Dynamic deformation monitoring of a transmission tower undergoing failure testing by close range terrestrial photogrammetry

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Key words: Deformation measurement, engineering survey, photogrammetry, risk management

SUMMARY

This paper details the application of close range terrestrial photogrammetry in the full scale failure testing of an in situ electricity transmission tower in an effort to provide dynamic deformation information for the purposes of informing asset maintenance and lifecycle design.

The photogrammetric methods applied used the commercially available “off the shelf” PhotoModeler software application and provides a proof of concept documenting a financially viable, holistic and efficient method for determination of complex deformation parameters and details of the towers performance.

This effort has contributed to a better understanding of a large and complex asset for the client and assists in development of rational maintenance activities that provide significant economic benefits.

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1. INTRODUCTION

Deformation monitoring is the systematic determination of the nature of change in shape, dimension or location of manmade or natural objects subject to stress. The information gathered from monitoring allows for informed and cost effective design, maintenance and risk management activities.

This paper describes the design and deployment of a commercial terrestrial photogrammetric solution for the dynamic deformation monitoring of a transmission line structure during an in-situ pull-over test. The capabilities, limitations and alternative applications of the full solution and of terrestrial photogrammetry in general are discussed.

Figure 1 – The decommissioned tower T26 after the pull-over test

2. THE PROJECT

Transpower initiated a project to gather tower and foundation performance information on their Road towers by performing a pull over test of tower T26 on the HAY-TKR-A Line near the Takapu Substation. The objective of the testing was to gain better understanding of the transmission tower structure and tower foundation behaviour under dynamic wind gusts or other short duration ultimate design loading (Lake, 2011). The knowledge gained would be used for risk assessment and maintenance actions for similar structures across the transmission network. The decommissioning of this in-situ suspension tower presented an opportunity to gain this knowledge.

Figure 2 – Decommissioned tower T26 and adjacent live tower T26A

The specific monitoring aims were to determine the lateral load capacity in its in-service arrangement and to confirm the foundation performance during pull-over testing. This was achieved by a combination of direct measurement sensors comprising of load cells, tower member strain gauges and foundation stub potentiometers, and non-contact measurement by survey monitoring of tower, member and foundation displacements.

Simulation of design loading was achieved by a rigging arrangement that connected each pair of tower cross arms with an independent cable run through ground anchors placed to match design vertical and transverse load ratios terminating at a pair of dozers winches. The dozer winches were configured to allow for controlled applied load to simulate both a static loading and a dynamic short duration loading sequence.

Monitoring of the tower performance required the continuous determination of tower deflections and deformation during both static and dynamic loading sequences. Monitoring outputs were to be 3D coordinates with repeatability (precision) of 2-3mm and accuracy relative to ground control of 4-5mm. Deformations had to be synchronised to the applied load to allow for meaningful comparison with direct measurement outputs.

Monitoring of ground and foundation deformation required the continuous determination of foundation stake and ground surface uplift during both static and dynamic loading sequences. Again monitoring outputs were to be 3D coordinates with repeatability (precision) of 2-3mm and accuracy relative to ground control of 4-5mm and uplift had to be synchronised to the applied load.

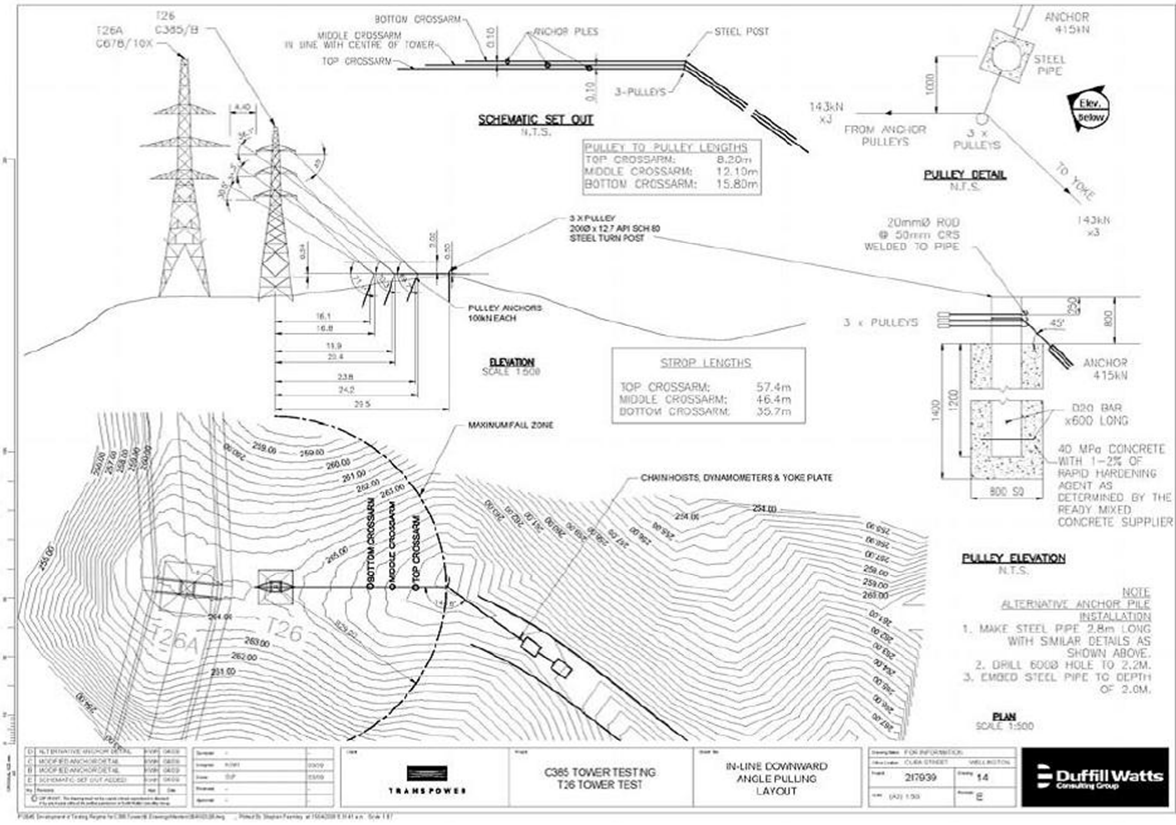


Figure 3 – Testing arrangement

The completion of loading, direct measurement and non-contact survey monitoring activities needed to be undertaken under strict health and safety conditions. Principally this necessitated all operators to be housed in a protective cabin or beyond site barriers during each test sequence.

The key elements of the monitoring system design were therefore, the ability to capture short duration dynamic deformations of hundreds of test points on a complex structure and its foundations to millimetre accuracy, synchronised with load, in a restrictive operating space and to a tight project budget.

CPG identified terrestrial photogrammetry captured from an adjacent live tower as being the most appropriate method to achieve all these aims with a single solution.

3. THE MEASURING SYSTEM

Following the review of available techniques and the identification of terrestrial photogrammetry as the most appropriate monitoring method for this application a comprehensive system design and proof of concept programme was undertaken to find the final practical solution for deployment. This design programme involved the review, procurement and testing of the individual field and office system components, proof of concept testing of the full operation system against the monitoring specification and detailing of practical system deployment.

The final solution had to be commercially viable and suitable for practitioners not specialised in photogrammetric practice and theory. The primary design driver for system development therefore came from the software selection. A review of commercial close-range photogrammetry software identified PhotoModeler by Eos Systems as a suitable option. A quality technical users guide and an extensive library of product testing and project example literature allowed for immediate advances in knowledge on imaging requirements such as camera selection, arrangement and triggering; model constraint requirements such as project control and target options and; processing requirements such as practical modelling workflows and most importantly the model accuracy expectations.

The solution deployed following this design and proof of concept process consisted of 11 Canon 1000D (10 Mega-pixel) digital SLR cameras, each equipped with a variable zoom lens (18-55mm), synchronised for dynamic conditions using a custom-built relay switch triggered by a Canon TR-80-C6 timer set for 1sec shutter release. Synchronised sets of images were processed using PhotoModeler, utilising PhotoModeler's coded RAD targets mounted on and around the tower structure and foundations for automated model resolution to the required 2-5mm measurement accuracy. Individual tower members and foundation and ground surface deformation measurement involved the manual modelling of 35mm and 100mm polystyrene balls and 35mm dots on customised adhesive tape strips. Model control was provided by static state coordination of RAD target centres by reflectorless total station.

3.1 Imaging

Figure 4 – Canon EOS 1000D DSLR, SDHC card and mounting system

The principle considerations for camera selection for this project were whether the cameras SD card write speeds could cope with highest resolution image capture at minimum 1 sec time-lapse rate; whether sub-pixel target centre marking could be achievable given the cameras sensor resolution and expected camera-to-target distances; could the camera triggering be suitably synchronised and; could the cameras be installed and triggered remotely.

Initial SD card testing indicated that the supplied Class 2 SDHC cards were too slow and a buffer delay was being introduced when images were being captured at the desired 1s time-lapse rate. These cards were substituted by faster Class 4 cards. There was a request to investigate the potential of sub 1s continuous shutter release if required. A full year had passed since our initial card investigations and in that time super-fast Class 10 cards had become available for reasonable cost. A full set of these were purchased after testing proved the cards could handle the maximum 3 Hz frame-rate achievable on the Canon 1000D DSLR's in expected lighting conditions.

After a review of the PhotoModeler documentation a proof of concept trial was undertaken with a set of magnetic and reflective 200x200mm coded RAD targets manufactured for this purpose to determine whether the camera / target combination would allow for successful automated sub-pixel marking at expected camera to target distances. The trial also allowed the first assessment of the minimum image and image overlap requirements for model resolution to the required precisions. In the trial automatic model resolution was acceptably achieved from four coincident photo overlaps, with 80% of the coded targets auto-marking and referencing. The remainder were manually sub-pixel marked and referenced.

A synchronisation switch with 12 camera outputs and a 5V signal output for synchronisation with external systems, triggered by a single Canon TR-80-C6 timer, was developed by Opus and office tested with 5 no. cameras connected to the switch with 20m length shielded dual-core cables. The synchronisation results from testing were excellent. Testing involved projecting a 100ms digital clock onto a wall and capturing synchronised images over a period of time and comparing the displayed time at each epoch from each camera to determine the variation. Synchronisation delays in the order of 100-200 ms were achieved. This result meant that we were confident that targets would be captured simultaneously (within sub-millimetre variations) at each epoch by the full camera array.

Figure 5 – Trigger Switch and Timer

Breeze Systems DSLR Remote Pro Multi-camera utility meant running on laptops was selected to manage the synchronisation of the camera clocks, live-view camera placement and initial camera setup. The distances from camera to laptop (up to 20m) direct single USB cable connection was not possible, with the maximum viable length of a USB cable being 5m. USB repeaters were used to extend the cable length up to 20m or Cat 5e cable and fibre optic extenders are available for longer lengths. We decided to use a USB server hub which connects to an ethernet LAN. In this case we chose the Network USB Hub from Belkin. Each hub has 5 no. USB output ports to connect to the cameras using a standard 5m USB cable with one single ethernet port to connect the hub to the laptop with any length Cat5e cable.

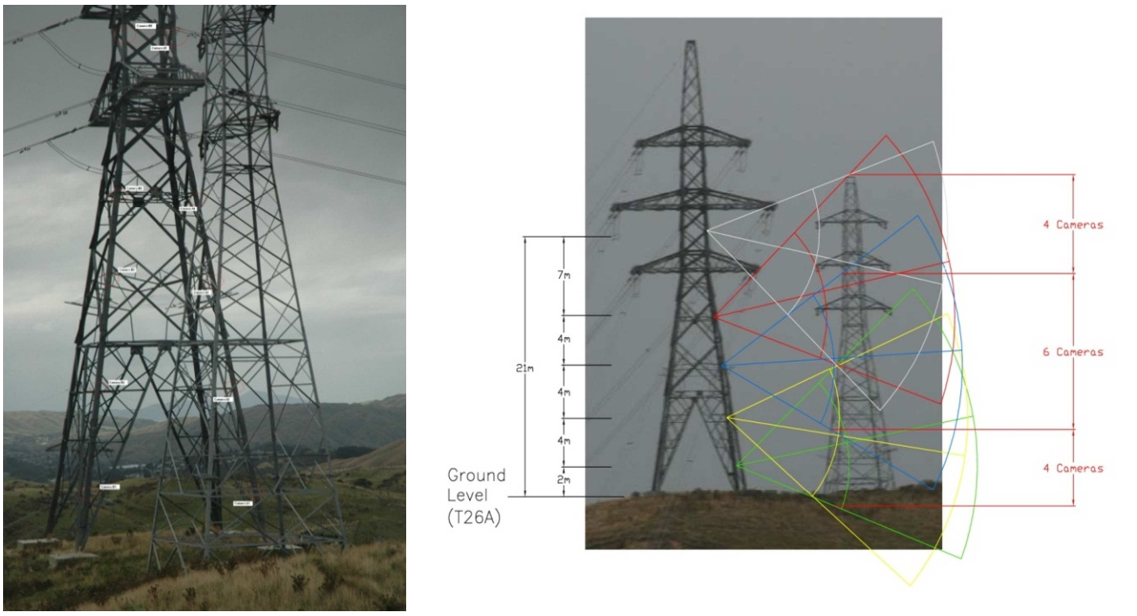


Figure 6 – Final camera field-of-view and mounting location diagrams

The proof of concept testing identified that the resolution of the full tower photogrammetric model to the accuracies specified meant we needed a minimum of 2 no. over-lapping fields-of-view across the whole structure and associated ground monitoring area with camera to target distances no more than 25m. This was achievable with ten cameras mounted on the adjacent live tower in rows of two, carefully orientated to ensure adequate overlap. The final mounting locations and orientation of the cameras was determined and undertaken after the key members and nodes on the structure had been identified and physically marked on site by the structural engineering team.

The final deployed solution captured hundreds of epoch image sets at 1 Hz, with each image set consisting of synchronised partially overlapping images from 11 cameras. Each epoch image set could be treated as a separate photogrammetric model related back to the starting epoch by the static control targets.

3.2 Control and Targets

Constraints and control points are used in photogrammetry to resolve the model into a known coordinate system; to improve the accuracy of the model and; in the case of dynamic monitoring to relate individual epoch models together and back to a zero state. They provide input into the definition of scale, rotation and translation for the model. A control point is a feature in the image set that has known X, Y, Z values. A constraint is a piece of additional information about relationships between features in single or multiple images.

The design considerations for ground control and target selection and arrangement were driven by the requirements of dynamic time-lapse photogrammetric modelling. Static control, that is coordinated points in the imagery that will not move during the dynamic testing, are required to provide coordinate system definition and to relate moving targets back to a reference frame. Dynamic targets needed to be designed and placed at a density to enable the individual epoch models to resolve to the required accuracy and in locations so that strategic structural and geotechnical deformation information could be determined directly from target metrics.

Static control was provided by 200x200mm coded RAD targets placed on tripods within view around the base of the tower and on two static reference beams located either side of the tower leg stubs. Dynamic control of the tower structure was provided by RAD targets distributed at strategic locations on the tower members. Coded targets allow PhotoModeler to uniquely identify each target and automatically match them across overlapping images. In addition to the RAD targets rolls of adhesive tape with 35mm black dots printed in a stager with 100mm centres were deployed. This tape strip could be attached to any member with coordinates for each dot manually extracted from the model where required. Dynamic control of foundation and ground monitoring was provided by 35mm polystyrene balls placed on the surface in grid above the foundation grillages and 100mm polystyrene balls placed on the top of stakes established to monitor sub ground uplift above the grillages at different depths. Ball centres could be manually identified using sub-pixel marking functions in PhotoModeler where required.

The RAD targets were used for model resolution, control and constraint at each project epoch. Independent coordinates for all RAD target centres were determined from reflectorless total station from rigorously established ground control marks. Proof of concept testing identified that at least 14 sub-pixel marked RAD targets common to overlapping images were required to resolve the model to the 2-5mm accuracy required. Of those a minimum of 3 static targets were required to fix the model into the site coordinate system and an additional set of distance constraints were required to fix scale in each datum axis. The distance constraints were introduced by calculating the join distance between coordinates as derived by total station on certain target pairs and fixing these distances in the model.

The deformation marker balls were office tested to determine performance of sub-pixel marking and model resolution under site conditions. The lighting conditions were varied to test for the effects of shadowing on auto-marking. It was noted that overhead lighting caused a shadowing effect to the underside of the balls causing the sub-pixel marking to resolve an ellipse weighted towards the top of the balls not the centre. This effect could be minimised by using artificial frontal lighting or by manual centring where lighting effects cannot be removed. This resulting marking was consistent across all photos with the model results for these points within the 1-3mm range. A simple deformation displacement test was also performed by raising the 35mm deformation markers fixed to a solid board by known amounts and re-capturing the 4 overlapping images for each state. By also including static RAD control targets to the images we were able to determine that the calculated vertical displacement agreed with known values to within the required sub 5mm accuracy.

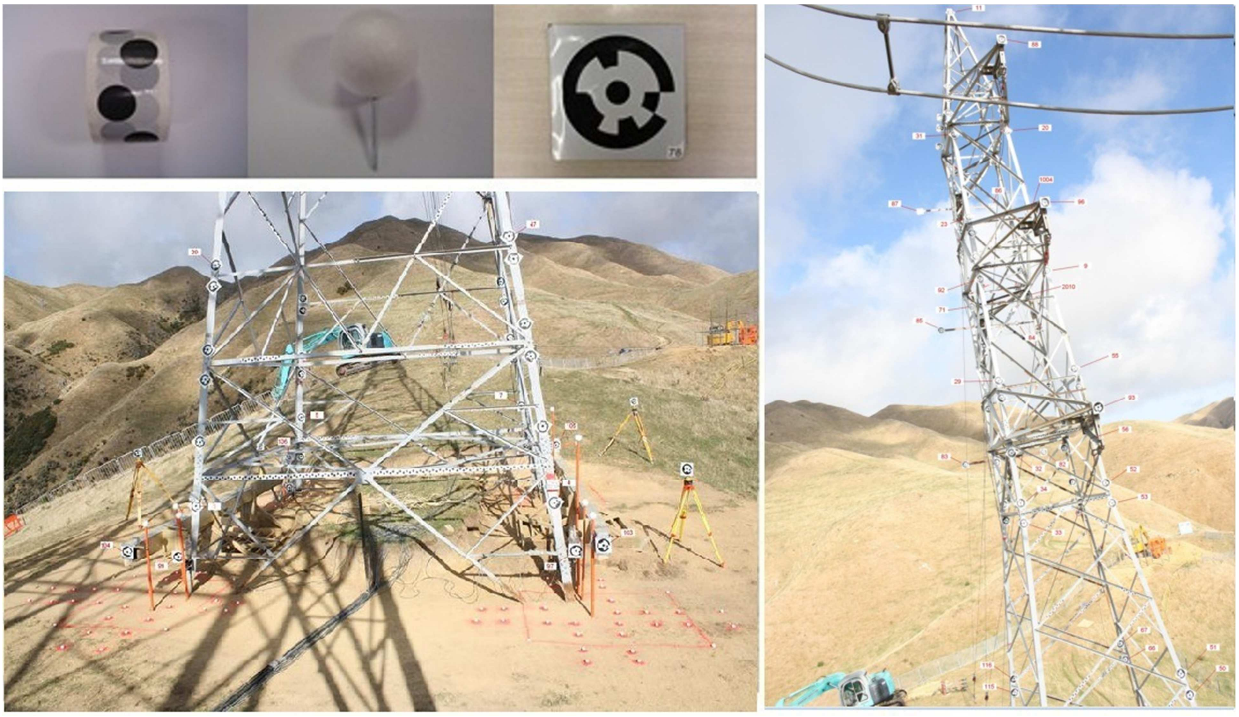


Figure 7 – Target design and positioning

3.3 Processing

The processing elements to derive coordinates and measurements from raw field data can be broken down into survey control processing, image processing and monitoring output generation.

Survey control processing takes site control network observations and monitoring target observations from the total station setups and applies rigorous network adjustment routines to derive final ground control and monitoring target coordinates and accuracy estimates. For this project observations were captured with a Trimble S6 total station and coordinate determination was performed with the LINZ SNAP programme.

Image processing deploys photogrammetric principles to derive coordinates or measurements from photos. The image capture methodology produced hundreds of one second epoch image sets from the fixed cameras. PhotoModeler was used to generate the metrics from these image sets. Each epoch was treated as a separate model with independent output metrics.

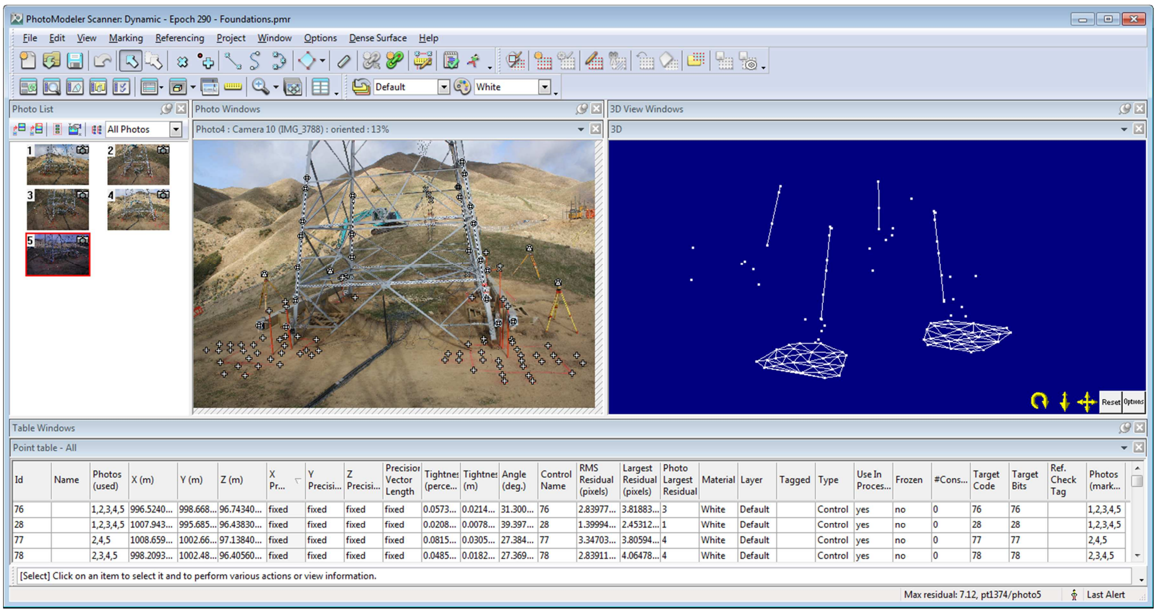


Figure 8 – PhotoModeler Processing Environment

Issues with mounting and configuration by riggers resulted in non-firing of 3 cameras. The incomplete image set required a change in processing methodology. The foundation and tower image sets were separated because of insufficient overlap and processed independently. Images from the designed 4 (+1) camera stations were available for foundation monitoring. 6 camera stations were designed for the tower monitoring, however images from only 3 of these were available for modelling.

The processing workflow deployed for foundation monitoring was to first resolve the unconstrained model for the initial static state, corresponding to epoch 0 of the static test. This model was then constrained by introducing fixed control, then distance constraints. This process was repeated at each milestone epoch.

Resolving the unconstrained photogrammetric model at any particular epoch is partly automated in PhotoModeler. The synchronised images from the 4 or 5 camera stations are first extracted from the image archive. These are then loaded into PhotoModeler as an *Automated Coded Target Project*. This automated routine requests a camera calibration, interrogates each image for coded targets, references common targets, orientates the images and calculates unconstrained coordinates for targets and camera stations. Additional coded-targets that were not automatically identified in the images are manually sub-pixel marked to improve target coverage and provide consistent control sets across epochs. The unconstrained model has no scale or rotation.

Resolving the constrained model fits the photogrammetry network into a 3D coordinate frame, thus solving for scale and rotation. This is achieved by introducing fixed control points for a selection of the targets. For this project these control points were the coordinates derived from reflectorless total station of the four targets on survey tripods located outside the zone of ground deformation around the test tower. For the model to correctly resolve it is necessary to completely recalculate the orientation of all photos.

The fixed control points only provide limited constraints in the model because they are not well distributed around the photos. The arrangement of the camera stations relative to the tower subject creates slightly weaker network geometry in the Y axis. To improve the model, particularly in this Y direction we can introduce two-point fixed distance constraints. The join distances between target centres coordinated by reflectorless total station can be introduced as constraints in the model. To ensure consistent model results between milestones it is necessary to reproduce the same fixed point and distance constraints at each test epoch. The fixed control points remain static throughout the test. The coordinates for target points used for distance constraints change through the test, however the nature of movement in the tower structure and along the instrument beams strongly suggest the relative distances between the identified target pairs will not change significantly. The same distance constraints can therefore be applied across all milestone models.

One of the primary goals of the foundation monitoring was to model the effect of compression and uplift of foundation grillages on the surface and at varying depths down to the grillages themselves. This was achieved by observing the Z values of 35mm polystyrene balls pinned to the surface in a grid above the grillages and of 100mm balls fixed to the tops of foundation stakes drilled to varying depths around the leg stubs. Monitoring these marker balls in PhotoModeler involved the manual sub-pixel marking and referencing of ball centres that featured in 3 or more synchronised images in the constrained models for each identified milestone and the calculation of changes in resultant Z coordinates from the static state coordinates for those balls.

The metrics output from each resolved and constrained foundation model were coordinates in the X, Y and Z directions in terms of the site coordinate system and 3D surfaces derived from the ground marker ball coordinates. The calculation of changes to target coordinates over time and the graphical representation of that change is handled outside of PhotoModeler. The coordinate change calculations were managed in Excel and the 3D graphical time-series in Visual Computing Lab's Meshlab, Google Sketchup and AutoDesk Civil 3D.

Like the foundation monitoring processing methodology the processing workflow for tower monitoring started by first resolving the unconstrained model for the initial static state, corresponding to epoch 0 of the static test. The primary difference from the foundation modelling methodology was that there were no static fixed control targets in the tower image set, so fixing the unconstrained models into a 3D coordinate frame required a new approach. Network coordinates were available for RAD target centres in the tower image set as captured by reflectorless total station at epoch 0 of the static test. As with the foundation modelling the join distance between these targets could be introduced as two-point fixed distance constraints in tower modelling to provide rigorous control of model scale. Then by treating these targets as fixed control in the epoch 0 model the network coordinates of the camera station positions could be determined, with these camera station coordinates fixed in subsequent test epochs. Two assumptions are made here, firstly that the strains introduced on the tower members during the testing doesn't alter the relative distances between the selected distance constraint targets, and secondly the cameras do not move during the duration of the testing.

The metrics output from each resolved and constrained tower model were coordinates in the X, Y and Z directions in terms of the site coordinate system. The calculation of changes to target coordinates over time and the graphical representation of that change is handled outside of PhotoModeler. The coordinate change calculations and representation of that change were managed in AutoCAD.

4. RESULTS

The objective of the monitoring was to determine displacement metrics for several key foundation and tower elements. These included uplift and compression information on the four tower leg stubs; stability information on the static instrument beams; uplift and compression of the ground at different depths above the foundation grillages, as represented by marker balls placed on foundation stakes; deformation of the ground at the surface above the foundation grillages; and deflection information of the tower structure itself. This information was required for various milestone epochs during the testing cycle.

Analysis of results produced the following broad conclusions. There was up to 50mm of uplift and 40mm of compression of the leg stubs; the instrument beam did not remain static during the test; the sub-ground uplift from grillage depth correlated with surface deformation; sub-ground and surface ground deformation on compression legs was minimal; surface deformation on uplift legs correlated with leg stub metrics and appears to support the conclusion that the grillage was pulled up in cone shape; the tower top moved up to 700mm in direction of pull just before failure; displacement of tower monitoring points was due to both rotation off vertical in tower due to uplift and compression of foundations (approx. 500mm) and distortion in the structure itself (approx. 200mm).

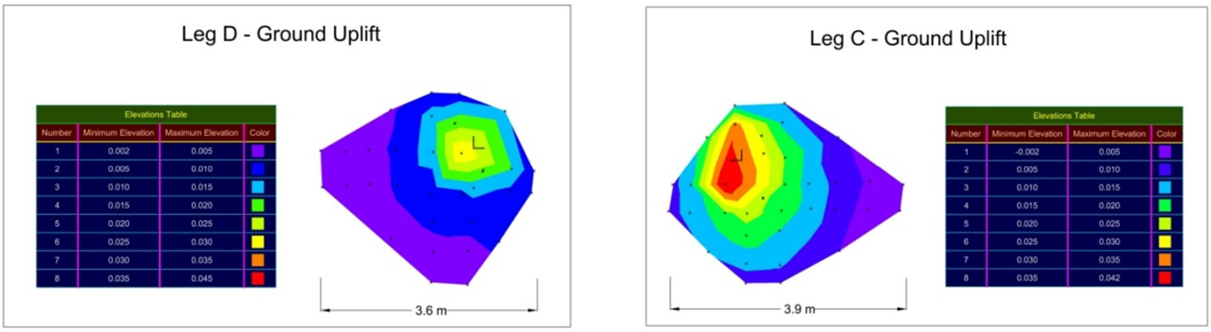
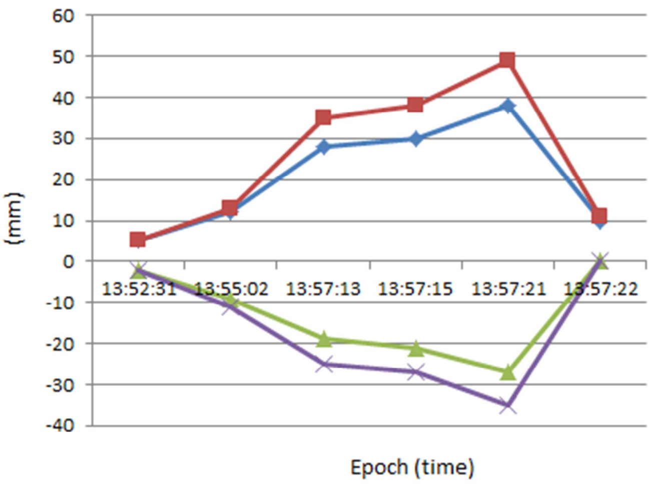


Figure 9 – Uplift on ground marker balls from initial to pre-failure epoch models during dynamic test



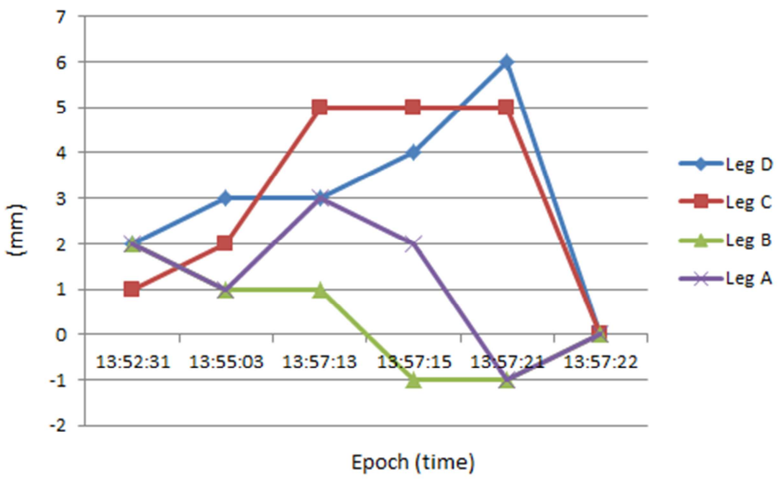


Figure 10 – Uplift and Compression at Tower Leg Stubs during dynamic test sequence

Figure 11 – Verticle Displacement of Static Instrument Beam during dynamic test sequence

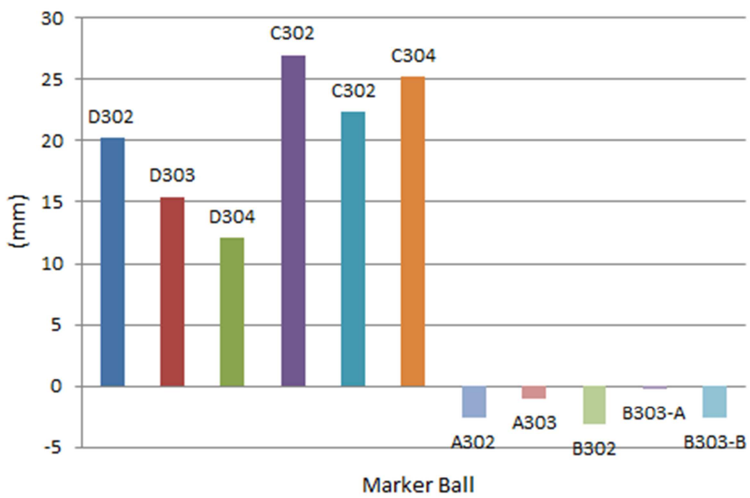


Figure 12 – Verticle Displacement on foundation stake balls from initial to pre-failure epoch during dynamic test

5. DISCUSSION

5.1 Data Accuracy

To give confidence in the processing methodology and photogrammetric network three quality assessments could be undertaken. The first two assessments were an analysis of individual network adjustment residuals and the analysis of model repeatability from sequential epochs of synchronised image sets with the tower in a static state. The third quality test is the comparison of calculated leg stub displacements compared with the independent potentiometer readings measured off the static instrument beam.

The first two assessments showed a good correlation between model adjustment residuals and accuracy indicators, and variation in resultant coordinates between subsequent static state models. All indicators from target metrics generated from 4 or more overlapping images where in the 2-5mm repeatability range.

The final independent quality assessment showed that with corrections for instrument beam movement applied the uplift and compression metrics for each leg stub from the photogrammetry and potentiometer (Pot) systems agreed to within the quoted 2-5mm accuracy specification.

Dynamic test 24.04.10	CPG Data											Opus Data from CD Tables (uncorrected for IB movement)												
			Leg A	Leg B	Leg C	Leg D	Leg A	Leg B	Leg C	Leg D						Leg C	Leg B	Leg A	Leg D	Leg A	Leg B	Leg C	Leg D
Survey Models Requested	Alternative Milestones Processed	ms	IB Targets mm	mm	mm	mm	Leg Stub Targets mm	mm	mm	mm	Time	ms	Tom kN	Dick kN	Harry kN	Strain_1 με	Strain_2 με	Strain_3 με	Strain_4 με	Pot_3 (A) mm	Pot_4 (B) mm	Pot_2 (C) mm	Pot_1 (D) mm
Marker Balls IB & Pot Target	13:52:31	1	2	2	1	2	-2	-2	5	5	13:52:31	23	2.6	2.8	2.7	-11	-5	-13	14	-3.3	-3.2	3.8	3.3
Marker Balls IB & Pot Target	13:55:03	1	1	1	2	3	-11	-9	13	12	13:55:02	999	34.5	34.3	34.1	486	-598	-591	511	-8.6	-7.5	10.3	8.2
Marker Balls IB & Pot Target	13:57:21	1	-1	-1	5	6	-35	-27	49	38	13:57:21	1	56.9	57.5	57.7	875	-1050	-1047	910	-31.2	-23.9	41.9	31.0
Marker Balls IB & Pot Target	13:57:22	1	0	0	0	-2	N/A	N/A	11	10	13:57:22	1	27.3	33.9	37.1	83	-1629	-1317	221	-31.3	-22.2	28.9	20.5

Figure 13 – Comparison of photogrammetry and potentiometer readings of leg stub displacement

5.2 Deployment Issues and System Limitations

Much was learned during the project on the issues and limitations of terrestrial photogrammetry and the project solution in particular. Access to camera locations, deployment in harsh climate and time pressured scenarios, effects of lighting conditions, accuracy verses camera location, targeting, and the time required to process imagery and produce outputs are all worthy of particular consideration. These considerations can be broken down into deployment and system design / methodology learning's.

Deployment issues were encountered in this project and these affected the quality and completeness of achievable outputs. 8 of the 11 cameras deployed needed to be placed, orientated and configured by tower maintenance riggers. Pre-test site trials established that the remote installation of cameras using the Breeze Systems DSLR Remote Pro utility and Belkin Network USB hub could be achieved but that system robustness and installation speed were risks. Robustness of the cameras themselves, especially weather-tightness and the USB ports were also reasons for concern. It was decided to go ahead with installation of cameras on the day of the test, rather than risking damage to cameras from the elements from pre-installation. Unfortunately time-pressures, known weaknesses in the remote networking system and rigger error resulted in 3 of the 11 cameras not firing during the pull-over tests. This incomplete dataset resulted in the change of processing methodology described. It was also noted that bright frontal lighting conditions resulted in over exposure of some of the reflective RAD targets.

The accuracy of dimension / position metrics from a photogrammetric system is dictated by the size of pixels relative to the feature being measured. The size of pixels across a targeted feature is dictated primarily by the distance the camera is from the subject. The use of targets, sub-pixel marking and highest practicable camera image resolution assists with refining the accuracy of the model and feature metrics. Processing is time intensive. Efficiencies can be made by using automatic target recognition over manual marking where possible.

6. CONCLUSION

The monitoring of the dynamic change of multiple points of interest whether in structures or topography, or indeed any suitable objects in motion, is difficult or costly with traditional non-contact surveying or direct measurement sensors.

This paper presents an effective and commercially viable technique that can be deployed by surveying practitioners without specialist photogrammetric experience. The solution is scalable from the multi-sensor deployment for rapid change, close-range, high accuracy monitoring described in this paper to single sensor deployments for slow change, long-range, lower accuracy applications, such as slip monitoring.

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