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Digital close-range photogrammetric application to small-scale physical simulation experiment

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Abstract: In order to research the possibility of digital close-range photogrammetric surveying in small scale physical simulation experiment, physical model coinciding with engineering practice was constructed based on similar theory. The datum processing method and surveying precision of digital close-range photogrammetric were analyzed. And the function relationship between overburden subsidence factor q_r and the ratio z/H of stratum horizon z and mining depth H was researched. The results show that surveying points position mean error along horizontal direction is ±0.131 mm and vertical direction is ±0.192 mm. Therefore, multi-taking station cross direction digital close-range photogrammetric can completely satisfy the precision need of physical simulation experiment. And the empirical formula can be utilized to represent evolution law of stratum subsidence factor.
Key words: close-range photogrammetric; physical simulation; light-rays adjustment; surveying precision; subsidence factor

1 Introduction

At present physical simulation experiment has been one of very effective methods in researching engineering problems due to its characteristics of intuition, great adaptability, quickly obtaining related parameters and conclusion [1−3]. In recent years as coal mining intensity has been increasing step by step, mining depth are growing at the speed of 8−12 m/a [4−6]. Theory and practice have been shown that regulation of stratum movement in deep mining had self-features. When utilizing physical simulation experiment to research rock mass stress field, displacement field and strain field, it has been not satisfied practical need if still use traditional large-scale model. So constructing small-scale model to make theory and field surveying research greater meets engineering requirement. For stratum movement surveying, classical theodolite surveying method is often adopted. However, for the physical model which owns much surveying point density and many surveying points, requires detail knowing overburden movement situation, the method not only time-and-labor consumption but requiring higher precision as mining depth has been increasing and model scale becoming smaller. If still using conventional theodolite to survey, points 3-D coordinate will cause error, and the smaller scale model, the more of the points, the larger of the error. Therefore, choosing a quick, precise, convenient surveying method is obviously necessary and urgent. Theory and practice have shown that digital close-range photogrametric is especially suitable to treat group of points surveying. Furthermore, some research achievement has been obtained home and abroad [7−9]. Yet this method still needs to check whether it applies to small-scale physical simulation experiment and stratum movement analysis.

2 Physical model construction

The geological background of this experiment is No.1 mining section whose coal seam is merged by 1# and 2# coal. Coal thickness is 4.5 m by mean, coal dip angle is semi-flat and mining depth is 460−500 m. Mean loess bed thickness of Quaternary is 100 m. Comprehensive machinery, whole-thickness, strike longwall and backsetp mining method were used with

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whole caving to manage gob. The mining section was 600 m long in strike, 630 m in dip which was divided three panels to mine and every one is 210 m by mean.

According to similar theory, coal seam condition, mining section situation and experiment destination combined with engineering, 2D simulation experiment stage belonging to China University of Ming and Technology (Beijing) was utilized, whose sizes of length, width and height were respectively 4 200 mm, 250 mm and 2 000 mm. Due to average mining depth reaching 480 m, simulated stratum thickness is 500 m if 20 m coal floor thickness is added, which will simulate whole-stratum movement process. Therefore, the model geometry scale is set 1:300. After doing large quantities of similar material ratio experiment, model severe ratio is set 0.6, according to which calculated similar time is 17.32. This experiment aggregate is fine sand and cementing materials are lime and gypsum. According to the above parameters, the thickness of the simulated strata, bulk density and compressive strength calculation are listed in Table 1.

According to model scale and research destination combining with engineering practice, surveying points were set in overburden. The method of close-range photogrammetry needed to layout passive brighten return signs. In order to survey conveniently, reflection plates were nailed on the model through pins. For analyzing resolving results precision, fourteen known coordinates image-control points were arranged on model frame. The model of arranged surveying points is presented in Fig. 1.

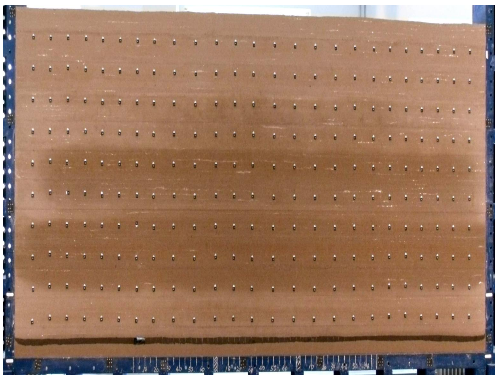

Fig. 1 Surveying points layout of simulation material experiment

3 Datum process and precision analysis for close-range photogrammetry

Any surveying method cannot ignore controlling surveying accuracy. To obtain high precision calculation results, especially for small scale physical simulation experiment, light-pencil adjustment resolving method whose theory was refined had better be used based on collinearity equation to calculate surveying points 3D coordinates [10]. For light-pencil adjustment resolving method needs to iterate calculation, high precision initial values were required. Nevertheless, direct linear transformation based on non-measuring camera could provide high precision initial parameters values. Therefore, calculation process included as the following three aspects:

1) Utilizing direct linear transformation method to resolve initial object space coordinates: Direct linear transformation method was deduced from collineation equation, according to which direct linear transformation basic equation could be deduced as formula (1) by utilizing direct linear transformation theory.

$$\begin{cases} x = \dfrac{L_1X + L_2Y + L_3Z + L_4}{L_9X + L_{10}Y + L_{11}Z + 1} \\ y = \dfrac{L_5X + L_6Y + L_7Z + L_8}{L_9X + L_{10}Y + L_{11}Z + 1} \end{cases} \tag{1}$$

Table 1 Mechanical parameters of similar material simulation

Stratum	Situ stratum			Simulation stratum			Material mixture ratio
	Thickness/ m	Compressive strength/MPa	Bulk density/ (g·cm^{-3})	Thickness/ cm	Compressive strength/kPa	Bulk density/ (g·cm^{-3})	
Loess	100	0.011	1.80	33.3	0.023	1.125	12:1:0
Silty mudstones	80	28	2.40	26.7	58.333	1.500	11:9:1
Siltstone	120	35	2.60	40.0	72.917	1.625	10:8:2
Fine-grained siltstone	100	45	3.50	33.3	93.750	2.188	8:6:4
Silty sandstone	40	30	2.60	13.3	62.500	1.625	9:8:2
Mudstone	40	20	2.40	13.3	52.083	1.500	10:8:2
Coal	9	15	1.44	3.0	31.250	0.900	8:7:3
Sandstone	20	50	2.60	6.7	104.167	1.625	7:5:5

where x and y are imagine coordinates; X, Y, and Z are object space coordinates; L_1−L_{11} are transformation parameters between imagine coordinates and object space coordinates.

If six object space control points and its imagines coordinates were given, according to formula (1), parameters for L_1−L_{11} could be resolved through which inner orientation element L_1−L_{11} could be calculated. Then approximate object space coordinates of undetermined points could be resolved by substituting imagine points coordinate for formula (1). To resolve three indeterminates X, Y, Z, at least three equations should be listed whose meaning was that at least two images should be taken and their L coefficients respectively were L_1, L_2, ⋯, L_{11} and L'_1, L'_2, ⋯, L'_{11}. When neglecting one formula, the equation group for resolving X, Y, Z was:

$$\begin{bmatrix} L_1 + xL_9 & L_2 + xL_{10} & L_3 + xL_{11} \\ L_5 + xL_9 & L_6 + yL_{10} & L_7 + yL_{11} \\ L_1' + x'L_9' & L_2' + x'L_{10}' & L_3' + x'L_{11}' \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} + \begin{bmatrix} L_4 + x \\ L_8 + y \\ L_4' + x'' \end{bmatrix} = 0 \tag{2}$$

If a couple of corresponding image points coordinates (x_1, y_1) and (x_2, y_2) which were stereo couple-image were known, according to formula corresponding initial object space coordinate values could be calculated.

2) Utilizing light-pencil adjustment to resolve object space coordinates: In fact, image plan coordinates of cardinal points were not strictly zero, but existed a slight value (x_0, y_0). Besides, due to interference factors such as object lens deformation of photograph lens, all image points' position relative their theory ones (x, y) also existed deviation (Δx, Δy). So collinearity equation of actual image points was [11−12]:

$$\begin{cases} x - x_0 + \Delta x = -f \dfrac{a_1(X - X_S) + b_1(Y - Y_S) + c_1(Z - Z_S)}{a_3(X - X_S) + b_3(Y - Y_S) + c_3(Z - Z_S)} \\ y - y_0 + \Delta y = -f \dfrac{a_2(X - X_S) + b_2(Y - Y_S) + c_2(Z - Z_S)}{a_3(X - X_S) + b_3(Y - Y_S) + c_3(Z - Z_S)} \end{cases} \tag{3}$$

where Δx and Δy are system error compensation of image points coordinates.

System error of digital camera mainly came from digital photo deformation and camera lens distortion, which could be expressed as:

$$\begin{cases} \Delta x = x'(K_1 r^2 + K_2 r^4) + P_1(r^2 + 2x'^2) + 2P_2 x'y' \\ \Delta y = y'(K_1 r^2 + K_2 r^4) + 2P_1 x'y' + P_2(r^2 + 2y'^2) + A_1 x' + A_2 y' \end{cases} \tag{4}$$

where $x' = x - x_0$, $y' = y - y_0$; K_1 and K_2 are radial distortion factors; $r^2 = x'^2 + y'^2$; P_1 and P_2 are tangential distortion corrected factors; A_1 and A_2 are affine transformation parameters which could compensate digital image deformation.

Error equation (5) of light-pencil adjustment could be obtained through linearizing formula (3) by utilizing Taylor formula.

$$\begin{cases} v_x = \dfrac{\partial x}{\partial X_S}\Delta X_S + \dfrac{\partial x}{\partial Y_S}\Delta Y_S + \dfrac{\partial x}{\partial Z_S}\Delta Z_S + \dfrac{\partial x}{\partial \varphi}\Delta\varphi + \dfrac{\partial x}{\partial w}\Delta w + \\ \quad \dfrac{\partial x}{\partial k}\Delta k + \dfrac{\partial x}{\partial X}\Delta X + \dfrac{\partial x}{\partial Y}\Delta Y + \dfrac{\partial x}{\partial Z}\Delta Z + \dfrac{\partial x}{\partial f}\Delta f + \dfrac{\partial x}{\partial x_0}\Delta x_0 + \\ \quad \dfrac{\partial x}{\partial y_0}\Delta y_0 + \dfrac{\partial x}{\partial K_1}\Delta K_1 + \dfrac{\partial x}{\partial K_2}\Delta K_2 + \dfrac{\partial x}{\partial P_1}\Delta P_1 + \dfrac{\partial x}{\partial P_2}\Delta P_2 - l_x \\ v_Y = \dfrac{\partial Y}{\partial X_S}\Delta X_S + \dfrac{\partial Y}{\partial Y_S}\Delta Y_S + \dfrac{\partial Y}{\partial Z_S}\Delta Z_S + \dfrac{\partial Y}{\partial \varphi}\Delta\varphi + \dfrac{\partial Y}{\partial w}\Delta w + \\ \quad \dfrac{\partial Y}{\partial k}\Delta k + \dfrac{\partial Y}{\partial X}\Delta X + \dfrac{\partial Y}{\partial Y}\Delta Y + \dfrac{\partial Y}{\partial Z}\Delta Z + \dfrac{\partial Y}{\partial f}\Delta f + \dfrac{\partial Y}{\partial x_0}\Delta x_0 + \\ \quad \dfrac{\partial Y}{\partial y_0}\Delta y_0 + \dfrac{\partial Y}{\partial K_1}\Delta K_1 + \dfrac{\partial Y}{\partial K_2}\Delta K_2 + \dfrac{\partial Y}{\partial P_1}\Delta P_1 + \dfrac{\partial Y}{\partial P_2}\Delta P_2 - l_Y \end{cases} \tag{5}$$

3) Precision evaluation of digital close-range photogrammetry: The digital close-range photogrammetry's resolving precision should be known accurately. Object space coordinate calculation precision of this method was mainly controlled by the number of image-control points, photo-taking style and layout form, position surveying precision of image-control points, measuring precision of image coordinate and charge coupled device (CCD) camera geometric resolution. Close-range photogrammetry precision evaluation were mainly from three aspects, estimation precision, inner precision and external precision, among which external precision was an indexing method which could reflect objective precision. Most popular method was to use large quantities of additional control points. Through comparison between designing coordinates and analytic ones of control points, coordinates mean-error and points position error distribution could be analyzed, which could be listed in Table 2.

For every group image points was independently resolved, it could be supposed that resolving precision of every group image points should be identical. Close-range photogrammetr resolving mean error could be calculated by Bythell formula. Points position resolving mean error for horizontal direction m_x=0.131 mm. Points position resolving mean error for vertical direction m_y=0.192 mm.

For this test model scale was 1/300, by conversion field horizontal direction point's position surveying absolute mean error was ±39 mm and vertical horizontal point's position surveying absolute mean error was ±39 mm. So, multi-taking station cross direction digital close-

Table 2 Precision analysis of digital close-range photogrammetry

Image-control point	Surveying coordinate/mm		Resolving coordinate/mm		Error/mm	
	x	*y*	*x*	*y*	Δ*x*	Δ*y*
C25	3 015.619	53.659	3 015.671	53.659	0.052	0
C26	−276.439	2 128.843	−276.424	2 129.166	0.015	0.323
C27	1 665.559	2 222.791	1 665.334	2 222.494	−0.225	−0.297
C28	−255.986	744.698	−255.965	744.769	0.021	0.071
C29	1 077.351	15.039	1 077.463	15.013	0.112	−0.026
C30	1 775.836	29.624	1 775.940	29.581	0.104	−0.043
C31	3 987.958	1 769.103	3 987.795	1 768.945	−0.163	−0.158
C34	−268.646	1 172.370	−268.568	1 172.466	0.078	0.096
C35	612.086	19.427	612.125	19.380	0.039	−0.047
C36	2 458.675	51.912	2 458.717	51.896	0.042	−0.016
C37	3 999.292	1 293.443	3 999.141	1 293.300	−0.151	−0.143
C38	3 468.936	57.094	3 468.926	57.115	−0.010	0.021
C40	1 084.407	2 220.479	1 084.700	2 220.949	0.293	0.470
C41	0	0	−0.030	−0.046	−0.030	−0.046

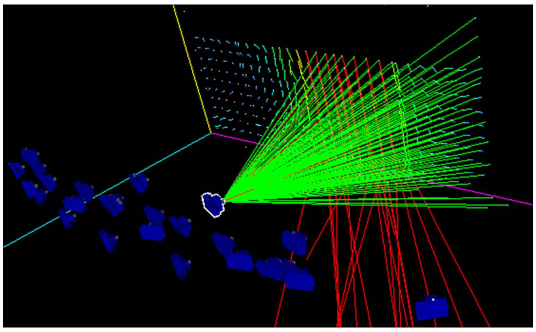

Fig. 2 One close-range photogrammetry to measure many points

range photogrammetric method can completely satisfy the precision need of physical simulation experiment. Figure 2 shows the graphic of one close-range photogrammetry to measure many points.

4 Subsidence factor evolution regulation of overburden

Research has shown that the relationship between overburden subsidence factor q_r and ratio of stratum horizon divided mining depth *z*/*H* could be expressed by $q_r = 1-(1-z/H)^n(1-q)$, where q is the surface subsidence factor, and n is the influence factor of subsidence coefficient [13].

To check adoption of this math model, according to physical simulation surveying datum overburden subsidence measuring datum were fitted when face advanced 525 m from cut-off (face reached sufficient mining). Table 3 shows surveying value of *z*/*H* and subsidence factor for corresponding points. Figure 3 shows the fit results. Table 4 represents the regression analysis result of non-linear curve fitting and Table 5 shows the fit parameters.

From Table 4 and Table 5, sum of squares of fit residual was only 0.013 4 that was very small and R^2 was 0.904, which showed good fit results. Fitted math model was $q_r = 1-0.279\times(1-z/H)^{0.523}$.

Table 3 Surveying value of *z*/*H* and subsidence factor for corresponding points

Point	*z*/*H*	Subsidence factor	Point	*z*/*H*	Subsidence factor
1.11	0.088	0.751	10.12	0.938	0.950
2.11	0.094	0.765	2.13	0.188	0.785
3.11	0.179	0.750	3.13	0.281	0.771
4.11	0.188	0.760	4.13	0.375	0.770
5.11	0.267	0.769	5.13	0.469	0.782
6.11	0.281	0.750	6.13	0.563	0.790
7.11	0.375	0.790	7.13	0.656	0.848
8.11	0.392	0.775	8.13	0.750	0.840
9.11	0.469	0.812	9.13	0.844	0.882
10.11	0.477	0.760	2.14	0.188	0.760
1.12	0.542	0.805	3.14	0.281	0.743
2.12	0.563	0.796	4.14	0.375	0.755
3.12	0.625	0.825	5.14	0.469	0.775
4.12	0.656	0.833	6.14	0.563	0.830
5.12	0.750	0.855	7.14	0.656	0.815
6.12	0.760	0.866	8.14	0.750	0.876
7.12	0.833	0.925	9.14	0.844	0.910
8.12	0.844	0.901	10.14	0.938	0.942
9.12	0.921	0.960			

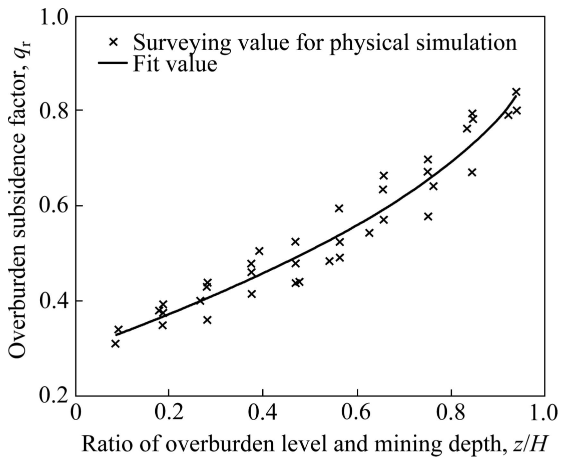

Fig. 3 Relationship between overburden levels and subsidence factor

Table 4 Regression analysis of non-linear curve fitting

Item	Degree of freedom	Sum of squares	Mean square	*F* value
Regression	2	24.898 0	3.528 0	180
Residual	35	0.013 4	0.019 6	
Total	37	24.911 0		

Table 5 Fitting parameters and precision evaluating index

m		*n*		Statistics	
Value	Standard error	Value	Standard error	Reduced Chi-Sqr	Adj. R-square
0.279	0.007 43	0.513	0.035 40	3.838×10^{-4}	0.904

From Table 2 it could be represented that influence factor *n* of subsidence coefficient was 0.523, which was uniform with field surveying calculation result. Surface subsidence factor q=1−0.279=0.721 could be also calculated, which was uniform with analysis result q=0.72 of field surveying datum. Therefore the relation between overburden subsidence factor and z/H was correct.

5 Conclusions

1) It was time- and strength-consuming if using traditional theodolite surveying, which could not realize timing surveying of all points. However, multi-taking station cross direction digital close-range photogrammetric could quickly and accurately calculate batch points space position of small scale physical simulation.

2) Object space coordinates initial value were resolved by using Utilizing direct linear transformation method, based on which light-pencil adjustment whose theory was refined was utilized to calculate 3D coordinates. By comparison between designing coordinates and analytic ones of control points, points position resolving mean error for horizontal direction m_x=0.131 mm. Points position resolving mean error for vertical direction m_y=0.192 mm. Multi-taking station cross direction digital close-range photogrammetric can completely satisfy the precision need of physical simulation experiment.

3) Through processing surveying datum and comparing to field surveying datum, it has been shown that empirical formula expressed as $q_r = 1 - 0.279\times(1 - z/H)^{0.523}$ could represent the relationship between overburden subsidence factor q_r and z/H.

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