PHOTOGRAMMETRIC MEASUREMENT OF MOVEMENTS IN TUNNEL MODEL TESTING

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INTRODUCTION

A tunnel research project provided the opportunity to demonstrate the applicability of a large-format, non-metric camera for close-range measurements. It also provided a practical situation to study the merits of additional parameters for modeling image distortions, and the effectiveness of distance measurements as controls.

A Kodak, bellow-type, press camera with a 200 x 250 mm format and a 241.3-mm focal length lens was used to photograph the tunnel model. Vertical photographs were taken from two positions at a height of 3.84 m above the model. The base distance between the two camera stations was 0.57 m, yielding a B/H ratio of 0.15 and an average photo scale of about 1/16. The three dimensional positions of about 350 target points on the tunnel model were determined from a stereoscopic pair of photographs for each loading of the tunnel model. Comparison of the computed positions for successive loadings then provided a measure on the amount and pattern of displacement at each target point.

Image coordinates were measured with a Wild STK-1 stereocomparator, which had a least count of 1 μm. The same data were processed using three different analytical approaches: 1) bundle adjustment with 12 X-Y-Z control points, 2) bundle adjustment with 12 X-Y-Z control points and additional parameters, and 3) bundle adjustment with two X-Y-Z control points supplemented by 15 object-space distances. The computed movement vectors at 15 check points, which were located outside of the tunnel model area and were known to have practically zero movements, provided a direct check on the relative merits of the three analytical approaches.

A similar camera with a focal length of 304.8 mm was used to measure the displacement of sand particles around a tunnel model (Wong and Vonerohe, 1983). The method of motion parallax was used and the photo scale was 1/5.5. The motion vectors were measured with an estimated standard error of $\pm$ 0.09 mm. The results showed that good measurement accuracy could be achieved with a large format bellow-type camera.

The effectiveness of additional parameters in modeling lens and film distortions was reported in a recent paper by Welch and Jordan (1983). A Honeywell Pentax Spotmatic 35-mm SLR camera equipped with a wide-angle lens (f = 21 mm) was used to photograph a stream channel for the purpose of studying channel erosion. The film negatives were enlarged by factors ranging from 9.2 to 7.2 and printed as positive film transparencies on Agfa Gevaert thick base (7 mil) film. Coordinates of points on the positive transparencies were measured with a cartographic digitizer which had a 25 μm resolution. The orientations of the camera were determined by resection, and the coordinates of object points were computed by intersection. Welch and Jordan reported that the use of additional parameters to model lens and film distortions reduced the image residuals from $\pm$ 30 μm to $\pm$ 11 μm in resection.

This paper will also report results which show that significant improvement in accuracy (though not as dramatic as that reported by Welch and Jordan) can be achieved with additional parameters.

The Tunnel Model

Figure 1 shows the general layout of the tunnel model. A tunnel opening measuring about 457.2 mm in diameter was formed by 114.3 mm x 114.3 mm x 508 mm long precast concrete blocks. Each block was reinforced with a 12.7-mm diameter steel bar along its center line, and was bracketed with a 19-mm thick steel plate at each end. These blocks were arranged to simulate jointed rocks. Partial blocks were used along the tunnel opening to form a circular opening. About 60 holes, each measuring 4.76 mm in diameter and 304.8-mm long, were drilled into the concrete blocks from the inside surface of the tunnel opening. Steel rods (1.6 mm in diameter) were inserted into these holes and grouted in place to simulate rock bolts. The concrete blocks were confined on three sides by fixed massive concrete abutments. On the fourth side, the concrete blocks were kept in place by a 152.4-mm thick steel plate. A series of hydraulic rams applied pressure to the steel plate to simulate the effects of overlying rock layers. A maximum surface pressure of 3,300 pounds per square inch (psi) could be applied.

During a test, the surface pressure was increased at about 200-psi increments until either the maximum pressure of 3,300 psi was reached or the collapse of the tunnel wall. Dial gauges which had a sensitivity of 0.0025 mm were mounted against the steel plate to measure the deflections on the plate. Dial gauges with sensitivity of 0.025 mm were mounted against the tunnel wall to measure the deformation of the tunnel opening.

Photogrammetric method was used to measure the lateral movement of the individual concrete blocks surrounding the tunnel opening.

The purpose of the research was to study the influence of the rock bolts on the deformation characteristics of the tunnel opening under different patterns of jointed rocks.

PHOTOGRAPHY AND CONTROLS

A Kodak, bellow-type, press camera which had a 200 x 250-mm picture format and a 214.3-mm focal length was used to photograph the tunnel model. Photographs were taken vertically from a steel platform which was raised to a height of 0.57 m above the model. See Figure 2. The camera was mounted on a base carriage which could be moved laterally along two guide rails. Adjustable stoppers on the guide rails were used to position the camera carriage for proper stereoscopic coverage. To take a stereoscopic pair of photographs of the tunnel model, a photograph was first taken with the camera carriage positioned against one set of stoppers. The carriage with the camera was then moved along the guide rails to the second set of stoppers, and a second photograph was taken from that position.

During an actual test of the tunnel model, a stereoscopic pair of photographs was taken both at the beginning (with zero surface pressure on the model) and the end (with maximum surface pressure). Four to six additional stereo pairs were taken during various stages of loading. Shown in Figure 3 is part of a photograph used in measurement.

Thirty-one control points were located on the top surface of the concrete abutments, and were marked with red-and-white stick-on survey targets. The horizontal coordinates of these control points were determined by a least-squares adjustment of 152 measured distances. The computed X- and Y- coordinates had an estimated standard error of $\pm$ 0.6 mm. The relative elevations of all 31 control points were determined by differential leveling to an accuracy of $\pm$ 0.5 mm at 1 standard error. Of the 31 control points, only 12 control points were situated in the stereoscopic coverage area.

In addition to these control points, 15 check points were also located in the stereoscopic coverage area. These check points were also marked by red-and-white stick-on targets. The coordinates of these check points were not determined by distance measurements. However, since they were located in a stable area, the movement vectors computed at these check points between any two loading conditions should be equal to zero. Any non-zero vector at these check points then represented measurement error.

In order to provide a well defined measuring mark near the center of each concrete block, a target was pasted to the top end of the reinforcing bar of each block.

COORDINATE MEASUREMENTS

Image coordinates on the 200 mm x 250 mm film negative were measured with a Wild STK-1 stereocomparator, which had a least count of 1 μm. Since the camera had no fiducial marks and the picture format exceeded the 240 mm x 240 mm dimensions of the comparator carriage, a procedure was developed to approximately center the film negative on the comparator carriage. The midpoint of each side of the negative was first located by means of a graduated scale. A straight edge was then used to connect the two marks along the x-axis, and a sharp razor was used to scretch a fine line measuring about 1 inch long from each mark. Similar lines were made from the upper and lower edges of the negative to mark the y-axis. These four scretch lines were then used to center the negative on the carriage. At the end of the coordinate measurement process, a point randomly located at each of these four scretch lines was measured. The coordinates of these four points were then used to compute the coordinates of the center of the negative. All image coordinates were then subsequently translated according to the center coordinates.

Three repetitions were made on each image point.

ANALYTICAL SOLUTIONS

Object space coordinates were computed from each stereoscopic pair of photographs by three different approaches. These were:

1. Bundle adjustment with twelve (12) X-Y-Z control points.
2. Bundle adjustment with twelve (12) X-Y-Z control points and additional parameters for modeling lens and film distortions.
3. Bundle adjustment with two (2) X-Y-Z control points, fifteen (15) measured distances, ten (10) elevation points, and additional parameters for modeling lens and film distortions.

BUNDLE ADJUSTMENT WITH X-Y-Z Controls Only

A bundle adjustment using twelve full control points (X, Y and Z coordinates were known) was performed using a modified version of the SAPGOA program (Wong and Elphingstone, 1972; Wong, 1974). The interior orientation parameters were held fixed with $x_p = 0.000$ mm, $y_p = 0.000$ mm, and f = 241.300 mm. The X-, Y- and Z- coordinates of all the control points were weighted with a standard error of $\pm$ 0.6 mm. There was no correction applied to the image coordinates for lens and film distortions, and no additional parameters were included in the solution.

The image coordinates were weighted with a standard error of $\pm$ 0.02 mm.

BUNDLE ADJUSTMENT WITH X-Y-Z Controls AND ADDITIONAL PARAMETERS

A second bundle adjustment was performed using the same 12 full control points but with additional parameters to model lens and film distortions. The GEBAT-V program (El-Hakim, 1982) was used to perform the adjustment. The program used a harmonic function to model distortions as follows:

$$dV_x = (x_A - x_p) \cdot T \tag{1}$$

$$dV_y = (y_A - y_p) \cdot T \tag{2}$$

$$T = a_{00} + a_{11} \cos \lambda + b_{11} \sin \lambda + a_{20} r + a_{22} r \cos 2\lambda + b_{22} r \sin 2\lambda + a_{31} r^2 \cos \lambda + b_{31} \sin \lambda + \cdots \tag{3}$$

$$r = \sqrt{(x_A - x_p)^2 + (y_A - y_p)^2} \tag{4}$$

$$\lambda = \sin^{-1} \left(\frac{y_A - y_p}{r} \right) \tag{5}$$

where dV_x and dV_y are distortion corrections for the x_A and y_A coordinates of image point A; x_p and y_p are the image coordinates of the principal point; and a_{00}, a_{11}, b_{11}, a_{20}, a_{22}, b_{22}, a_{31} and b_{31} are the additional unknown parameters used to model lens and film distortions for each photograph.

BUNDLE ADJUSTMENT WITH DISTANCE CONTROLS AND ADDITIONAL PARAMETERS

A third bundle adjustment was performed to evaluate the effectiveness of distances as controls. This adjustment was also performed using the GEBAT-V program, and the same eight additional parameters were used to model distortions for each photograph. However, instead of using full control points only, this adjustment used only 2 full control points which were supplemented with 15 horizontal distances and 10 elevation points. The 15 distances were well distributed in the stereoscopic coverage area. The distances had an average standard error of ± 0.5 mm.

COMPARISON OF RESULTS

Figure 4 summarizes the results from the three analytical solutions for one set of test data. Six pairs of stereoscopic photographs were taken under different loading conditions. Thus, five movement vectors were computed for each of the 15 check points, yielding a total of 75 measured movement vectors, the true values of which were zero. The mean and standard deviation of the x-, y-, and z- components of these 75 movement vectors are given in Figure 4.

It can be seen from the results given in Figure 4 that significant improvement in accuracy was obtained by the use of additional parameters to model lens and film distortions. However, distances were not as effective as full controls in solving for the additional parameters. This was also evident from the computed values of the additional parameters. Figure 5 lists the means and standard deviations of the 8 additional parameters computed from the two bundle adjustments including additional parameters. Since the same camera was used in taking all 12 photographs, it could be expected that these additional parameters had a constant as well as a random component. This is evident from the results given in Figure 5. However, the standard deviations were generally larger for the adjustment using distance controls.

Interesting results were also obtained when the photogrammetric measurements were compared to dial gauge measurements. The movements at five points located on the 152.4-mm steel plates were measured by the photogrammetric method. There were also dial gauges located near the vicinity of these points. These gauges had a least count of 0.0025 mm. A comparison of the two independent sets of measurements showed that the gauge measurements were consistently too large by about 3.5 mm. After the gauge measurements had been corrected for the constant bias, the photogrammetric measurements were in excellent agreement with the gauge measurements. The differences computed for 25 movement vectors had a mean of -0.001 mm and a standard deviation of ± 0.5 mm. The biases on the gauge readings were most likely caused by unexpected movements on the fixed ends of the dial gauges. These results had prompted a review and perhaps redesign of the mounting system for the gauges.

Figure 6 shows the successive movement vectors at points around the tunnel opening for 6 loading conditions.

CONCLUSIONS

The photogrammetric system described here was designed to measure horizontal movements using a readily available camera. The ease of taking the photographs during model testing was also a major consideration. Obviously, the accuracy of height measurement could be significantly improved by using convergent photography. Positioning accuracy could also be improved by taking pictures from three or more camera positions, precalibration of the camera, and more accurate determination of the positions of the control points. Indeed, as the testing program continues, the present photogrammetric system will be modified to meet the accuracy need of the testing program.

The results obtained thus far clearly illustrated the importance of additional parameters in modeling lens and film distortions of non-metric cameras, and that full control points were more effective than distances in solving for these additional parameters.

The results also demonstrated the susceptibility of dial gauge measurements to bias errors, and that photogrammetric methods could play an important role in support of model testing in the laboratory.

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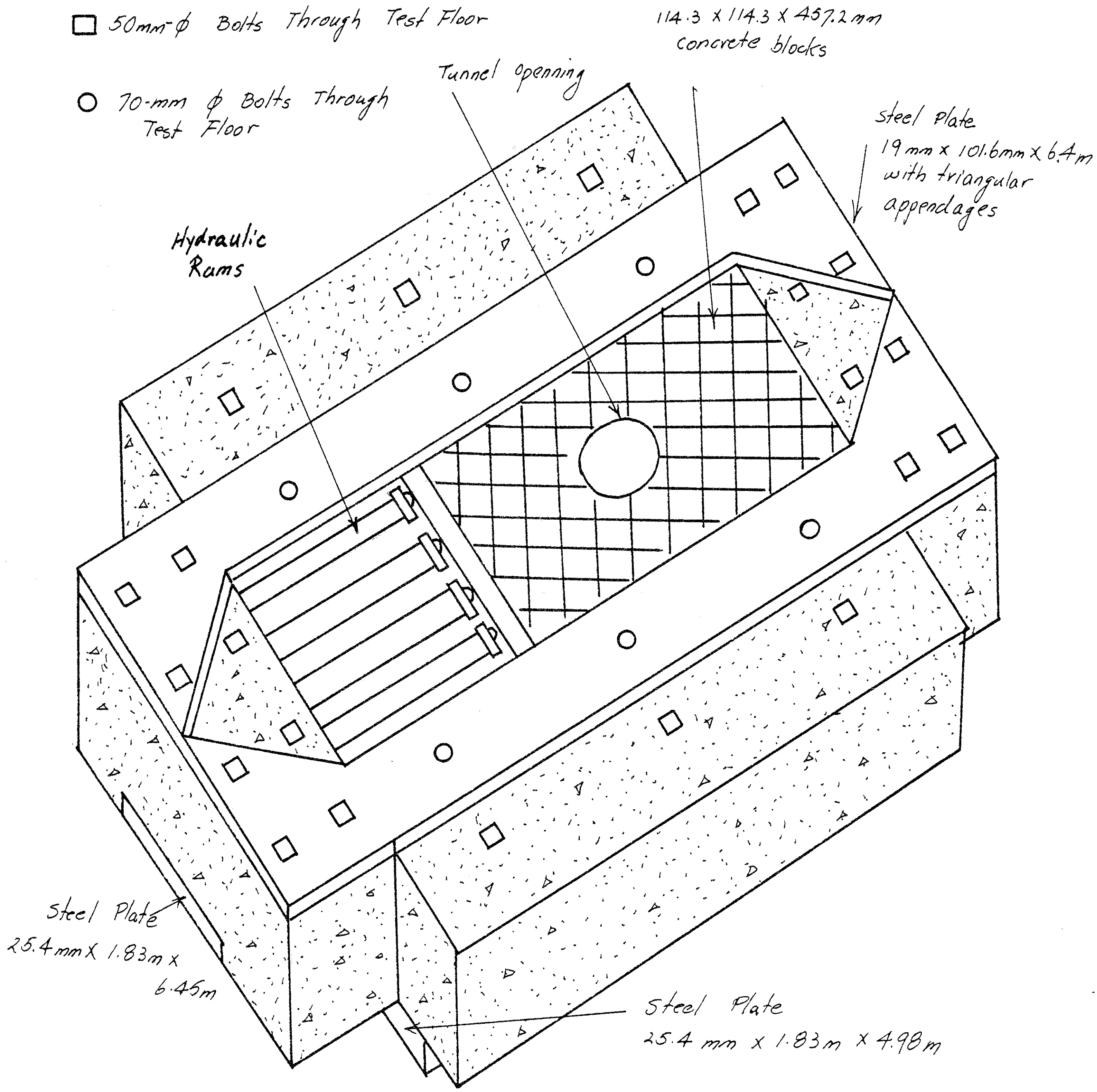


Figure 1. General Layout of Tunnel Model (From Drawing by Professor S.L. Paul)

Figure 2. Camera Mounted on A Raised Platform

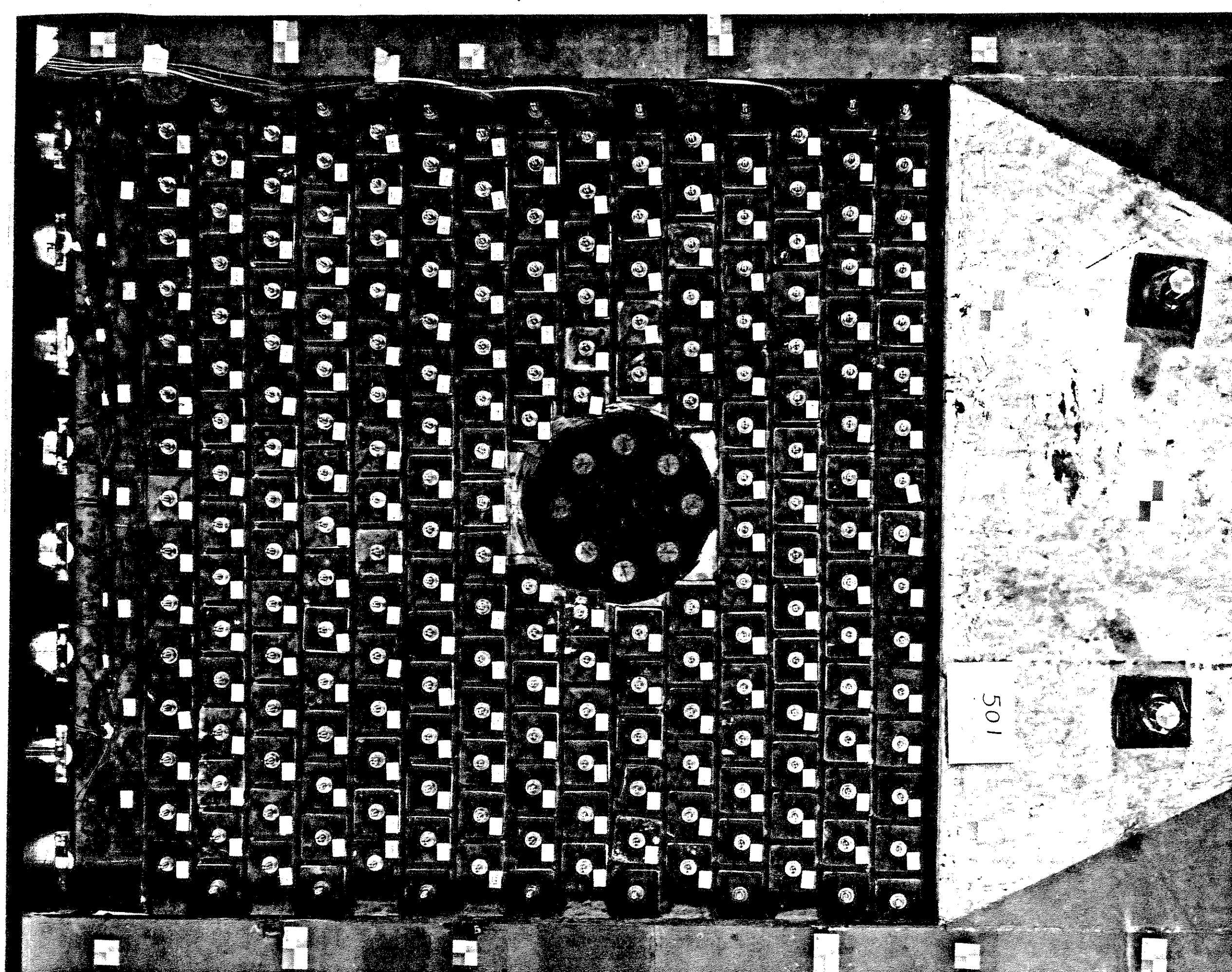


Figure 3. Part of A Photograph Used for Measurement

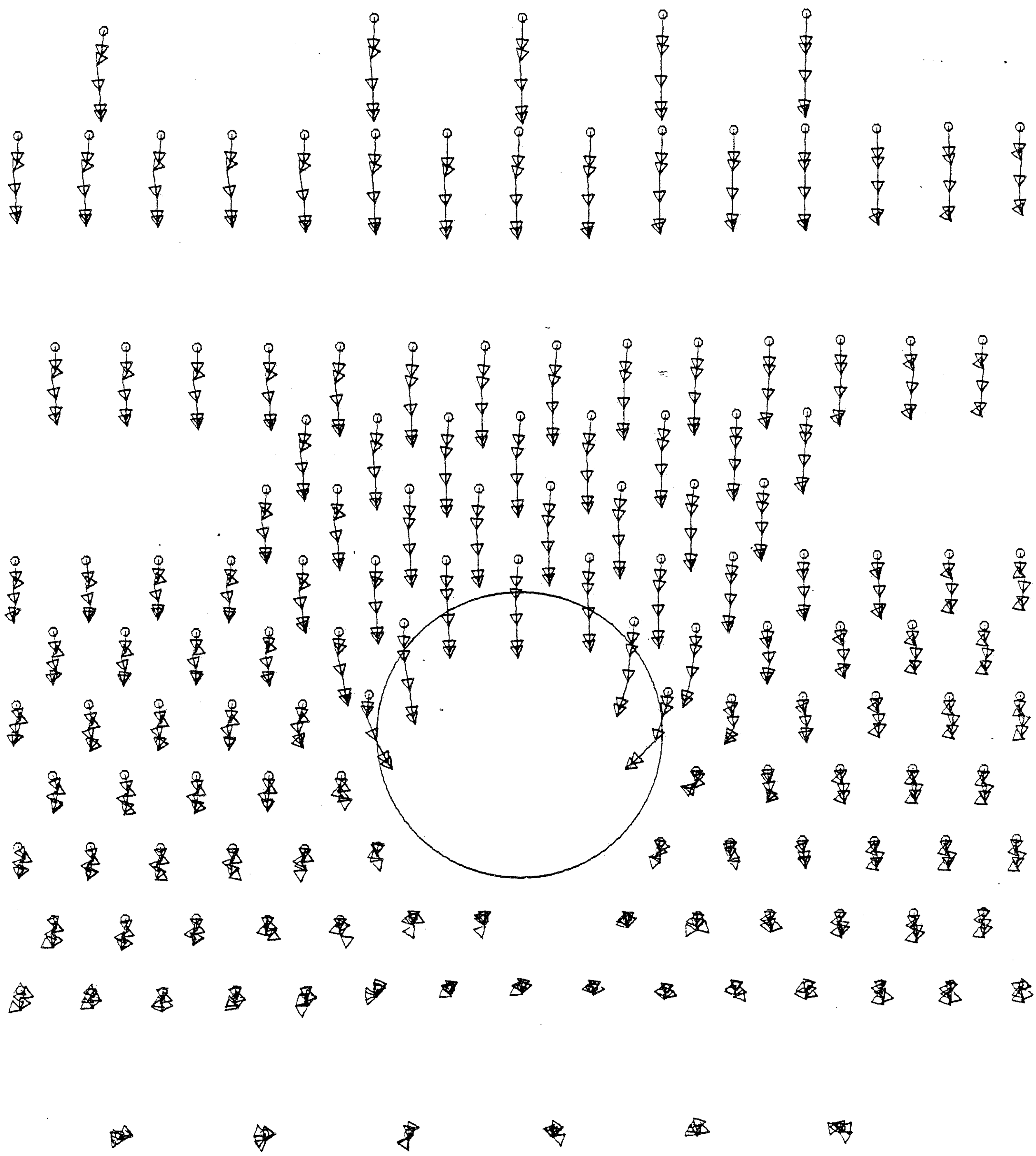
Figure 4. Accuracy of Analytical Solutions

Analytical Solutions	Errors in Computed Movement Vectors at Check Points with Sample Size = 75 (mean error ± standard deviation)		
	x-direction (mm)	y-direction (mm)	z-direction (mm)
Bundle Adjustment with Full Controls	-0.09 ± 2.4	+0.6 ± 1.8	+3 ± 9
Bundle Adjustment with Full Controls and Additional Parameters	+0.03 ± 1.4	-0.003 ± 1.1	+1.5 ± 5.5
Bundle Adjustment with Distance Control and Additional Parameters	-0.3 ± 1.9	-0.5 ± 1.4	+1 ± 4.9

Figure 5. Additional Parameters Computed from Adjustment

Parameters	Average value from 12 photographs (Mean ± std. dev.)	
	Bundle Adjustment with Full Controls	Bundle Adjustment with Distance and Elevation Controls
a_{00}	-0.0009 ± 0.002	-0.005 ± 0.003
a_{11}	-0.0019 ± 0.0007	-0.0018 ± 0.0007
b_{11}	+0.011* ± 0.002	+0.008* ± 0.001
a_{20}	0.002 ± 0.01	+0.030 ± 0.013
a_{22}	-0.046* ± 0.006	-0.051* ± 0.017
b_{22}	-0.007 ± 0.017	-0.021 ± 0.015
a_{31}	-0.005 ± 0.008	-0.004 ± 0.022
b_{31}	0.006* ± 0.002	+0.011 ± 0.006

*mean ≥ 3 x standard deviation



Position Scale 1 in. = 10. in.
Vector Scale 1 in. = 2. in.

Figure 6. Movement Vectors