}
A_1	0.042	– 0.162	0.255	– 0.283	0.763	– 0.615	– 0.811	– 0.820	– 0.670	0.470
A_2	0.410	– 0.239	0.337	– 0.192	– 0.554	0.610	0.000	– 0.820	– 0.670	0.470
A_3	– 0.392	– 0.018	– 0.133	0.000	– 0.463	0.271	0.144	– 0.820	– 0.670	0.470
B_1	0.289	– 0.554	0.745	0.366	0.571	– 0.000	– 0.433	– 0.820	– 0.670	0.470
B_2	– 0.654	– 0.011	0.295	0.013	– 0.006	0.263	– 0.082	– 0.820	– 0.670	0.470
B_3	– 0.054	– 0.068	0.431	0.397	– 0.463	0.148	0.397	– 0.820	– 0.670	0.470

Tab. 5: Vertical Coordinate Coefficients

	ρ_{Z1Z2}	ρ_{Z1Z3}	ρ_{Z1T}	ρ_{Z1M}	ρ_{Z1W}	ρ_{Z2Z3}	ρ_{Z2T}	ρ_{Z2M}	ρ_{Z2W}	ρ_{Z3T}	ρ_{Z3M}	ρ_{Z3W}
A	0.940	0.751	– 0.954	0.641	0.576	0.761	– 0.941	0.714	0.657	– 0.685	0.223	0.765
B	0.875	0.832	– 0.967	0.789	0.644	0.951	– 0.914	0.573	0.802	– 0.935	0.082	0.741
C	0.664	0.652	– 0.835	0.455	0.659	0.685	– 0.873	0.800	0.721	– 0.306	– 0.108	0.427

sub-patterns and could make us well understand the deformation features. In order to carry out the influential pattern analysis, some statistic mathematics are used to check up the relations between the deformation and the external factors (subsidence, subsidence speed, water level and season etc.) in order to find the most important factors. The principal component analysis, regression analysis, statistic analysis, correlation analysis and model significant test have been used for the deformation pattern analysis.

5 Example

Three stainless invar wires have been installed in the auxiliary shaft of Tongtan Coal Mine since March 1997, (A, B, C). Three points have installed for each wire along the shaft's wall. Tables 1 ~ 2 partly show the coordinate measurements. Table 3 partly presents the vertical strains and the other measurements. The correlation coefficients during the deformation pattern analysis are put in table 4 and table 5. During the deformation pattern analysis, the linear regression model and statisitical tests were used to find the shaft inclination deformation, bending deformation and the radial deformation. The correlation coefficients between the coordinates were used to find the shaft radial systematic deformation. The following conclusions are obtained:

- The shaft is only of the vertical compressed deformation pattern without displacement, inclination, bending and radial deformation.
- Vertical compressed deformation is at an annual average speed-1.1×10^{-4}/year, and correlated with temperature and water level.
- The vertical compressed deformation is variable in sine with season or temperature. This feature is the same as that found in the other mines [3].
- The most dangerous period for this shaft is during July to October, decreasing of the absolute value of vertical stress or expanding of the shaft.

References

[1] Coal Ministry and Fuxin Institute of Mining and Technology (Proceedings). Prevention and Cure for Shaft Damage, Coal Industry Publishing House of China, August 1985

[2] Lu Taihe: Exploitation of the Coal Column Under Shaft and Site. Coal Industry Publishing House, August 1990

[3] Haibei Mine Bureau: Studies on Surface Subsidence and Its Influence on Shaft in Linhuan Area. January 1991

[4] Song Zhengyuan: Analysis on Surface Subsidence of Xuhai Area. China Geology. No. 1 1996

[5] Song Zhengyuan: Discussion on Influence of Shaft Bending on Shaft Damage. Journal of Huainan Institute of Mining and Technology, No. 4 1994

[6] Yang Weiru: Studies on Problem of Shaft Damage in Huadong Area

[7] Ka Zhengxiu: Features of Stratums and Shaft Deformation in Huanghuai Area

[8] Zhu Xiubing: Studies on Auxiliary Shaft Deformation in Zhangshuanglou Mine

[9] Jin Fengxiang / Du Zhixing: Error Analysis on Shaft Deformation Measurement, August 1997

[10] Jin Fengxiang / Du Zhixing: Shaft Deformation Monitoring of Tongtan Coal Mine, August 1997

[11] Jin Fengxiang: Project Rapport of Shaft Deformation Monitoring System Study. July 1996

[12] Jin Fengxiang. Geometrical Features and Tests of GM Models. Chinese Journal of Nonferrous Metals. No. 2 1996

[13] Jin Fengxiang / Wang Tongxiao. Patter Recognition Problem in Deformation Monitoring and Analysis, Chinese Journal of Nonferrous Metals, No. 3 1997

[14] Jin Fengxiang / Wangtongxiao. Pattern Recognition on Surveying Information, Chinese Journal of Nonferrous Metals. No. 2. 1999

[15] Jin Fengxiang / Wang Tongxiao. Statistical Diagnostics and Deformation Monitoring Theory, Agricultural Scientific and Technical Press of China, Sept.1995

Adress of the author:
Jin Fengxiang, Dr.-Ing., Professor and Supervisor of Doctoral Student, Shandong University of Science and Technology, Tai'an, Shandong Prov. (271019) China,
Tel.: +86 53 86 22 70 99(o),
+86 53 86 22 69 98(h),
Fax: +86 53 86 22 74 15,
E-mail: jinfengxiang@yahoo.com, fxjin@sdust.edu.cn
http://myprofile.cos.com/jinfengxiang

Abstract

This paper presents the research in the fields of the shaft's deformation monitoring and deformation pattern analysis. Some geological reasons of deformation were studied and analyzed. Based on the deformation features, the methods used for the shaft deformation monitoring and deformation analysis are studied. A brief presentation is made on the methods used to deformation pattern analysis in the group. Some useful results and conclusions are introduced.