Analyzing crack development pattern of masonry structure in seismic oscillation by digital photography

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Abstract. In this study, digital photography is used to monitor the instantaneous deformation of a masonry wall in seismic oscillation. In order to obtain higher measurement accuracy, the image matching-time baseline parallax method (IM-TBPM) is used to correct errors caused by the change of intrinsic and extrinsic parameters of digital cameras. Results show that the average errors of control point C5 are 0.79mm, 0.44mm and 0.96mm in X, Z and comprehensive direction, respectively. The average errors of control point C6 are 0.49mm, 0.44mm and 0.71mm in X, Z and comprehensive direction, respectively. These suggest that IM-TBPM can meet the accuracy requirements of instantaneous deformation monitoring. In seismic oscillation the middle to lower of the masonry wall develops cracks firstly. Then the shear failure occurs on the middle of masonry wall. This study provides technical basis for analyzing the crack development pattern of masonry structure in seismic oscillation and have significant implications for improved construction of masonry structures in earthquake prone areas.

1. Introduction

The seismic resistance of masonry structures is always being a hotspot in the engineering in recent years, and the crack development of masonry structures is a problem to be solved. At present, structure tests [1], numerical simulation [2, 3] and shaking table [4] are conventional methods to study the crack development of masonry structure. However, structure tests are difficult to study masonry structure in seismic oscillation. Numerical simulation is invalid to study the crack development of masonry structure when the deformation of masonry structure is a little larger. Using shaking tables for large scale masonry structures is however challenging due to its limited bearing capacity and size. A new method is urgently needed to study the crack development of masonry structures in seismic oscillation. Digital photography, combining photogrammetric technique with information technology, presents an opportunity for monitoring the dynamic deformation of engineering structures by adopting a non-metric digital camera to monitor multiple points simultaneously and to capture the instantaneous deformation of a deformable object [5]. And, we can analyze the crack development of masonry structures in seismic oscillation based on these deformation data.

Many scholars [6-8] have hitherto studied the masonry structure by digital photography. This paper therefore adopted digital photography to monitor masonry structures in seismic oscillation to study their crack development. Furthermore, the image matching-time baseline parallax method (IM-TBPM) is presented in order to improve the measurement accuracy in the test.

2. Digital photography

2.1. Accuracy verification of non-metric digital cameras

This paper uses direct linear transformation method [9] to verify the digital camera. Firstly, eight or more control points with weights are reasonable distributed in the laboratory. Then, the indirect adjustment method is used to solve the data with consideration of L coefficient. The direct linear transformation method is showed as (1):

$$\left. \begin{array}{l} x - \dfrac{L_1 X + L_2 Y + L_3 Z + L_4}{L_9 X + L_{10} Y + L_{11} Z + 1} = 0 \\[4mm] z - \dfrac{L_5 X + L_6 Y + L_7 Z + L_8}{L_9 X + L_{10} Y + L_{11} Z + 1} = 0 \end{array} \right\} \tag{1}$$

Where x and z are image plane coordinates of deformation points without errors, X, Y and Z are the space coordinates of the correspondence deformation points, $L_i (i = 1,2,3, ,11)$ are the functions of the exterior and interior parameters of photogrammetry.

Linearize (1) and get error equation (2):

$$V = \begin{pmatrix} P_1 V_1 \\ P_2 V_2 \end{pmatrix} = \begin{pmatrix} M\,N \\ 0\;\;I \end{pmatrix} \begin{pmatrix} \Delta L \\ \Delta X \end{pmatrix} - \begin{pmatrix} W_1 \\ 0 \end{pmatrix} \tag{2}$$

Where P_1 and P_2 are the weight matrixes of image point observations and the control point observations respectively, ΔX is the correction matrix of the control points, N is the coefficient matrix of ΔX, M is the coefficient matrix of ΔL, W_1 is the constant matrix of image point observations.

Tasble1 shows that the measurement accuracy of the digital camera is within 1mm.

Table 1. Measurement accuracy/mm

Line	U0-U2	U1-U3	U2-U4
Calculation distance	588	596	599
Measurement distance	589	595	599
difference	1	1	0

2.2. Image matching-time baseline parallax

The time baseline parallax method was used in this study. In this method, when a point on an object moves from A to B (Figure 1), ΔX and ΔZ are:

$$\left. \begin{array}{l} \Delta X = \dfrac{SA}{Sa} \Delta P_x = M \Delta P_x \\[4mm] \Delta Z = \dfrac{SA}{Sa} \Delta P_z = M \Delta P_z \end{array} \right\} \tag{3}$$

Where M is the photographic scale, ΔX and ΔZ are the horizontal and vertical actual deformation of deformation point on object plane, ΔP_x and ΔP_z are the horizontal and vertical pixel displacement of deformation point on image plane, SA and Sa are the photographic distance and focus respectively.
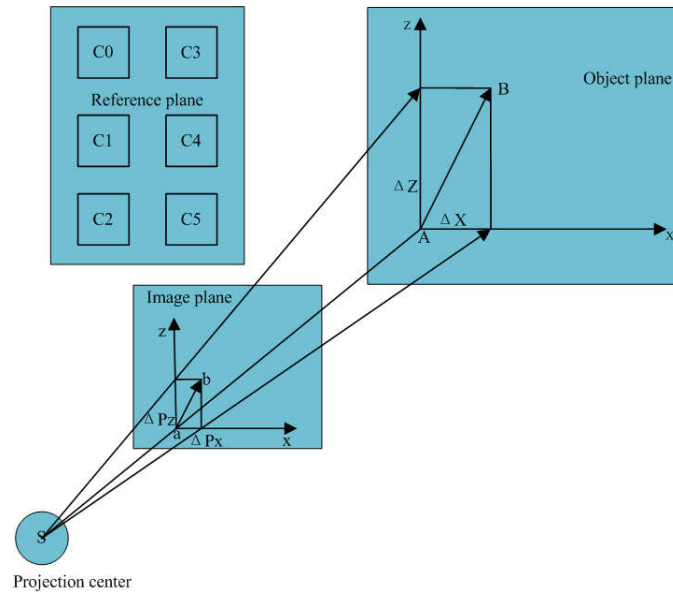

Figure 1. Image matching-time baseline parallax

However, a digital camera may move in the test and result in the change of intrinsic and extrinsic parameters. Thus, IM-TBPM is adopted to eliminate the parallax caused by the change of intrinsic and extrinsic parameters of the digital camera. For simplicity, IM-TBPM is a method that some points are laid at a stable place around the object to form a reference plane which is parallel to object plane and digital camera, and the infuence of camera vibration is eliminated through matching each photo based on reference plane.

The pixel displacement of deformation points on the image plane is corrected based on the parallaxes of the reference plane. Then, the corrected actual displacement of deformation points on object plane is obtained:

$$\left.\begin{array}{l} \Delta X = \dfrac{SA}{Sa}\Delta P'_x = M\Delta P'_x \\[2mm] \Delta Z = \dfrac{SA}{Sa}\Delta P'_z = M\Delta P'_z \end{array}\right\} \qquad (4)$$

Where $(\Delta X, \Delta Z)$ are the actual deformations of deformation points on the object plane, $(\Delta P'_x, \Delta P'_z)$ are the corrected pixel displacement of deformation points on the image plane respectively.

3. Masonry structure test in seismic oscillation

Figure 2(a) shows a simple experimental set-up: A pit (2.1m×1.4m×0.2m) was dug on the foundation and a manganese steel plate (2.3m×1.5m×0.15cm) was put above the pit. A masonry wall (1.2m×0.8m×0.24m) with bricks (240mm×115mm×53mm) was constructed On the steel plate. The impact hammer was a 25-kg iron cylinder (50cm in height and 12cm in diameter), whose upper was welded with an arc steel bar as a hook. Circular targets were evenly distributed on the bricks of brick

masonry wall without obscuring the connections between the bricks, and its diameter is less than 53mm as much as possible.
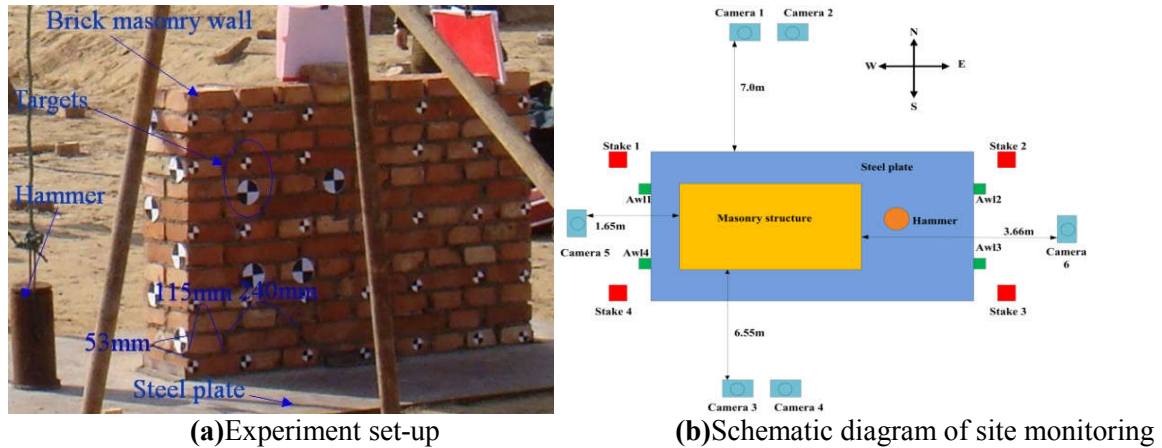

| (a)Experiment set-up | (b)Schematic diagram of site monitoring |

Figure 2. Monitoring system of masonry structure in seismic oscillation

Figure 2(b) illustrates the relative position of the monitoring system elements. In addition, the stakes were constructed at a stable place around the masonry wall, and reference points were laid on the stakes. Six digital cameras were used to capture instantaneous deformation of masonry wall when the 25-kg hammer fell freely and impacted the steel plate from a height of 0.3m, 0.6m, 0.9m, 1.2m, 1.5m, 1.8m, 2.1m, 2.4m, 2.7m, 3.0m, 3.3m, 3.6m, 3.9m, 4.2m, 4.5m, 4.8m, 5.1m, 5.4m and 5.4m.

4. Data analysis

In order to verify measurement accuracy of the image matching- time baseline parallax method(IM-TBPM), we select 2 reference points labeled as C5 and C6 (in Figure 4). These points do not move during the monitoring process. It is to say that their displacements are zero. However, the displacements of these reference points, obtained by IM-TBPM, in table 1 are not zero. These displacement values of these reference points can represent the measurement accuracy of digital photography. The photographing scale in this study is 0.65mm/pixel. The maximal errors of control point C5 are 1.46mm, 1.12mm and 1.56mm in X, Z and comprehensive direction, respectively. The average errors of control point C5 are 0.79mm, 0.44mm and 0.96mm in X, Z and comprehensive direction, respectively. The maximal errors of control point C6 are 0.80mm, 1.03mm and 1.20mm in X, Z and comprehensive direction, respectively. The average errors of control point C6 are 0.49mm, 0.44mm and 0.71mm in X, Z and comprehensive direction, respectively. Thus, IM-TBPM improves the measurement accuracy in this study.

Table 2. Measurement accuracy/mm

Test	C5			C6		
	X	Z	SQRT(X^2+Z^2)	X	Z	SQRT(X^2+Z^2)
1	0.81	0.31	0.87	0.48	0.49	0.69
2	0.71	0.07	0.71	0.56	0.30	0.64
3	0.92	0.39	1.00	0.75	0.68	1.01
4	0.29	1.12	1.16	0.14	0.44	0.46
5	0.95	0.12	0.96	0.38	0.06	0.38
6	0.90	0.30	0.95	0.81	0.46	0.93
7	0.33	0.83	0.89	0.27	0.18	0.32
8	0.89	0.21	0.91	0.41	0.47	0.62
9	0.62	0.49	0.79	0.03	0.72	0.72
10	0.57	0.84	1.02	0.40	0.28	0.49
11	0.50	0.50	0.71	0.01	1.03	1.03
12	0.57	0.18	0.60	0.40	0.04	0.40
13	0.96	0.23	0.99	0.80	0.38	0.89
14	1.46	0.56	1.56	0.81	0.44	0.92
15	0.85	0.72	1.11	0.70	0.90	1.14
16	0.96	0.21	0.98	0.80	0.89	1.20
17	1.40	0.57	1.51	0.84	0.25	0.88
18	0.06	0.40	0.40	0.11	0.23	0.25
19	1.18	0.23	1.20	0.53	0.03	0.53
Average	0.79	0.44	0.96	0.49	0.44	0.71

Based on the image matching-time baseline parallax method, we get the deformation data of deformation point U0, U1, U2, U3, U4 and U5 (in Figure 4). Some deformation data can be seen in Table 3.

Table 3. Deformation values of deformation points/mm

Test	U0		U1		U2		U3		U4		U5	
	X	Z	X	Z	X	Z	X	Z	X	Z	X	Z
14	2.96	1.09	2.51	2.05	2.61	1.90	2.75	0.31	2.86	2.39	1.28	2.24
15	3.09	1.97	2.18	2.79	2.92	1.96	2.81	1.44	2.45	2.83	1.52	2.55
16	3.71	1.05	3.36	1.97	3.55	1.79	3.51	1.07	3.71	2.56	2.23	2.38
17	6.26	0.91	6.24	3.31	6.23	3.52	4.73	1.12	6.39	3.53	5.81	3.19
18	7.38	0.07	6.91	3.31	7.55	3.77	5.08	1.69	7.95	4.38	6.92	4.28
19	7.29	2.34	8.53	4.27	9.76	4.57	6.94	1.58	9.85	4.09	9.41	4.93

In order to analyze the crack development of masonry wall in seismic oscillation, we depict deformation trend curve of deformation points. Figure 3 (a) shows that the obvious vertical crack develops between U0 and U4 as the maximal displacement difference of them is 4.31mm. Figure 3 (b) shows that the obvious horizontal crack develops between U0and U4 as the maximal deformation between them is 2.56mm. Moreover, the position between U2 and U5 and the position between U1and U4 also develop slight horizontal cracks. These conclusions are conform to the destructed masonry wall (in Figure 4), in which the obvious vertical and horizontal cracks occur on A, and slight horizontal crack occur on B and C. In addition, crack C and occurs from Test14, vertical crack of A occurs from 16, horizontal crack of A and crack B occur in test 19. Thus, in seismic oscillation the middle to lower of the masonry wall develops shear failure firstly. Then the bonding between bricks

and mud is invalid in the middle of the masonry wall. Lastly the shear failure occurs on the middle of masonry wall.
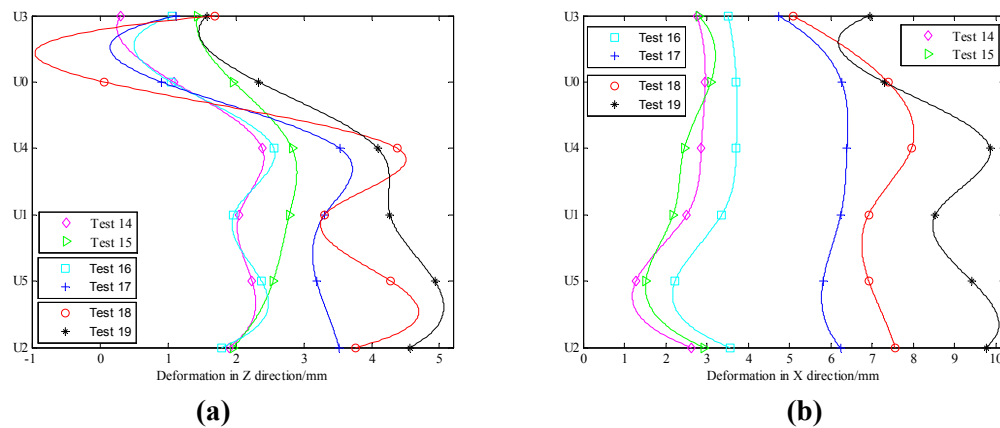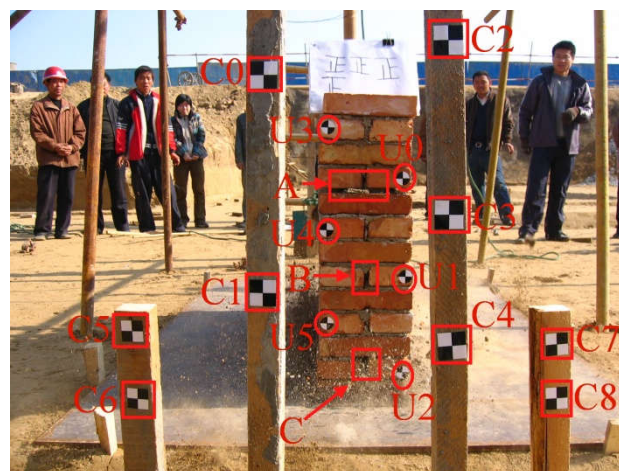

Figure 3. Deformation trend curves

Figure 4. Destructed masonry wall

5. Conclusion

This paper use digital photography to monitor instantaneous deformation of masonry wall to study its crack development pattern. And the image matching-time baseline parallax method is presented to improve the measurement accuracy in the test. The following conclusions are obtained:

(1) IM-TBPM improves the measurement accuracy in this study as the photographing scale in this study is 0.65mm/pixel, the average errors of control point C5 are 0.79mm, 0.44mm and 0.96mm in X, Z and comprehensive direction, respectively, and the average errors of control point C6 are 0.49mm, 0.44mm and 0.71mm in X, Z and comprehensive direction, respectively.

(2) In seismic oscillation the middle to lower of the masonry wall develops cracks firstly. Then the bonding between bricks and mud is invalid in the middle of the masonry wall, which results in the shear failure on the middle of masonry wall.

(3) In order to increase the seismic resistance of masonry wall, we can increase the mud cohesiveness between bricks, and constructional columns can be arranged on both sides of masonry wall to limit the crack development.

This study proves the feasibility of applying digital photography to monitor instantaneous deformations of a masonry structure to analyze its crack development pattern. It also provides a

technical basis for analyzing the failure pattern of large scale masonry structures in seismic oscillation and has significant implications for improved construction of masonry structures in earthquake prone areas.

Acknowledgements

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