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Application of Photogrammetric Monitoring on a HDD Installation in the City of Winston, Oregon

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ABSTRACT: The City of Winston's Parkway Lift Station Efficiency Upgrade project included the installation of 800 feet of 14-inch diameter high-density polyethylene pipe to convey flows from the lift station to the existing sanitary sewer collection system. The alignment of the sanitary force main crossed beneath several mature developed residential backyards and in close proximity to house footings, raised decks, patios, and beneath one above-ground pool. Due to the topography, confined work space, and existing surface features, horizontal directional drilling was determined to be the most suitable construction method for the installation of the force-main. While the potential for surface movements were minimal due to the soil conditions, this project provided an ideal opportunity to conduct a full-scale field evaluation of photogrammetry for monitoring surface movements. Preconstruction and post-construction surveys were undertaken by conventional survey and photogrammetric methods. This paper provides a brief description of the photogrammetric process applied to the monitoring of ground surface movements on the Parkway Lift Station force-main project. A comparison of conventional and photogrammetric measurements is provided along with conclusions and lessons learned. It is hypothesized that the photogrammetric methods utilized on this project could provide more cost effective and efficient means of monitoring the surface effects from trenchless installations in built up urban environments.

1. INTRODUCTION

Underground construction involving HDD and slip-lining was employed to replace two sanitary sewer force-mains running through the backyards of a residential neighborhood in Winston, Oregon. The close proximity of the new HDD installation to house footings, landscaping features, and backyard amenities was a public relations concern for the City. Even though the pipeline would be installed at a depth ranging from 20 to 30 feet below the ground surface through a rock formation (low quality mud stone), the City and residents were fearful that the "trenchless" HDD construction would create ground settlement or heave that could damage their homes. To address these concerns, a conventional, survey based, settlement monitoring program was specified for the project. The project engineer was also interested in evaluating a settlement monitoring program using the photogrammetric methods presented at the 2011 No-Dig Show in Washington DC (Lueke et al. 2011). It was thought that the project provided an exceptional opportunity to compare the photogrammetric method against conventional survey methods to determine its validity for future projects with similar concerns. The paper provides a summary of the photogrammetric method utilized to conduct the analysis and a comparison to the results obtained by conventional survey methods.

2. PROJECT BACKGROUND

After completing a new wastewater lift station in 2005, the City of Winston, Oregon (population 5,370) anticipated a long lived, relatively trouble free, pumping facility. Unfortunately, their new station turned out to be more of a liability than an asset. High electrical costs, safety issues, excessive pump maintenance, pump failures, and hydraulic surges at the WWTP were just a few of the problems being experienced.

After a new public works director and consulting engineer looked into the problems, it was determined that the lift station was sized properly for Oregon's wet winters, but not for the normal dry weather pumping conditions that exist for nearly 2/3rds of the year. Correcting the oversized station would require more effort than simply replacing oversized pumps with smaller units. The upgrade would also require a new electrical and control system and two new force-mains, each sized to handle the low and high flow conditions, respectively. Because the station was located in a densely developed neighborhood, the new pipelines could only be located in an existing 15 foot wide easement that ran directly adjacent to the residential housing units. Decks, fencing, pools, jacuzzis, and landscaping features encroached across most of the easement at each property, making an opencut installation virtually impossible.

Trenchless solutions were the obvious answer, and plans were prepared to install a new 14-inch diameter pipeline using HDD construction while the smaller 8-inch diameter pipeline would be installed in the old force-main by methods of slip-lining. The close proximity of the new HDD pipeline to home foundations and property improvements required that the City meet with and address the neighborhood concerns. The most pressing concerns raised by the residents were how the construction could impact their property and if the trenchless method would create settlement issues while the contractor was "boring" adjacent and below their houses. While settlement in the rock formation was not anticipated, a settlement monitoring program was proposed to satisfy the residents and provide the City with data that would refute any future claims for damages after the project was completed. The photogrammetric method was proposed as a test case and would be secondary to the primary ground measurement method, conventional surveying. Both methods were acceptable to the residents and successfully demonstrated the City's commitment to address the neighboring homeowner's concerns. The project was bid in late 2011 and completed in the spring of 2012 by Professional Underground Services, Inc. out of Eugene, Oregon. Funding for the project was provided by the Oregon Department of Energy - Energy Efficiency and Conservation Block Grant and the Clean Water State Revolving Fund (CWSRF).

3. PHOTOGRAMMETRY

Photogrammetry is a remote sensing technique in which the geometric properties of objects and surfaces can be determined from photographic images (Mikhail et al. 2001). The method used in this project is more appropriately termed stereo photogrammetry, and it is capable of determining the location of points on objects and surfaces in three dimensions through analysis of two or more photos taken from different positions of the target area. The fundamental principal used in photogrammetry is triangulation. Knowing that light travels in straight lines, and how the light is bent as it passes through the camera lens to reach the film (or sensor on a digital camera), one can use the principles of trigonometry to mathematically solve for the positions of points of interest and create an accurate three-dimensional model of the subject or area in the pictures. Once the model of the subject area is created, accurate measurements can be made in Cartesian coordinates.

Photogrammetry has seen application in monitoring and measuring displacements in many civil engineering and survey applications. Brachman et al. (2010) utilized photogrammetry to investigate ground surface displacement in three dimensions during trenchless pipe replacement in stiff clay. Yilmaz (2010) investigated the performance of close range photogrammetry in computing the volume of a natural hill with an irregular shape, and compared the process to classical surveying methods. Rieke-Zapp et al. (2009) developed a photogrammetric method for mapping rock outcrops and other objects in the field for earth scientists.

Photogrammetry has many advantages over more traditional methods of monitoring ground movements including conventional rod and level, survey triangulation (total station), and GPS survey (Gili et al. 2000, Lueke et al. 2010); some of these are as follows:

1. Simultaneous measurement of all targets/surface points in the area monitored – all targets in the camera's field of view can be measured;
2. Fast measurements – each measurement set requires a minimum of two pictures (more are preferable), the measurement of all targets is completed in the time required to take the pictures;
3. Minimal equipment required – camera and tripod, with a computer to process the photos;
4. No specialized equipment required – typically the equipment required to monitor ground movements, a camera, is generally standard issue for a foreman or superintendent;
5. Minimal training required for operator – operator must be familiar with operation of camera and how to stage pictures for optimal area coverage;
6. Quick turnaround for results – after downloading pictures to the computer, software can analyze photos in a matter of minutes and provide Cartesian coordinates for all targets included in the photos; and,
7. Measurement without access to targets – measurements can be made without having to access the area where the targets are located.

Previous work by Lueke et. al (2011) determined in controlled laboratory or field evaluations, that photogrammetric methods reliably measured simulated surface heave events. The field trials determined that this process was both precise (repeatable) and accurate (correct). The results indicated that there was a high correlation between photogrammetric and leveling methods for measuring changes in the elevation of surface targets. When comparing the elevation change determined by leveling and photogrammetric methods, they are within approximately 0.04 inches (1 mm) of each other. It was concluded that the accuracy of photogrammetric methods to measure surface heave had the same accuracy as conventional rod and level.

4. FIELD INVESTIGATION

The Parkway Lift Station Efficiency Upgrade project provided the ideal situation to investigate the field application of the photogrammetric process developed by the researchers for monitoring surface heave associated with directional drilling. In previous work the process was vetted in a laboratory environment and under controlled simulated field applications. This would be the first application under actual field conditions. The proposed borepath alignment passed beneath eight backyards, containing a variety of potential obstacles and constraints for optimal camera and target positioning.

Data acquisition (surveying) using photogrammetry involves taking a series of photographs of the area of interest that capture a specific moment or stage of the installation, then developing a three-dimensional model of the area using photogrammetric software. By knowing at least one dimension within the area of interest, the model can be calibrated allowing for accurate measurements between points within the model. Measurements can be made in all three dimensions. For this process to work at least two photographs are required (i.e. stereo-photogrammetry). However, much greater accuracy can be achieved with additional photos taken from a variety of positions. The ideal situation is using a total of four photographs with their field of view concentrated on the center of the area of interest, with each line of sight separated by 90-degrees, and each camera positioned such that the line of sight from the camera makes a 45-degree angle with the ground (being horizontal). This would be considered ideal coverage and allow for the highest precision and accuracy in the resulting computer model. Applications in the field do not allow for this ideal configuration – and as such this was one of the aspects of the research under examination.

For our analysis, the areas of interest were specific locations along the proposed borepath where we wanted to measure potential ground movements because of existing surface structures or changes in borepath trajectory. On directionally drilled installations ground movements may result from ground loss or borehole collapse (settlement), or over-pressurization of the borehole or inefficient removal of soil cuttings (heave). The conventional means of collecting ground surface movements is by measuring targets installed perpendicular to the purposed borepath to develop a surface profile. For this research we installed two surface profiles at each monitoring location three feet apart along the alignment, each consisting of five targets separated by one foot, perpendicular to the borepath (Figure 1). Additionally, two control targets were added to each monitoring site, a sufficient distance away from the area of potential ground movements. These control targets would be used to tie the resulting photogrammetric models to the project datum, and to provide fixed reference points to compare subsequent measurements between models.

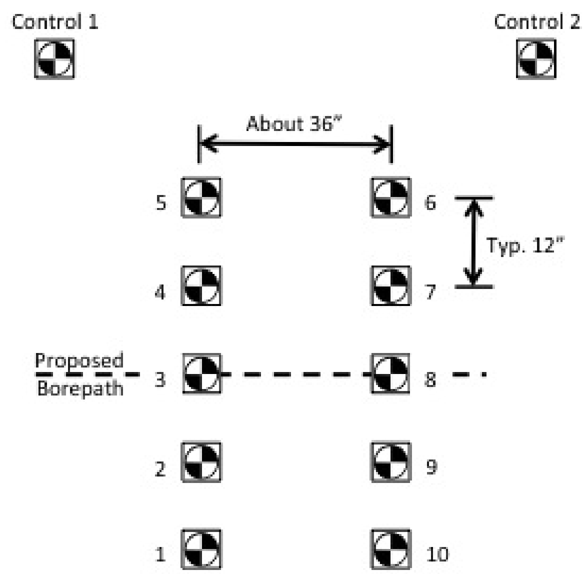

Figure 1. Typical Arrangement of Targets on Each Site

Targets used for this investigation consisted of square photo-reflective plates with white backgrounds and black markings. The plates were secured to aluminum rods to elevate them above the grass and vegetation. Wooden survey hubs were driven into the ground in the positions indicated by Figure 1, and then holes were drilled into the center of the hubs allowing for the insertion of the aluminum rods. The rods had stoppers at specific locations to allow for the consistent positioning of the target above the hubs. The survey hubs were driven flush to the ground and used for both the pre- and post-construction surveys. The elevated targets would be surveyed by photogrammetry, while the position of the hubs would be obtained by a conventional total station. While the actual position surveyed would be different, the relative position of each would be the same to allow a comparison of any ground movements.

Pre-construction surveys of the target sites were completed on September 22, 2011, and post-construction surveys completed on April 26, 2012. Pictures of the site and targets were then taken using a consumer-grade Canon Digital Rebel SLR camera with a 12-megapixel resolution and a 55mm focal length lens. Multiple photographs of each site were taken from a variety of angles and positions. While only four or five pictures were used to develop the model for each area of interest, we took upwards of 10 pictures per site and selected the photos that provided the best coverage to construct the computerized model. Each picture had to be framed such that all or the majority of all targets at a particular site were in the field of view of each photo taken. This was not entirely possible for each site due to vegetation and access, and for these sites more photos were required to construct the photogrammetric model.

Figure 2 provides a compilation of the photos utilized in the photogrammetric survey of one of the sites (site C-4). This set of photos illustrates some of the challenges experienced in data collection. For this site the deck prevented photos from being taken from one side of the targets. These photos were taken in the fall, while subsequent photos taken post-construction in the spring had a significant amount of vegetation beneath the deck that partially obscured the control targets. To calibrate the photogrammetric model measurements were used between targets 1 and 6, and 5 and 10 (Figure 1). One measurement was used to calibrate the model, while the other was used as verification once the scaling was completed.

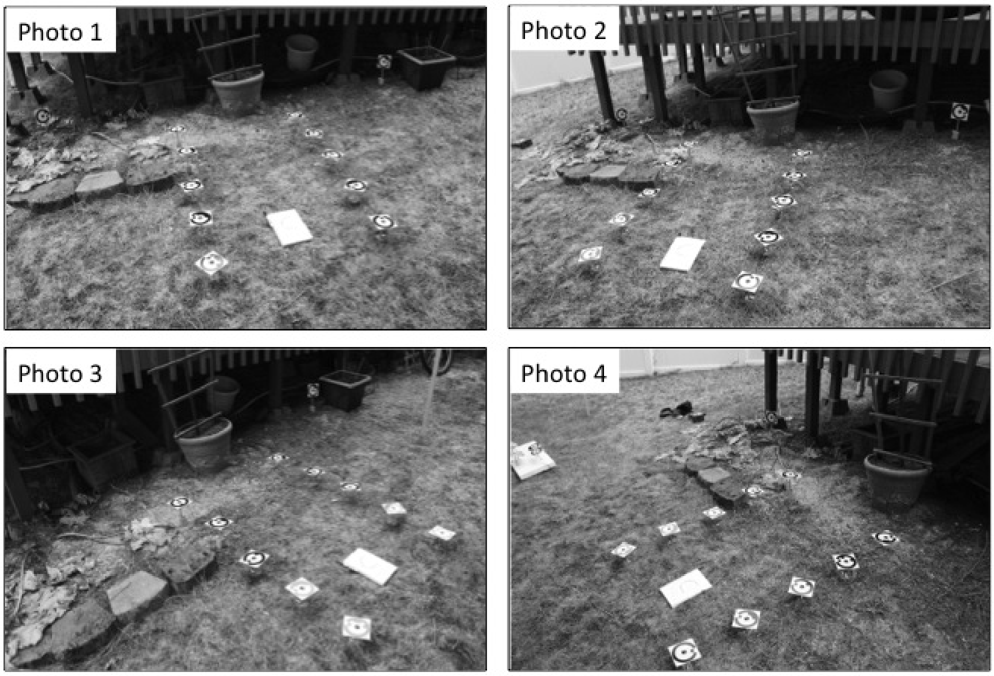

Figure 2. Photos Utilized to Build Photogrammetric Model of Site C-4

Six of the eight backyards were monitored with seven target sites (one backyard had two target sites A-0 and G-6). On completion of the post construction photos, only four of the sites were viable for constructing photogrammetric models (Table 1). Two of the sites were rendered invalid due to construction or activities of the homeowner, while site B-5 could not be modeled due to inconsistency in the control targets. Vertically orientated targets were generally used for the control points; however in photo set B one of the control points was setup accidently incorrectly with a horizontally orientated target.

Table 1. Summary of Photo Sets by Site

Site Photo Set September 22, 2011	Site Photo Set April 26, 2012	Site Code	Model Status
A	0	A-0	Targets destroyed during construction.
B	5	B-5	Control targets inconsistent.
C	4	C-4	Viable photo sets.
D	3	D-3	Viable photo sets.
E	2	E-2	Viable photo sets.
F	1	F-1	Viable photo sets.
G	6	G-6	Missing targets unable to set model orientation.

5. PHOTOGRAMMETRIC ANALYSIS

The three dimensional models of the target sites were created using the PhotoModeler software package, a commercially available photogrammetric processing application developed and distributed by EOS Systems Inc., Vancouver, British Columbia, Canada. PhotoModeler is a Windows-based software package that provides a user-friendly interface to conduct the photogrammetric analysis on consumer grade desktop computers, allowing the measurement and modeling of real world objects and scenes from photographs. Each target site was analyzed separately using their respective photographs.

Using the targets as common reference points between each photograph, PhotoModeler was able to construct a three-dimensional representation of the targets accounting for elevation and their relative position to each other. While we utilized "coded" targets (that are best described as concentric circles of unique patterns) to assist in automating the construction and analysis of the photo sites, manual target identification was utilized. This increased the processing time to about 20 minutes per site. The processing of the coded targets did not work due to the lighting conditions and resolution of the photos. Once the targets are identified on each photo, the three-dimensional model can be constructed in PhotoModeler. Figure 3 provides an example of the model created for Site C-4. This figure also illustrates the photos and position of the cameras utilized to construct the model.

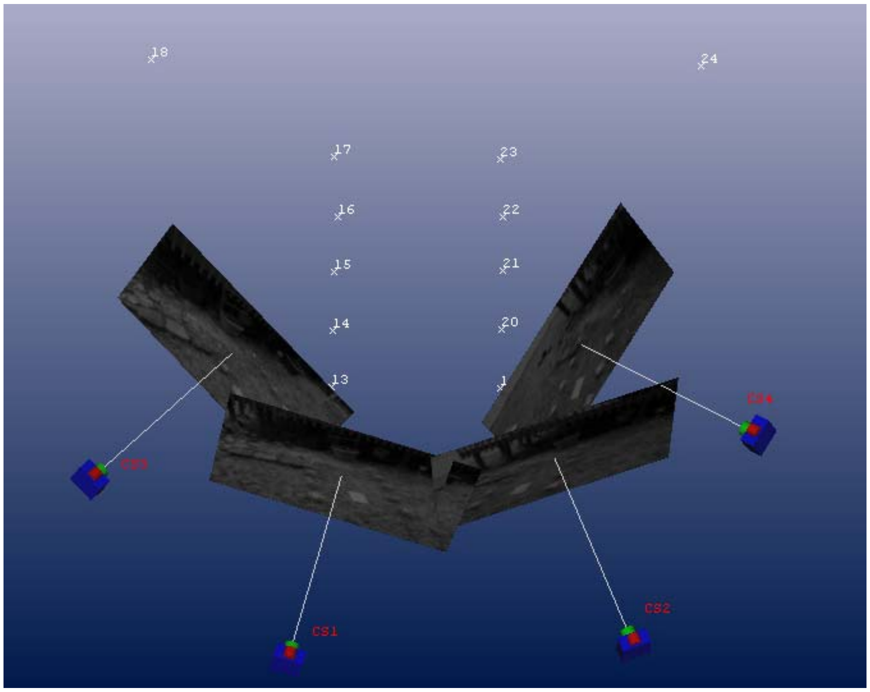

Figure 3. Three Dimensional Point Cloud with Camera Stations (Site C-4)

6. CONVENTIONAL SURVEY METHOD

Traditional land survey methods (Secord Order – Class I) were utilized for the ground monitoring analysis and comparison with the photogrammetric results. Pre- and post-construction data of each site (photo set) was performed by an experienced land surveyor and crew using Trigonometric Leveling. A Trimble S6 Robotic Total Station was used to run a closed level loop from known vertical control points beginning at the HDD launch side of the project, through all target sets, and ending on known vertical control points on the other side of the project. Excluding travel, each survey event required 2.0 worker days to complete including field work and data processing.

7. COMPARISON OF DATA

Pre- and post-construction data was processed for both survey and photogrammetric methods to determine the delta elevation for each target hub or coded target center. Data acquired from survey instruments was based on the center of the 2-inch by 2-inch wood hub, while the photogrammetric survey data was processed for the center of each "coded target" yielding elevation differences a known distance above the wood hub. Data comparisons shown in Table 2 are based on the relative elevation differences for pre- and post-construction data survey events for each method and its respective target.

Table 2. Comparison of Relative Difference between Pre- and Post Construction Settlement Monitoring Events for Conventional Survey and Photogrammetric Methods

	Site C		Site D		Site E		Site F	
Target	**Photo**	**Survey**	**Photo**	**Survey**	**Photo**	**Survey**	**Photo**	**Survey**
1	0.00	0.00	0.00	0.60	0.00	0.48	0.00	-0.12
2	0.05	0.12	0.04	0.48	0.06	0.36	-0.04	-0.24
3	0.00	0.00	0.03	0.36	0.01	0.24	-0.04	0.00
4	0.09	0.00	-0.03	0.48	-0.07	0.12	-0.04	-0.12
5	0.06	0.00	-0.01	0.36	0.01	0.00	0.01	-0.12
6	0.00	0.00	0.00	0.36	0.00	0.12	0.00	-0.24
7	0.04	0.12	0.08	0.48	-0.02	0.24	*	-0.12
8	0.02	0.00	0.03	0.48	0.05	0.24	-0.01	-0.12
9	0.10	0.12	0.02	0.48	0.08	0.24	-0.05	-0.24
10	0.05	0.00	0.00	0.60	0.01	0.24	0.01	*

Relative difference between pre- and post-construction measurements (inches)
Positive value indicates settlement
Negative value indicates heave
*insufficient data to resolve

8. CONCLUSIONS AND RECOMMENDATIONS

Based on the conventional survey data, changes in the ground elevation along the alignment were measured within the error associated with the equipment and personnel conducting the survey. Essentially, ground movements at the test sites did not occur or was un-measurable within the accuracy of conventional survey methods.

A direct comparison of data suggests that the photogrammetric methods are more accurate and have greater precision than conventional survey methods. For this analysis, photogrammetric methods provided measurement accuracy within ± 0.01 foot (0.10 inch) while conventional survey data were within ± 0.05 foot (0.60 inch). Vertical closure for the conventional survey was within 0.02 foot (1/4 inch) so differences between pre-and post-construction measurements may be related to the positioning of the rod or saturated ground conditions that caused the wooden hubs to swell. Errors may have been introduced into both survey methods because the wooden target mounts were difficult to maintain throughout the six-month duration of the project and several hubs were found to be disturbed or plugged by routine lawn care.

The photogrammetric method is very convenient and only requires a few minutes of field time. The camera and tripod are more portable, less susceptible to handling errors, and require one person with no special skills compared to conventional survey equipment which required an experienced team and Total Station equipment. Photogrammetric methods require some processing time before a measurement can be reported, while a conventional survey can provide an immediate result. The total time for conducting a photogrammetric survey was approximately one worker day or about half of the time required for conventional methods. On larger projects with more frequent monitoring events, even greater efficiencies could be realized, especially if a construction worker could conduct the photo monitoring event.

As with many new techniques, lessons were learned that can improve the accuracy of the method. The following recommendations are provided based on the work undertaken in this investigation:

- *Better Photogrammetric Control Points* – In this investigation two control points were utilized for each site, this resulted in some difficulty in orientating the model to the project datum. With two control points only the X and Y-axis could be orientated. A third control point at a higher elevation would assist in providing the perspective required to better orientate the Z-axis.
- *Better Targets* – On analysis of the photos it was observed that under the natural lighting conditions present on the site the photo reflective surface of the targets was too reflective. This resulted in a glare in the photo

obscuring the target and making the coded target ineffective. Increasing the height at which the photos were taken and using a "duller" reflective surface would improve the process.

- *Better Camera* – While the 12 megapixel consumer grade SLR camera was sufficient to collect the survey data, it was observed during the analysis that the photos were somewhat grainy and pixelated at the zoom required to manually identify the target center. This issue could be addressed using a higher resolution camera, decreasing the distance between the camera and targets, or using a larger target.
- *Improved Mounting Hub* – Mounting hubs were susceptible to damage and removal by homeowners. Alternate hub designs employing a hardened socket may ease target installation and repeatability of correct target placement.

Conventional survey methods are commonly required for ground movement monitoring programs during underground construction. Ground movement monitoring using photogrammetric methods can produce results similar to conventional survey methods. However, additional refinements to target setting, control, and design are required to improve precision, efficiency, and adaptability. The expediency and potential efficiency of photogrammetric ground monitoring warrant further analysis and additional test case comparisons.

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