Slab Diflection Analysis using Digital Close-Range Photogrammetry

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Abstract: ***In the construction field, deflections experienced during construction are costly and preventable. However, inspection programs employed today cannot adequately detect and manage deflections that occur on construction sites because current inspection programs are based on measurements at specific locations and times and are not integrated into complete electronic models. Testing and measuring are important examples of determining slabs deflection. Sometimes they require accurate measurements depending on the issue at hand. Close-range photogrammetry is one of the most important and accurate measuring techniques that does notrequire direct contact withan object. Additionally, most of the procedure for close-range photogrammetry can be carried out in the office. The objective of this paper is to present the use of close-range photogrammetry as a useful and accurate measuring tool for determining and analyzingslabs deflection in the construction field. We have applied close-range photogrammetry to a practical case in a construction site to demonstrate its application to the issues of construction slabs deflections.***

Keywords: Digital close-range photogrammetry; Measurements; Analysis; Construction; Concrete slab deflection

1. Introduction

Defects or failures in constructed facilities can result in very large costs. Even minor defects may require re-construction, and facility operations may be impaired, resulting inincreased costs and delays**[10]**. Effective managers ensure that a job or project is completed correctly the first time.

Defects experienced during construction are costly and preventable. However, inspectionprograms employed today cannot adequately detect and manage defects that occur on construction sites because current inspection programs are based on measurements at specific locations and times and are not integrated into complete electronic models. Emerging sensing technologies and project modeling capabilities are advancing the development of a quality formalismthat can be applied to active quality control (QC) on construction sites **[2]**.

Current approaches toQC on construction sites are not as effective as they could beat identifying defects early in the construction process. As a result, defects can go undetecteduntil the later phases and even the maintenance phase of construction. When detected late,defects can have costly ramifications. It has been noted that six to twelve percent of the construction cost iswasted due to repairing defective components detected late in the construction phase **[4]-[11]**and that five percent of the construction cost is wasted due to repairing defective components detectedduring the maintenance phase. Twenty to forty percent of all of the site defects referenced abovecan be attributed to theconstruction phase**[16]**.

According to a study by**[15]**, 54% of all construction defects are related to human factors suchas unskilled workers or insufficient supervision of construction work. Furthermore, **[15]**found that twelvepercent of construction defects are due to material and system failures. These statisticsemphasize the importance of effective inspection to achieve higher construction quality. In addition, careful inspection during construction has been identified as one of the most importantfactors in preventing structural failures during construction **[19]**.

The status of the work being conducted at construction sites changescontinuously as the constructionprojects evolve over time. Current surveying and QC approaches are not effective because they only provide data at specific locations and times to represent the construction work. Additionally, the generated data are interpreted manually and are not integrated electronically into the projectdesign and schedule. Consequently, project managers do not receive complete and accurateinformation about the current status of the construction work. This incomplete information limits a project manager’s ability to easily identify and manage defectsand actively control and manage construction projects. There have been recent advances in generating 3D environments using laser scanning technologies and in acquiring information about as-built environments. These advances create an opportunity to explore the technological feasibility of frequently gathering complete andaccurate 3D and material quality data about as-built construction.

Current construction practicesutilize as-built records in the form of site photos annotated with detected information for QA and defect investigation. At construction sites, site engineers routinely take site photos of an ongoing project to keep timely records for documentation. Recent advances in electro-optical technologies have empowered off-the-shelf digital cameras to obtain high quality images while maintaining the portability and convenience of picture taking**[5]**. With site photos, a particular state of the site situation, including building products, construction resources and site layout, can be easily captured and saved **[6]**.

Utilizing photos and photography techniques to cater to the needs of problem solving has been applied in a variety of disciplines. In regard to applications in construction engineering and project management, **[13]**investigated the actual site progress by contrasting the photo-generated 3D site models to the as-planned virtual reality scenes.

[17]employed construction site photos to implement a panorama view of the site situation for better site supervision. Site photos have also been analytically processed by contractors to measure 3D geometries of buildings adjacent to the construction site to preserve evidence against potential construction-caused damage claims**[14]**. In addition, **[5]** and **[6]** advanced a time-lapse photography technique for project management by recording activities of a construction site with a series of photographs and enabling the playback at optional frame rates. Dealing with photos is just a way to gather information and measurementsthat provide only 2D information.Three-dimensional measurementsare in great demand forquality measuring tools in the construction field. One of the most important 3D measuring techniques is digital close-range photogrammetry.

Digital close-range photogrammetry is a measurement techniquethat is used to acquire 3D spatial information that is captured on images about an object. Digitalclose-range photogrammetry derives measurements from digital images rather than measuring the object itself. Photogrammetry offers several advantages over the conventional and well-known land surveying methods. First, it is possible to map objects using photogrammetry that are unreachable or too dangerous to reach on foot. Second, photogrammetry provides a flexible framework because all data needed to perform the mapping can be obtained immediately, permanently and at a fixed cost with one photographic acquisition**[8]**. The mapping process can then be implemented at any time thereafter. Cost-effectiveness is a third advantage of photogrammetry in comparison to conventional surveying or geodetic techniques. Finally, photogrammetry provides several kinds of digital products such as 3D models, digital maps, digital elevation models and orthoimages. Due to these capabilities, digital close-range photogrammetry is appropriate for a variety of applications ranging from industry to archaeology **[12]**. Digital close-range photogrammetry is used mainly for obtaining 3D measurements of photographed objects.

2. Practical Slab Deflection Investigations

During a construction project, some defects may arise. Thequality team may face critical issues that require measurements in two or three dimensionsfor the team to make an accurate and timely decision. The measurements were obtained by using digital close-range photogrammetric techniques. The used camera characteristics and the used photogrammetric software will be presented in details hereunder. Also, a practical defect issue (slab deflection)thatrequired 3D measurements will be presented too.

The Used Camera

An Olympus Camera C-2/D-230 with 5.5 mm focal length lens has been used for both practical cases. The camera can take photos at four different resolutions, but 1600 x 1200 was used during this investigation. Some of its technical specifications are as follow:

- Effective number of pixels: 1.96 million
- Imager: 1/2.7 inch CCD solid-state image pickup, 2.14 million pixels.
- Lens: Olympus lens 5.5 mm, F2.8 (equivalent to 36 mm lens in 35 mm format), 5 lenses in 4 groups including 1 glass aspherical lens.
- Digital tele: .6x, 2x, 2.5x (3.2x, 4x, 5x in SQ2 mode).
- Programmed auto: F2.8, F5.6, F9.1,1/2 – 1/800 sec. (with mechanical shutter), 2 – 1/800 sec. in Slow Synchronisation mode. QuickTime Motion JPEG image mode: 1/30 – 1/10,000 sec.
- Sensitivity Auto: (ISO 100 – 400).

Used Software

The core of any good photogrammetric package is a powerful bundle adjustment algorithm. A bundle adjustment is a complex algorithm that optimizes all the data presented (camera information, user and system photo markings, etc) to indicate the best positions and angles of the camera at time of exposure, and the positions of the 3D data points. The software used in this study was PhotoModeler version 3 from ESO system inc.**[9]**. Nowadays, a new version of PhotoModeler is released (version 6) which offers automated camera calibration with sub-pixel measurements, which was not available at the time of study.

Eos' Bundle Adjustment provides camera self-calibration and full error propagation. PhotoModeler does some camera self-calibration, during its 3D processing, when there are sufficient marked points on the photographs. A less than ideal calibration will still produce good models when the model has many points in it. With Self-Calibration PhotoModeler makes minor adjustments to the camera parameters on a per-photograph basis to account for changes in focal length, principal point and lens distortion as the camera lens is focused.

PhotoModeler uses a standard lens distortion formulation with four parameters, which is a subsample of the parameter set introduced by**[3]**. The following formulas describe how PhotoModeler applies the distortion corrections. The compensation for any point (x, y) of the image surface is given by**[18]**:

$$xc = x + rx + px$$

$$yc = y + ry + py$$

Where xc, yc is the corrected image point, rx is the x-component of the radial lens distortion correction, ry is the y-component of the radial lens distortion correction, px is the x-component of the decentering lens distortion correction, and py is the y-component of the decentering lens distortion correction. The formula used by PhotoModeler for r (redial lens distortion) is given by:

$$r = K1 * r^2 + K2 * r^4$$

Where $r^2 = x^2 + y^2$

The formulas used by PhotoModeler for decentering lens distortion are:

$$px = P1 * (r^2 + 2 * x^2) + 2 * P2 * x * y$$

$$py = P2 * (r^2 + 2 * y^2) + 2 * P1 * x * y$$

Photogrammetric Procedure

Several images were taken using the used cameras in order to fulfill the requirement of this version of the PhotoModeler software. The photos were imported and the points were marked in one of the photos and then referenced in the other photos. Several repeats were made to achieve the best accuracy. Cameras self-calibrations were done during the photogrammetric solution to achieve the best accuracy.

PhotoModeler does scaling in different ways, scale only, scale & rotate, 3 points. Scale & rotate was used in this study. To define the model scale a distance between two points must be known and three points should be defined for the coordinates system, origin point, x-axis, and Y-axis. The Z-axis is the perpendicular to the X-Y plane from the origin point.

Concrete Slab Deflection

A limited value of slab deflection is expected in all construction projects. This value is dependent on the use of steel bars, the slab thickness and the clear span. Slab deflection is very dangerous if its value exceeds the allowable structural deflection value. The allowable structural deflection value is L/250, where L is the clear span. The architectural allowable deflection value is L/360, which is based on concerns about whether the deflection is notable by the naked eye or not.

During a routine inspection, deflection in part of the second-floor slab in one of the construction projects was noted from a distance by the naked eye. The issue was critical and dangerous, and immediate action needed to be taken to investigate the problem. The defective slabwas inspected, and a quick decision was made to obtain accurate surveying measurements of the deflected slab to find out the value of the deflection at each position on the deflected part of the 2nd floor.

The surveying measurements could have been obtained by taking direct or indirect measurements. It wasdecidedto take indirect measurements using digital close-range photogrammetry becauseclose-range photogrammetry is an accurate technique, it is low cost, and the results can be obtained and analyzed in the office, and the photos can be used for documentation purposes.

Several photos were taken from different locationsto ensureeffective coverage and accurate results using armature camera. The photos were taken of the top and the bottom of the slab. Photos were also taken from outside of the building to help combine the measurements from the top and the bottom of the slab.Natural texture targets points were marked and referenced on the photos for the top and bottom surfaces of the deflected slab. The photogrammetric results (Spatial coordinated of the marked points) were exported in a text file for further analysis. The results were imported,analyzed, and drawn using Surfer software, version 8. Figures 1-5 show the contour maps, 3Dcontour maps, anda vector map for the deflected slab.

The deflection values that were obtained from the photogrammetric measurements were very concerning. The maximum deflection value was 6.4 cm, which is approximately double the allowable structural deflectionvalue limit (L/250) and three times the allowable architecturalstructural deflection value limit (L/360).

We identified different causes for the slab deflection in this case. The most significant cause was the early removal of the formwork, especially if the slab design is critical.The slab's formwork had been removed after only nine days instead of the twenty-eight days that were required for the slab to reach 100% of the concrete comprehensive strength according to the projects' specifications.Moreover, the slab had been loaded by the upper slab formwork and concrete was poured without propping the deflected slab. The load above the deflected slab consisted of the weight of the upper slab framework, the weight of the concrete slab and the weight of the laborers working on the third-floor slab. The deflected slab had been loaded by about 850 Kg/m^2 which is considerably more than the deflected slab's design load.This discrepancy between the design load and the applied load would lead to a significant deflection, even if the slab formwork had not been removed early.

As seen in the figures below, the top and the bottom deflection contour maps are not identical. The contours for the top and bottom are almost the same in the front part of the deflected slab, but the contours are different in the back part of the deflected slab. The difference in the contour mapsis because the top surface of the slabwas subjected to the poured concrete levels, meaning that the thickness of the slabwas not uniform. Additionally, the concentration of the bluecolor in Figures 1 and 2 indicates the locations on the slab that had no deflection.These locations wereadjacent to the columns or in a column strip with small clear spans. Figures 3 and 4 show the contour maps of the slab's top and bottom in 3D.

The vector map (Figure 5) shows the direction of the deflection.The tails of the arrowsindicate the high points, andthe heads of the arrows indicate the low points.

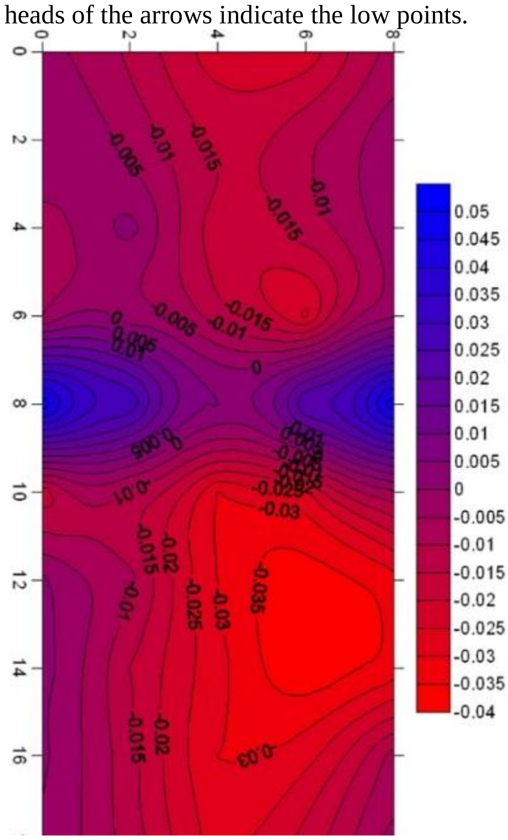

Figure 1: Contour map (top)

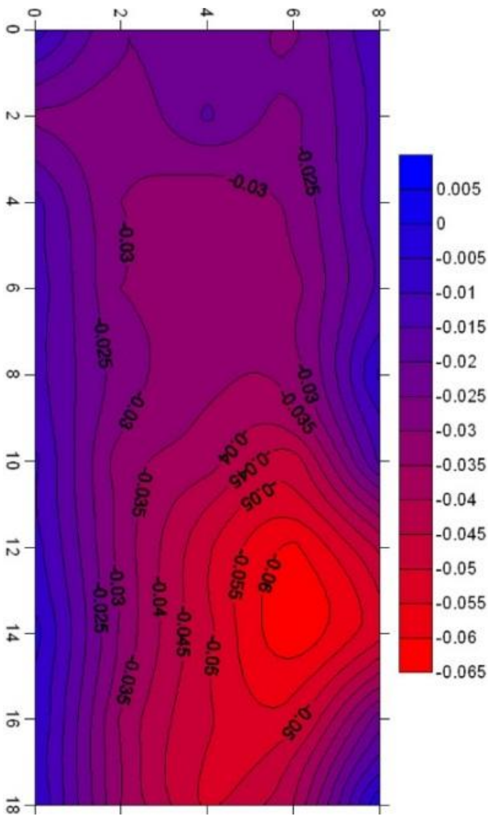

Figure 2: Contour map (bottom)

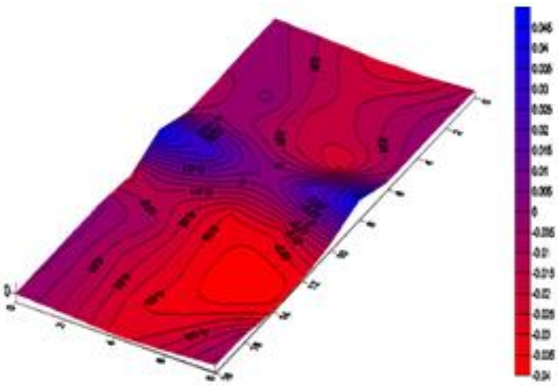

Figure 3:3D Contour map (top)

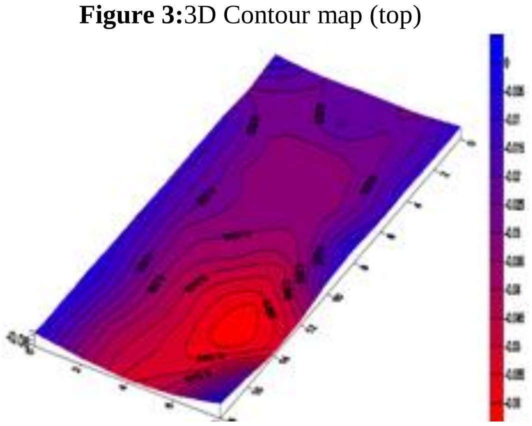

Figure 4: 3D contour map (bottom)

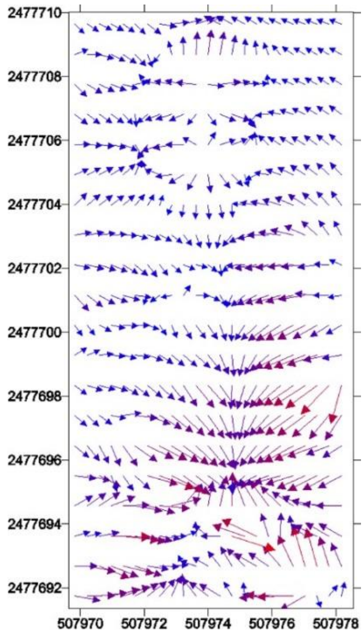

Figure 5: vector map (Bottom)

3. Conclusion

The construction field is full of critical issues that arise from time to time. Some of these issues require accurate 3D measurements to check, investigate, and test the on-site activities or the provided materials. Digital close-range photogrammetry is an accurate measurement technology that has been widely used in several applications that require 3D measurements. A practical case has been presented in this research to show the advantages of using digital close-range photogrammetry as a slabdeflection analysis 3D measuring tool. This technique can also be applied toother issues that may need accurate 3D measurementsranging in size from a single millimeter to an entire structure. The results from this study show that digital close-range photogrammetry can extract measurement values using 2D contour maps, 3D contour maps, and vector maps. There are also other presentation media, such as 3D computer models, animations, image maps, and surface maps that can be produced from the application of digital close-range photogrammetry butwere not presented in this research.

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