Monitoring Deep Mining Similarity Material Model of Super-Thick and Weak Cementation Overburden by Digital Photography

Guojian Zhang\textsuperscript{1,2,3}, Yi'nan Lv\textsuperscript{4}, Guangli Guo\textsuperscript{1,3,*} and Chengxin Yu\textsuperscript{5}

\textsuperscript{1}Jiangsu Key Laboratory of Resources and Environmental Information Engineering, China University of Mining and Technology, Xuzhou 221116, China
\textsuperscript{2}NASG Key Laboratory of Land Environment and Disaster Monitoring, China University of Mining and Technology, Xuzhou 221116, China
\textsuperscript{3}School of Environmental Science and Spatial Informatics, China University of Mining and Technology, Xuzhou 221116, China
\textsuperscript{4}School of Architecture & Design, China University of Mining and Technology, Xuzhou 221116, China
\textsuperscript{5}Business School, Shandong Jianzhu University, Ji’nan 250101, China

*Corresponding author e-mail: guo_gli@126.com

Abstract. In this paper, the similarity material model is conducted to investigate the movement law and failure pattern of the super-thick weak cementation overburden. In addition, the photographing scale transformation-time baseline parallax (PST-TBP) method and the Xi’an Jiaotong University Digital Close-range Industrial Photogrammetry System (XJTUDP) software were used to monitor similarity material model. The findings can be summarized as follows: (1) To some extent the PST-TBP method can make up for the deficiency of the XJTUDP software because its measurement accuracy is about 0.5mm; (2) The first breaking span of the immediate roof reached 240m, and the cyclic fracturing length was about 60m. It still shows the characteristics of the inadequate mining when the surface reaches fully mining. It needs more mining space to reach fully mining; (3) The (PST-TBP) method and the XJTUDP measurement system provide technical support to study the dynamic development process of regional deformation caused by deep mining.

1. Introduction

Similar material model is one of the important means to study strata movement of deep coal mining. With the increasing of mining depth, the overburden movement expanded, the underground mining activity and the associated characteristic of the surface deformation response is much more complicated. The mining surface deformation problem has been extended from single working face mining to multi-working face mining or even Regional deformation response caused by multi-areas mining. Therefore, the overall dynamic monitoring of similar material models in deep mining is particularly important. At present, there are popular with Light lens method, Small steel ruler-level method, Three-dimensional laser scanning, Total station 3d measurement, Displacement meter method, Digital speckle correlation method and Insert stitch method [1]. But these methods are time-consuming and laborious, and cannot
realize the overall dynamic monitoring of similar material models in deep mining. Traditional photogrammetry technology such as DPA-Pro system and XJTUDP measurement system [2] can monitor similar material model with high accuracy, but it cannot realize the overall dynamic monitoring of similar material models.

In this paper, we used a monocular digital photography based on photographing scale transformation-time baseline parallax (PST-TBP) method [3-5] and the XJTUDP measurement system to monitor deep mining similar material models of the super-thick and weak cementation overburden. We can monitor the overall dynamic monitoring of similar material model to study the dynamic development process of regional deformation and get the data of some important deformation points with high accuracy.

2. Photographing Scale Transformation-Time Baseline Parallax Method

In general, the Xi'an Jiaotong University Digital Close-range Industrial Photogrammetry System (XJTUDP) can monitor the model during mining with the measurement accuracy of 0.064mm [2]. The PST-TBP method was the first time to be used to monitor the similar material model, and its monitoring principle is detailed as follows:

In Figure 1 (a), a schematic diagram of a CCD (Charge Coupled Device) camera capturing images at different photographing distances \(H_3\) and \(H_4\). In the schematic diagram, the distance between the optical origin (o) and the front end of the camera is \(H_2\). \(D_1\) on the reference plane and \(D_2\) on the object plane are the real-world length formed by the view field of the camera at photographing distance \(H_3\) and \(H_4\) respectively. \(H_1\) is the focal length of a camera, \(N\) is the maximal pixel number in a horizontal scan line of an image plane, and \(N\) is fixed and known as a priori irrelevant of the photographing distances.

![Figure 1. Photographing scale transformation-time baseline parallax method [3]](image)

In Figure 1 (b), on the object plane, \(\Delta x^{de}\) and \(\Delta z^{de}\) of the corresponding deformation point are:

\[
\begin{align*}
\Delta x^{de} &= \frac{SA_a}{Sa} \Delta p_x^{de} = m \cdot \Delta p_x^{de} \\
\Delta z^{de} &= \frac{SA_a}{Sa} \Delta p_z^{de} = m \cdot \Delta p_z^{de}
\end{align*}
\]

Where \(m\) is the photographing scale on the reference plane, \(\Delta x^{de}\) and \(\Delta z^{de}\) are the horizontal and vertical deformation of deformation point on the object plane, \(\Delta p_x^{de}\) and \(\Delta p_z^{de}\) are the horizontal and
vertical parallax of the correspondence image point on the image plane. Note that there exist systematic errors in \( \Delta p^d \) and \( \Delta p^d \).

According to the photographing scale difference between the control plane and the object plane, we got the actual deformation of the deformation points:

\[
\begin{align*}
\Delta x_{\text{pst} i}^d &= \Delta x_{\text{de}} \cdot \Delta x_{\text{de}}^d, \\
\Delta z_{\text{pst} i}^d &= \Delta z_{\text{de}} \cdot \Delta z_{\text{de}}^d
\end{align*}
\]

Where \( \Delta x_{\text{pst} i}^d \) and \( \Delta z_{\text{pst} i}^d \) are the actual spatial deformations on the object plane of deformation points, \( i=1,2,3 \ldots n \), \( \Delta x_{\text{de}} \) is the coefficient of the photographing scale transformation, and \( \Delta z_{\text{de}} = \frac{H_4}{H_3} \), \( (\text{cor} \Delta x_{\text{de}}, \text{cor} \Delta z_{\text{de}}) \) are the corrected displacements on the reference plane of deformation points.

3. Monitoring Test of Deep Mining Similarity Material Model

In the test, we used the verified camera. Its maximum error, minimum error and mean square error were 0.28pixel (0.40mm), 0.039pixel (0.05mm) and 0.1pixel (0.14mm), respectively [6]. The camera and its parameters are detailed in Figure 2 and Table 1.

**Table 1.** Parameters of the Sony-350 camera [7]

| Type              | Sensor   | Sensor scale  | Focal length | Active pixels  |
|-------------------|----------|---------------|--------------|----------------|
| Sony DSLR A350 (Sony-350) | CCD       | 23.5×15.7mm   | 35mm (27-375) | 4592×3056 pixels |

In order to improve the accuracy as much as possible, the camera was close to the similar material model. Multiple cameras were used to the similar material model simultaneously, and each camera was used to monitor parts of a similar material model. In order to facilitate the stitching of the final images, the monitoring range of each camera had a certain cross area. The field monitoring schematic diagram was showed in Figure 2:

![Figure 2](https://example.com/figure2.png)

The monitoring process was detailed as follows: (1) Cameras 1 and 2 were located in front left and front right of similar material model. They were 2.5 meters away from the similar material model. Then, we levelled and focused the camera, and made it aim at the similar material model; (2) The cameras
remained stable in the test, photograph the similar material model many times. We selected the highest quality image as the reference image before mining; (3) The similar material model was photographed with the two cameras at the same time after mining the similar material model every time. Lastly, fifteen image sequences were obtained.

4. Data Analysis
In order to evaluate the measurement accuracy of the PST-TBP method, we selected control points labeled as R42–R43 and R19–R21, and their displacements are detailed in Table 6. Table 6 shows that the average errors of the right and left camera are 0.43mm and 0.52mm, respectively.

Table 2. Checkpoint displacement observations/mm

| No. | Left images | Right images |
|-----|-------------|--------------|
|     | DZ42        | DZ43         | DZ19 | DZ20 | DZ21 |
| P1  | -0.48       | -0.25        | 0.99 | 0.97 | 0.8  |
| P2  | -0.41       | -0.12        | 0.34 | 0.68 | 0.34 |
| P3  | -0.66       | -0.16        | 0.5  | 0.77 | -0.06|
| P4  | -0.19       | 0.72         | 0.23 | 0.01 | 0.61 |
| P5  | -0.33       | 0.09         | 0.4  | 0.4  | 0.73 |
| P6  | -0.26       | -0.69        | 0.95 | 0.52 | -0.09|
| P7  | -0.36       | -0.66        | 0.57 | 0.37 | 0.16 |
| P8  | -0.25       | 0.54         | 0.04 | 0.83 | 0.02 |
| P9  | -0.75       | -0.68        | 0.12 | 0.5  | -0.1 |
| P10 | 0.19        | 0.2          | 0.5  | -0.12| -0.35|
| P11 | -0.58       | -0.58        | 0.89 | 0.33 | 0.18 |
| P12 | -0.24       | 0.2          | 0.25 | 0.28 | 0.14 |
| P13 | -0.4        | 0.28         | 0.89 | 0.59 | 0.25 |
| P14 | -0.42       | -0.21        | 0.41 | 0.07 | 0.2  |
| P15 | -0.43       | 0.02         | 0.57 | 0.77 | 0.42 |

Accuracy: $m_{\text{Left}} = \pm 0.43 \text{mm}$, $m_{\text{Right}} = \pm 0.52 \text{mm}$

Figure 3. The comparison chart of horizontal movement curves

Figure 3 (a) shows the deformation curve of the immediate roof, and Figure 3 (b) shows the deformation curve of the surface. In Figure 3 (a), the immediate roof suddenly fell when the strike length was 240m, and the immediate roof fell for the second time when the strike length was 300m. Then, the
Immediate roof continues to collapse as the length in the strike direction was increasing. In Figure 3 (b), the surface barely sank when the length was 60m in the strike direction. The surface subsidence was 65mm, 103mm, 120mm, 170mm, 359mm and 480mm when the strike length was 180m, 300m, 480m, 660m, 840m and 900m, respectively. In the same mining degree, the surface subsidence of the super-thick and weak cementation overburden mining is clearly small, and it takes more mining space to achieve full mining.

Because the PST-TBP method was firstly applied in monitoring the similar material model and was still in the exploration stage, we did not use it to the overall dynamic monitoring of similar material model. This paper used it to monitor the similar material model to make up for the lacks of the XJTUDP software, which often failed to identify some important points.

5. Conclusion

In this work, we used a monocular digital photography based on photographing scale transformation-time baseline parallax (PST-TBP) method and the XJTUDP measurement system to monitor deep mining similar material models of the super-thick and weak cementation overburden. The following findings were obtained:

1. To some extent the PST-TBP method can make up for the lacks of the XJTUDP software. The average errors of the right and left camera are 0.46mm and 0.48mm, respectively.

2. The first breaking span of the immediate roof reached 240m, and the cyclic fracturing length was about 60m, which were larger than that of the Carboniferous Permian coal seam in the middle-eastern mining area of China.

3. In the same mining degree, the surface subsidence of deep mining with the super-thick and weak cementation overburden in western China is much smaller than that of deep mining with the middle hard overburden in eastern China. It still shows the characteristics of the inadequate mining when the surface reaches fully mining.

4. The (PST-TBP) method and the XJTUDP measurement system provide a new way to monitor the overall dynamic monitoring of similar material model to study the dynamic development process of regional deformation caused by deep mining.

Acknowledgements

The authors gratefully acknowledge the financial support from the National Natural Science Foundation Item (Grant No.: 51974292), Postgraduate Research & Practice Innovation Program of Jiangsu Province (Grant No.: KYCX19_2162), Postgraduate Research & Practice Innovation Program of China University of Mining and Technology (Grant No.: KYCX19_2162) and Science and Technology Project of Shandong province, China (Grant No.: 2010GZX20125).

References

[1] J. Zhu, G. Guo, J. Zha, and Q. Guo, "Optical image method to deformation monitoring of similar material model," Journal of China University of Mining & Technology, vol. 44, 2015.

[2] K. Wu, G.-L. Cheng, and D.-W. Zhou, "Experimental research on dynamic movement in strata overlying coal mines using similar material modeling," Arabian Journal of Geosciences, vol. 8, pp. 6521-6534, 2015.

[3] G. Zhang, G. Guo, C. Yu, L. Li, S. Hu, and X. Wang, "Monitoring Instantaneous Dynamic Displacements of Masonry Walls in Seismic Oscillation Outdoors by Monocular Digital Photography," Mathematical Problems in Engineering, Vol. 2018, No. 1, pp.1-15, 2018.

[4] G. Zhang, G. Guo, C. Yu, and L. Li, "MONITORING DYNAMIC GLOBAL DEFLECTION OF A BRIDGE BY MONOCULAR DIGITAL PHOTOGRAPHY," CIVIL ENGINEERING JOURNAL-STAEBNIB OZBZ, Vol. 27, No. 2, pp. 168-182, 2018.

[5] G. Zhang, S. Liu, T. Zhao, and C. Yu, "Exploring of PST-TBPM in monitoring bridge dynamic deflection in vibration," in IOP Conference series: earth and environmental science, 2018, p. 022045.
[6] F. Xu, C. Yu, G. Huang, and Y. Liu, "The monitor of steel structure bend deformation based on digital photogrammetry," Geomatics and Information Science of Wuhan University, pp. 256-260, 2001.

[7] G. Zhang, G. Guo, L. Li, and C. Yu, "Study on the dynamic properties of a suspended bridge using monocular digital photography to monitor the bridge dynamic deformation," Journal of Civil Structural Health Monitoring, vol. 8, pp. 555-567, 2018.