Automatic detection method for verticality of bridge pier based on BIM and point cloud

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ABSTRACT: Bridge pier is a building that supports bridge span structure and transmits dead load and live load to foundation. As the main supporting structure of the whole bridge, the perpendicularity of the pier is particularly important. Among them, for the pier with high height, the influence of perpendicularity deviation on the quality of pier is more obvious. In this paper, an automatic detection method of pier perpendicularity is proposed. The 3D laser point cloud is used to obtain the spatial attitude of the pier, and the point cloud of the reliable feature surface of the pier is extracted by combining the automatic recognition algorithm. According to the principle of statistical correlation, the characteristic surface data of piers are processed to get the actual center line and section of piers. At last, we update the BIM model of the designed pier with the center line and section and analyze the 3D deviation between the updated BIM model of the pier and the point cloud. We apply this method to the verticality detection of several bridges. The results show that the method is reliable and robust.

1. INTRODUCTION

With the rapid development of the transportation industry in the world, more and more world-class bridges have come out one after another. As the backbone of the whole bridge, the pier transfers all the loads of the superstructure to the foundation, and its quality directly affects the overall service life of the bridge. With the improvement of construction technology, the construction height of the pier is also increasing. The height of the pier of He Zhang grand bridge, known as "the highest high town in Asia", has reached an amazing 195m (Yang 2014). Among them, the problem of pier perpendicularity deviation has always been the research focus of many scholars (Liu et al. 2018).Tie et al (2017). Made a quantitative analysis on the problem of pier perpendicularity deviation by using the finite element model, and the results showed that the pier perpendicularity deviation had a great influence on the bearing capacity of the bridge; Ding et al (2019). Realized the rapid measurement of pier perpendicularity by using the total station free station non-contact measurement method; Qiu et al (2018). Improved the method of least square fitting circular curve, fast Check the perpendicularity of pier quickly. The main basis of the above research is the limited data points collected by the total station, but as a three-dimensional structure, the method of determining the perpendicularity of the pier by the limited points measured by the total station is not very convincing, in fact, the problem of the detection of the perpendicularity deviation of the pier has not been solved.

As another technological innovation after GPS technology, 3D laser scanning technology has been widely used in the field of deformation monitoring(Deng et al. 2018). 3D laser scanning technology can easily obtain the surface features of the structure, and has the advantages of high data accuracy and easy post-processing. Huang et al (2012). combined the 3D laser scanning technology with the verticality detection of piers, used the advantages of 3D laser scanning to indirectly measure the verticality of piers, and obtained the verticality deviation of piers. The above research focuses on the feasibility of 3D laser scanning applied to the measurement of pier perpendicularity. The method used to deal with the perpendicularity of the pier is relatively basic, and the calculation method of the perpendicularity deviation is not elaborated in detail. The obtained perpendicularity of the pier is only based on the deviation values of several pier sections, so the perpendicularity is not accurate. Based on the research background of the hollow thin-walled rectangular high pier, starting from all the point cloud data of the pier, the deviation value of the characteristic points of each horizontal section of the pier is calculated by the automatic algorithm, and the accuracy of the algorithm is verified by the BIM model, and the perpendicularity of the pier is studied in depth.

2. BASIC PRINCIPLE OF PIER VERTICALITY DETECTION

The hollow thin-walled rectangular pier has very strong geometry, so the problem of finding the perpendicularity of the pier in reality can be transformed into the problem of finding the center line of three-dimensional structure in geometry. The line is made up of numerous points. In mathematics, it is much easier to find the coordinates of the points than to find the three-dimensional curves directly. Therefore, the author uses the dimension reduction method to convert the problem of finding the three-dimensional center line of the pier into the problem of finding the plane center point, which is the characteristic point of the horizontal section of the pier. The pier is cut into several small rectangles according to the horizontal direction, and then the geometric principle is used to solve the centroid of the rectangle. Finally, the distance between the centroid of each section and the theoretical center point is obtained, that is, the deviation value of the pier.

The solutions to the problem of pier perpendicularity on the geometric level are given above. A point cloud is a collection of numerous points with three-dimensional coordinates. When processing point cloud, it can be roughly divided into three stages: data preparation, data analysis and result analysis. See Figure 1 for data processing flow chart.

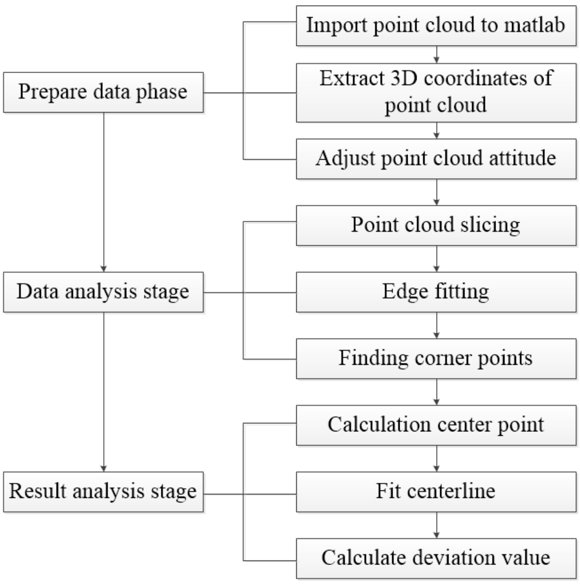


Figure 1. Data processing steps

3. POINT CLOUD DATA COLLECTION AND PREPROCESSING

3.1 *Point cloud data collection method*

The point cloud data needed by the Research Institute comes from a highway bridge under construction. The bridge pier is 66.53m high. See Fig. 2 for site scanning of piers. It can be seen from the figure that there must be deviation in the process of segmental pouring of piers. The traditional method of measuring the perpendicularity of piers can not fully reflect the deviation of piers. 3D laser scanning technology can fully capture the surface characteristics of the structure, give the structure location parameters, and make up for the shortcomings of single point measurement of total station.

In order to ensure the accuracy of scanning, six stations and three groups of target ball points are set when the pier is scanned by a method such as x-330 scanner. As shown in Figure 3. Survey stations 1-6 are around the high pier and about 30m away from the high pier. Three sets of target balls are placed between six stations. The first group of target balls kept intervisibility with the test station 1.2. The second group of target balls kept intervisibility with the measuring station 1.2.3. The third group kept intervisibility with the measuring station 3.4.5.6. In this way, at least one set of target ball point cloud data can be collected for each station, which is convenient for point cloud splicing.

Figure 2. Field scan

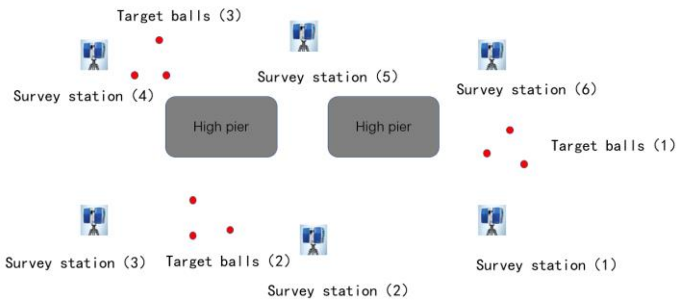
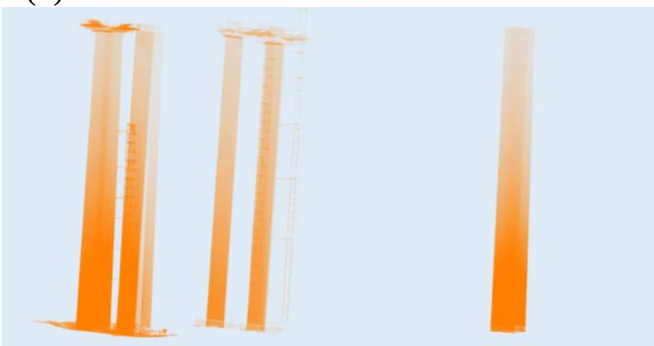


Figure 3. Scanning scheme

3.2 *Point cloud model point cloud data preprocessing*

The data collected from field work contains a lot of noise that can not be used for research, such as fence point cloud at the bottom of pier, tower crane point cloud, etc. The original data of point cloud is shown in Figure 4 (a). When analyzing the perpendicularity of the bridge pier, additional miscellaneous points will certainly have a certain impact on the algorithm, so it is necessary to reduce the noise of the point cloud. There are two common noise reduction algorithms, namely statistical filtering algorithm and radius filtering algorithm. Lu et al. (2019) made a comparative analysis on the noise reduction effect of the two methods. For the pier structure, the statistical filtering algorithm can better complete the noise reduction work, but due to the limitations of the algorithm itself, the point cloud of the auxiliary facilities cannot be removed, so it is necessary to import the point cloud into Geomagic to manually delete the noise, and the point cloud is as shown in Figure 4 (b).



a. Point cloud raw data   b. point cloud after processing

Figure 4. Point cloud processing

4. POINT CLOUD DATA PROCESSING

4.1 *Extract segment center point*

The initial position of the point cloud in the coordinate system is not conducive to the calculation of the center point of the segment. Before extracting the center point of the segment, the attitude of the pier needs to be adjusted so that the vertical direction of the pier is parallel to the Z coordinate axis. Firstly, the point cloud is imported into Matlab, and the rotation formula is used to adjust the point cloud

$$\begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta & 0 \\ 0 & -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 & \sin\theta & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\theta & 0 & \cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 & 0 \\ \sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} \quad (3)$$

Formula (1) (2) (3) is the rotation formula around the x, y, z coordinate axes. Where, x' y' z' is the coordinate value after rotation, x y z is the coordinate value before rotation, and θ is the angle to be rotated.

The point cloud is divided into 308 segments, each segment is 0.216m high. The point cloud of pier section is shown in Figure 5 (a). The Z coordinate of segment point cloud is eliminated, and the 3D point cloud data is reduced to 2D. Extract the point cloud on any side of the rectangle, as shown in Figure 5 (b). You can choose the line function as the fitting curve, because the point cloud is approximately near a straight line, that is

$$p(x) = a_0 + a_1 x \quad (4)$$

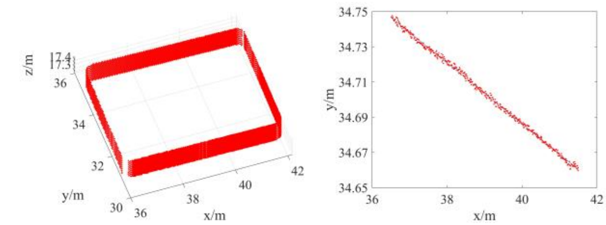
In formula (4), $p(x)$ is the polynomial to be fitted, a_0 nd a_1 are polynomial coefficients.

The point cloud data is taken into the normal equation of polynomial fitting:

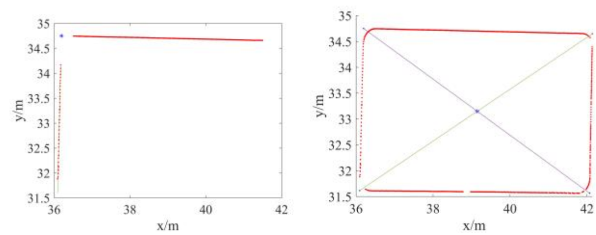
$$\begin{bmatrix} m+1 & \sum_{i=0}^{m} x_i & \cdots & \sum_{i=0}^{m} x_i^n \\ \sum_{i=0}^{m} x_i & \sum_{i=0}^{m} x_i^2 & \cdots & \sum_{i=0}^{m} x_i^{n+1} \\ \vdots & \vdots & & \vdots \\ \sum_{i=0}^{m} x_i^n & \sum_{i=0}^{m} x_i^{n+1} & \cdots & \sum_{i=0}^{m} x_i^{2n} \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ \vdots \\ a_n \end{bmatrix} = \begin{bmatrix} \sum_{i=0}^{m} y_i \\ \sum_{i=0}^{m} x_i y_i \\ \vdots \\ \sum_{i=0}^{m} x_i^n y_i \end{bmatrix}, \quad i = 1, 2, \ldots, n \quad (5)$$

In formula (5), M is the number of point clouds to be fitted, and N is the number of polynomial terms.

If we solve a_0 and a_1, we will get the fitting line equation of an edge. The linear equations of the other three sides are obtained in turn, and then the linear equations of the adjacent sides are combined to obtain a corner of the rectangle, as shown in Fig. 5 (c). After obtaining four corner points, use the known two diagonal points to solve the diagonal equation, and then set up the diagonal equation to get the center point of this section, as shown in Figure 5 (d).



(a) Point cloud of pier section (b) point cloud fitting of side



(c) Point cloud corner of pier segment (d) point cloud center of pier segment

Figure 5. Data analysis stage diagram

4.2 *Analysis of perpendicularity deviation*

The center point of the section represents the actual center position of this section of the pier. Figure 6 shows the plan of the cloud at the pier. The blue point represents the center point of the pier, and the red point represents the cloud at the pier. Figure 7 is the fitting diagram of the center line, the blue far point represents the center point of the pier section, and the red represents the fitting center line. It can be clearly seen from the figure that the deviation of the pier. The actual center line of the pier is an irregular curve. When the construction height of the pier does not reach 40m, the deviation value does not change significantly. When the construction height of the pier reaches 40 m, there will be a large deviation and the deviation value will change significantly, and then some correction will be made in the construction process.

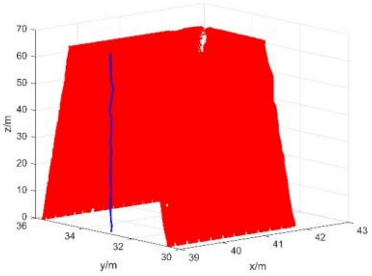


Figure 6. Point cloud section of bridge pier

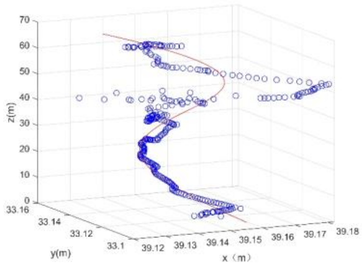


Figure 7. Centerline fit

Due to the lack of theoretical center line as a reference, it is impossible to obtain the deviation value of each section of the pier. The author takes the average value of 20 points at the bottom of the pier as the theoretical center point, based on which the deviation analysis is carried out.

Table 1 shows the coordinates of the bottom 20 center points, the mean values in X direction and Y direction respectively.

Table 1. Coordinates of pier center point

number	X/m	Y/m	number	X/m	Y/m
1	39.1503	33.1 234	11	39.1538	33.1187
2	39.1519	33.1 227	12	39.1536	33.1186
3	39.1522	33.1 228	13	39.1548	33.1182
4	39.1523	33.1 227	14	39.1542	33.1167
5	39.1527	33.1 214	15	39.1543	33.1161
6	39.1548	33.1 161	16	39.1543	33.1155
7	39.1529	33.1 206	17	39.1545	33.1149
8	39.1527	33.1 214	18	39.1546	33.1145
9	39.1528	33.1 202	19	39.1548	33.1138
10	39.1539	33.1 192	20	39.1552	33.1132

$$\overline{X} = \frac{1}{n}\sum_{i=1}^{n} X_i = 39.15$$

$$\overline{Y} = \frac{1}{n}\sum_{i=1}^{n} Y_i = 33.12$$

The point (39.15, 33.12) is the theoretical center line of the pier, and the equation of the center line of the pier is as follows:

$$\left.\begin{matrix} X = 39.15 \\ Y = 33.12 \end{matrix}\right\} \quad (6)$$

The distance between a point and a line can be obtained by knowing the line equation. Because the straight line is parallel to the Z coordinate axis, in order to simplify the calculation process, the length of the straight line is set to 1 m, and the distance from the center point to the theoretical center line is obtained by using Helen formula

$$p = (a+b+c) \div 2$$

$$S = \sqrt{p(p-a)(p-b)(p-c)} \quad (7)$$

$$h = 2S \div c$$

In formula (7), a, b and c are the three side lengths of the triangle, S is the area of the triangle, and H is the height of the triangle, that is, the deviation value.

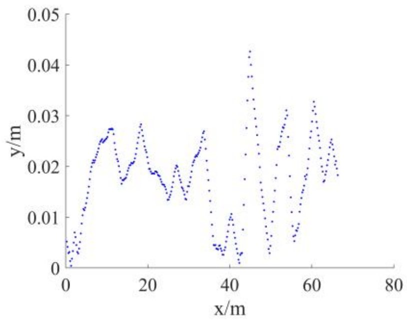
In order to facilitate observation, the deviation figure 8 of pier perpendicularity is obtained after the theoretical center line is set to zero.

Figure 8 (a) shows the distribution of the deviation values along the height. It can be seen from the figure that when the height of the pier is less than 10m, the deviation value of the pier is within 1cm, and then the deviation value expands with the increase of the height of the pier. When the height of pier reaches 30 m, the deviation of perpendicularity is unstable and fluctuates obviously. When the construction height reaches 45m, the maximum deviation occurs.

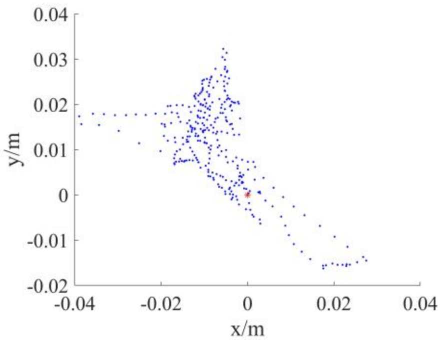
Figure 8 (b) is the top view of pier deviation. It can be seen from the figure that the deviation values of bridge piers in the transverse direction and along the bridge direction are within 3cm. The inclination of the pier is not along the direction of the transverse bridge or along the bridge, but in both the longitudinal and transverse directions, and the deviation trend is relatively uniform.

Figure 8 (c) shows the deviation values of piers in the transverse direction. When the height of bridge pier is within 50m, the deviation value of transverse bridge pier is small and the fluctuation of deviation value is small; when the height of bridge pier exceeds 45m, the fluctuation range of deviation value becomes larger.

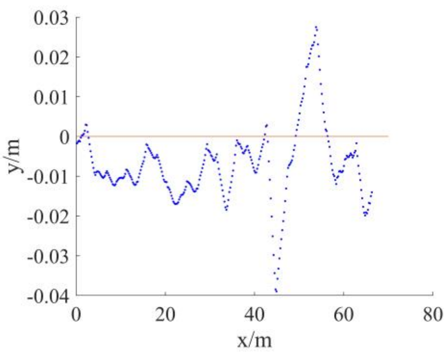
Figure 8 (d) shows the deviation values of piers along the bridge. In the whole process of pier construction, the deviation value is unstable and fluctuates greatly.



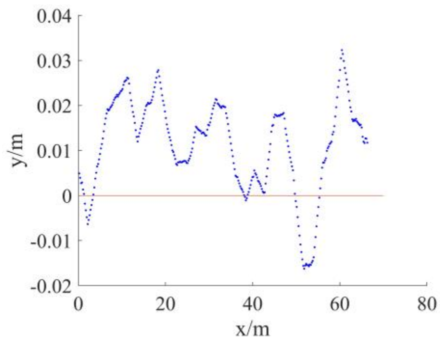
(a) Distribution diagram of deviation extension height



(b) top view of pier deviation



(c) Deviation in transverse direction



(d) deviation in longitudinal direction

Figure 8. Deviation analysis chart

(Note: the x-axis in figure (a) (c) (d) represents the pier height, and the y-axis represents the deviation value. Figure (b) x axis represents the deviation value in transverse direction, Y axis represents the deviation value in longitudinal direction, and red asterisk represents the theoretical center point)

According to the formula, the perpendicularity of 308 characteristic points of the pier is calculated, as shown in Figure 9.

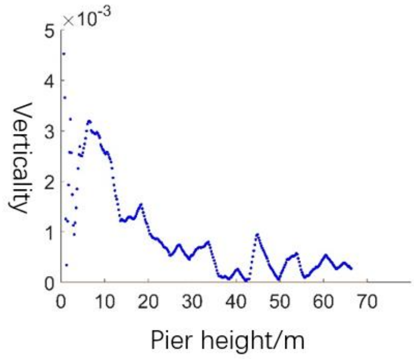


Figure 9. Verticality of pier

It can be seen from figure 9 that the perpendicularity of piers tends to decrease with the increase of pier height. The perpendicularity of the bottom of the pier is larger, because the height difference of the characteristic points at the bottom of the pier is small, and the perpendicularity is larger under the same deviation. Compared with Figure8 (a), it can be seen that the place with the largest deviation is not necessarily the place with the largest perpendicularity.

4.3 *Accuracy verification*

The deviation values of the piers in the transverse and longitudinal directions are calculated by the above algorithm, and the maximum deviation values of the piers are calculated, and the variation diagram of the perpendicularity of the piers with the height of the piers is given. In order to verify the accuracy of the above algorithm, the author analyzes the accuracy of the automatic algorithm by using the characteristics of BIM model, such as strong interaction and high modeling accuracy.

The BIM model of the pier is imported into the Geomagic point cloud processing software, and the point cloud and BIM model are aligned with the bottom of the pier as a reference. The deviation between point cloud and BIM model is calculated by the 3D analysis function of the software, as shown in Figure10. The maximum deviation of the pier calculated by the algorithm is 0.046m, and the maximum deviation obtained by the automatic analysis of Geomagic is 0.049m, the error rate is about 6%, which meets the accuracy requirements.

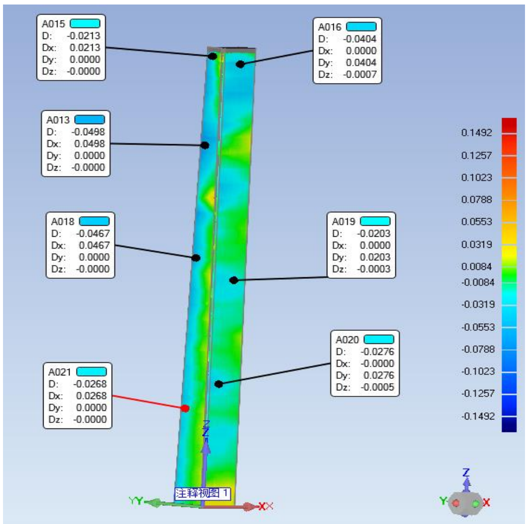


Figure 10. Comparison of 3D deviation

5. CONCLUSION AND PROSPECT

3D laser scanning technology can obtain all geometric information of bridge pier structure. In this paper, the geometric characteristics of the rectangular thin-walled pier structure are analyzed, the perpendicularity of the high pier is analyzed, and the method to analyze the perpendicularity of the pier is put forward. According to the data relationship, the following conclusions are obtained:

1. Through 3D laser scanning to obtain point cloud data, the perpendicularity deviation of each height point of pier can be obtained. The deviation of perpendicularity increases with the increase of pier height, and the deviation is unstable finally.

2. The variation range of the deviation value of the pier is small in the direction of the transverse bridge (the long side of the rectangular pier) and large in the direction along the bridge (the short side of the rectangular pier).

3. The inclination of the pier is roughly along a diagonal direction of the rectangular pier.

4. The maximum horizontal deviation of the characteristic point of the pier is not necessarily the maximum perpendicularity of the pier, and the occurrence of the maximum horizontal deviation is random and unpredictable, so the accuracy of the result obtained by measuring the perpendicularity of the pier with the total station single point is insufficient.

After calculating the actual center line of the pier, using the actual center line data to reverse modify the modeling parameters of the BIM model of the pier, the BIM model corresponding to the actual state of the pier is obtained. Record the pier perpendicularity data under each working condition, and provide information support for the future bridge maintenance. The method of modifying BIM model with real 3D data is not only suitable for bridge piers. Bridge abutment, precast beam and other structures can be modified, but the corresponding algorithm needs to be developed to extract structural parameters automatically and efficiently, and more efforts need to be made in this respect.

6. ACKNOWLEDGMENTS

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