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Port Botany Expansion Precision Monitoring Survey: Overcoming a Dynamic Environment

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ABSTRACT

In 2011, NSW Public Works' surveyors commenced a series of precision monitoring survey deployments at the newly established Port Botany Expansion site. With the site consisting of 72 hectares of reclaimed land, establishing high-order survey accuracy over the site presented several challenges. The project involved extending the primary survey control network throughout the site, and then undertaking the precise measurement of nearly 1,000 settlement points. NSW Public Works became involved with this project at a time when the site was effectively clear and free of obstructions, making the planned methodology for the initial survey relatively straightforward to execute. When the surveyors returned to undertake further epochs through 2011 and 2012, construction of the new port facility had gathered pace and the challenges associated with a large scale construction site forced a complete re-design of the earlier methodology. With many of the original sightlines now obstructed by construction activity, the initial survey control network was compromised to the point of being rendered obsolete. Despite the challenges this site presented, NSW Public Works has been able to successfully maintain the integrity of the survey control network and provide the client with accurate, reliable and repeatable results. This was achieved by capitalising on the availability and rigour of CORSnet-NSW, by utilising a wide range of instrumentation, employing robust field techniques, and by rigorous least squares analysis and network optimisation. This paper follows the development of this project over a 2-year period, explains the initial and re-designed methodology, and discusses the challenges that have been overcome to achieve a successful project outcome.

KEYWORDS: *Precise monitoring, NSW Public Works, least squares, CORSnet-NSW, optimisation.*

1 INTRODUCTION

The Port Botany Expansion (PBE) is a site consisting of over 72 hectares of reclaimed land adjacent to the existing Port Botany container terminal in Sydney. Once operational, this new terminal will provide more than double the capacity of container freight through the main Sydney shipping port. The site is approximately 1,200 m long by 600 m wide. The two main features of the site considered in this paper are the terminal surface and the crane rail beams.

For the purpose of this discussion, the port expansion project will be described as two distinct phases. The first phase of the project (Phase One) involved the reclamation and construction of the terminal surface area, and then the subsequent construction of the surrounding crane beam pairs. Gantry cranes will run along rail slots within each crane beam, loading and unloading ships that will dock alongside the new terminal. This phase commenced in 2008 and was completed in mid-2011 (Figure 1a).

The next phase of the project (Phase Two) was to then develop the terminal surface into an operational port. This would involve stripping back the reclaimed land, re-compacting and re-laying the sub-grade, adding drainage, and then finishing the hardstand with asphalt and concrete along with the construction of other on-site port infrastructure such as buildings and automated container stackers. This stage commenced in mid-2012 and is currently in progress at the time of publication of this paper (Figure 1b).

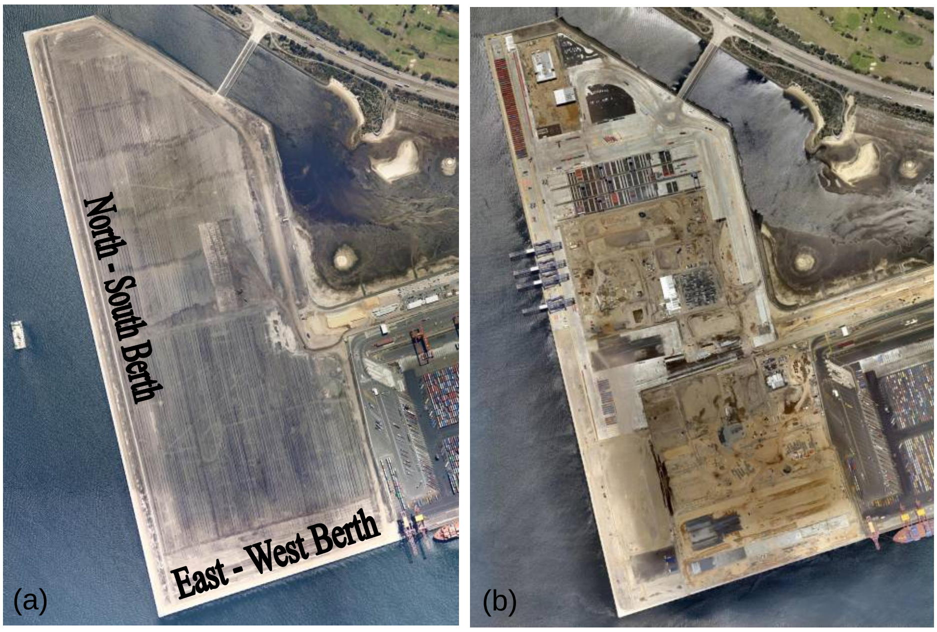

Figure 1: (a) Activity post Phase One construction and (b) during Phase Two construction.

2 PROJECT OBJECTIVES

As part of the contractual agreements between the port owner and the constructing contractor, on-going precise monitoring surveys of the terminal surface and the crane rail beams were required post construction. These survey results were required firstly to ensure that any faults in the construction were being identified as early as possible and secondly that the expected settlement of the terminal surface and the crane rail beams was within design tolerances. This survey information would then provide the basis for any claims against the contractor during the defects liability period.

The concrete crane rail beams consist of a pair of long concrete coping beams laid on top of a series of vertical piles cored into bedrock under the sea floor. A major risk identified with the crane rails was that any deformation in the concrete crane beams or the slots within the beams could make the gantry cranes work inefficiently or, worse, potentially jam the wheels of the cranes thus bringing the operation of the port to a standstill and costing untold sums in lost productivity. Accordingly, the crane rail beams were required to be monitored by precise survey both in the horizontal (X,Y) as well as the vertical (Z) dimensions as accurately as possible. The settling of the terminal surface, which consisted of reclaimed land, was assessed as being not as critical a risk and as such was only required to be monitored in the vertical (Z) dimension.

In general, the surveys were designed to yield absolute horizontal positions to ±6 mm and vertical positions to ±2 mm. Clearly, relative accuracy between observed points is far higher than the absolute accuracy.

3 SURVEY INFRASTRUCTURE AND INSTRUMENTATION

3.1 Crane Rail Settlement Points

The pairs of crane rail beams run the entire length of both the western and southern sides of the terminal. In total, there are nearly two kilometres of parallel concrete rail beams set at approximately 35 m centres. Pairs of stainless steel pins were installed at 25 m intervals into each beam (Figure 2a). These pins were installed during construction as settlement pins for monitoring survey purposes. There are four settlement pins every 25 m along the western and southern docks, making a total of nearly 300 settlement pins that are required to be measured accurately in X,Y and Z dimensions.

For horizontal measurements, each settlement pin is radiated from two stations by high-precision total station to a prism with mini-pole and a stable mini-tripod specially fabricated for this project (Figure 2b). For this operation, a Leica TM30 precise robotic total station was deployed. This instrument is a 0.5” angular accuracy instrument with distance measurements accurate to ±(1 mm + 1 ppm). Kestrel weather stations were deployed to take meteorological observations at each end of the control sightlines. The vertical component of the monitoring was determined by precise levelling using an invar barcode staff, stabilising rods and a Leica DNA03 precise digital level.

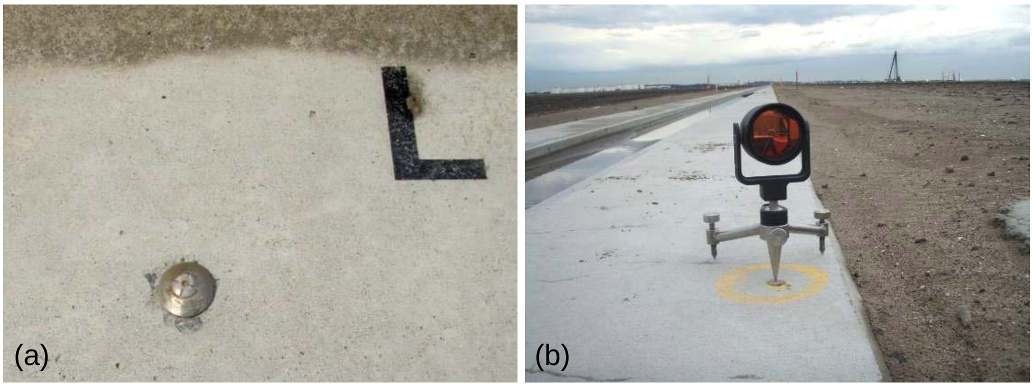

Figure 2: (a) Stainless steel settlement pin in crane rail and (b) prism set up on settlement pin using mini-tripod and mini-pole.

3.2 Terminal Surface Settlement Pins

Terminal surface settlement pins consist of a galvanised spike placed in a concrete pad in the surface. These marks were installed on a 50 m grid throughout the reclaimed land area. In addition, these marks were installed in groups between the crane rails. In total, there are approximately 600 terminal surface settlement pins covering the site. These marks were levelled only, initially using an invar barcode staff and stabilising rods, however in subsequent surveys the specifications were amended slightly to allow the use of a fibreglass barcode staff. There are also additional marks outside of the main site that are included in the overall monitoring project, however the monitoring of those marks is not discussed in this paper.

3.3 Survey Control Pillars

Adjacent to the site and prior to NSW Public Works becoming involved in the project, three concrete plinths containing a State Survey Mark (SSM) had been installed along Foreshore Road. These marks formed the primary survey control infrastructure that had been used by the construction contractor's surveyor during the reclamation phase of the project. Once NSW Public Works became involved in the project in June 2011, and in partnership with the client, the plinths were upgraded to standard concrete survey pillars with pillar plates. Also, an additional three concrete survey pillars and ten removable steel pillars were installed. The removable steel pillars were installed along the dockside of the new terminal in the concrete crane rail beam. The primary motivation for the installation of these additional pillars (concrete and steel) was to improve the repeatability of the surveys by reducing centring errors associated with survey tripods set up over ground marks, ensure the same geometry was repeatedly observed, maximise on-site observation efficiency, and bring nominally stable levelling bench marks closer to site. Figure 3 shows the survey control infrastructure at various points in the project's development.

Figure 3: Survey pillars – yellow triangles indicate primary control.

4 SURVEY CONTROL DEVELOPMENT

4.1 Phase One Survey Control Network – Post Reclamation

The new survey control network that was designed to take the project forward following the initial stages of the construction and creation of the site had been installed by October 2011. As discussed, this control network consisted of a series of both concrete survey pillars and removable steel pillars.

The first survey using this control network was undertaken by NSW Public Works in September 2011 and is referred to as epoch 1. Where possible, the sightlines of this epoch 1 survey control network were observed for the following repeat surveys, i.e. epoch 2 in December 2011 and epoch 3 in June 2012. Epochs 1, 2 and 3 are referred to as part of the Phase One surveys. The observed sightlines between the concrete and steel pillars for each of these Phase One surveys is shown in Figure 4.

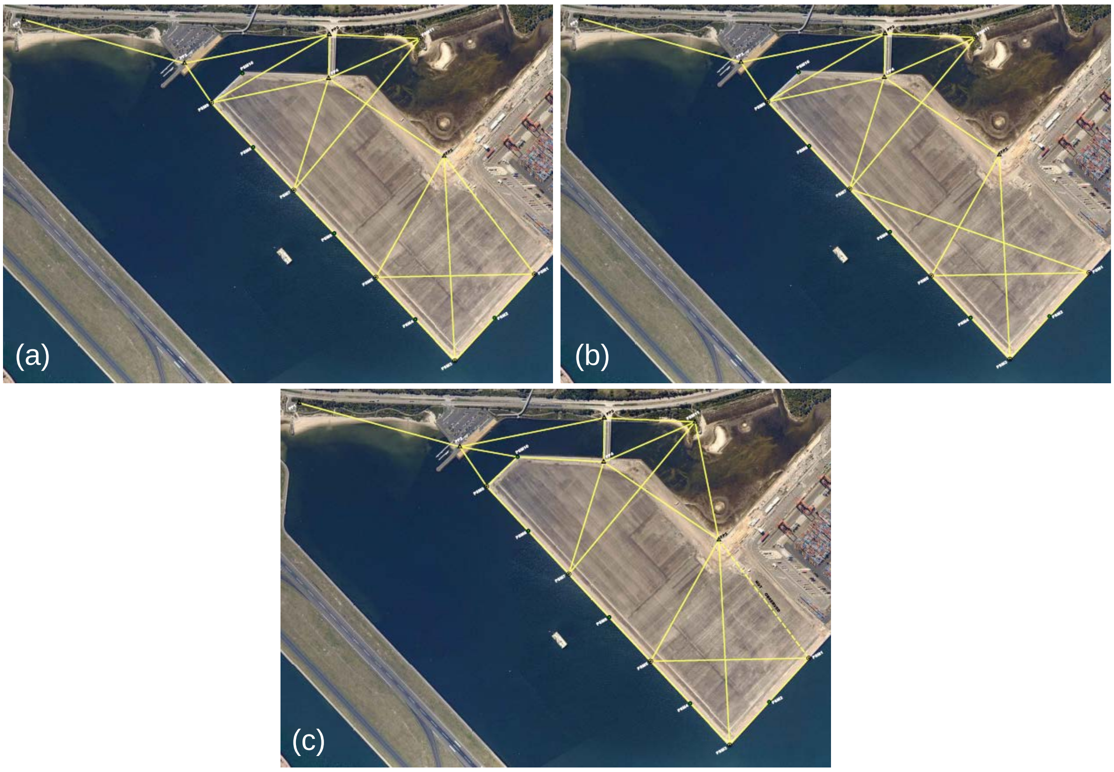

Figure 4: Survey control network for (a) epoch 1, (b) epoch 2 and (c) epoch 3.

4.2 Phase One Surveys – Results and Limitations

Epochs 1, 2 and 3 utilised the Phase One control network for the purpose of monitoring the crane rails and initial terminal surface settlement during a dormant period in the construction of the new port facility between the initial reclamation (Phase One) and the construction of the final hardstand and port facilities (Phase Two). While sightlines between the pillars where possible, the initial survey control network provided a reliable and reasonably robust geometric framework upon which to base the observations to the settlement pins. The network provided good results in terms of a least squares analysis, particularly where braced quadrilateral or triangular geometry was observable.

Despite using precise instrumentation and robust techniques, the overall geometry of the network was not ideal, and as a consequence optimum results could not be possible. Whilst the error ellipses derived from the least squares analysis were small and acceptable in the northern portion of the site (close to primary control), those in the southern portion of the site fell outside the preferred tolerances. The geometric strength of the network was limited by the nature of the site and the availability of additional control stations. Primarily the control for the survey was being propagated south over a long distance from the relatively short bas lines between the primary survey control concrete pillars along Foreshore Road (see Figure 3). Furthermore, the connection of the site ‘proper’ to Foreshore Road (across the Penrhyn Estuary) was based on a number of smaller triangles.

As the overall geometry, particularly in the east-west direction, was not strong, several options were considered to strengthen the network using total station observations of direction and distance between additional survey pillars and fixed prisms. One option considered was the installation of remote marks along the airport's third runway and the installation of pillars along the breakwall south of the current terminal. The aim of these potential improvements was to strengthen the connection of the site proper with the Foreshore Road baselines and reduce the likelihood of 'swings' in the network at its southern extremities. These options were eventually dismissed due to the likelihood that they were not viable or repeatable into the future.

Whilst the network had to date proven adequate for the task of monitoring the site in the dormant period between construction Phases One and Two, it was accepted that:

- The existing network was compromised with respect to redundancy, i.e. survey results are susceptible to yielding erroneous movements due to inconsistency in lines of sight observed.
- It had not been possible to observe a consistent set of lines of sight from one epoch to the next due to site obstructions, the loss of a single line of sight having a substantial impact on an already minimalist network.
- The existing network was reliant on the observation of lines of sight that cross the entire site, which where almost certainly not going to be clear during the construction and/or operational phases of the container terminal.

4.3 Phase Two Survey Control Network – Facilities Construction and Operational Port

By the time the epoch 4 survey was requested, the site had started to become a construction zone once again (Phase Two) with construction of the hardstand and port facilities having commenced (Figure 5). The increase in construction activity, including vehicle and plant movements, the creation of stockpiles and installation of site sheds, forced an immediate rethink into the methodology that had been previously employed. Many of the existing terminal surface settlement points were being progressively destroyed and some settlement pins on the crane beams were also obstructed by temporary stockpiles of equipment and materials including a jersey kerb that was placed half the length of the waterside dock. Multiple site inductions, inspections, medicals, discussions and safety briefings followed.

Figure 5: Dramatic change in site conditions from Phase One to Phase Two of construction.

A site inspection prior to the epoch 4 survey revealed that many of the total station sightlines available in earlier surveys were now not observable due to construction activity. NSW Public

Works carried out an assessment of the remaining lines of the network and found that of the 25 lines of sight which would ideally be observed in both directions (Figure 6), only the following could be observed at the time of epoch 4:

- 10 lines shown in green (observable in both directions).
- 1 line shown in yellow (observable in one direction only).
- 3 lines shown in red (observable in both directions but compromised by site obstructions).

The blue lines shown in Figure 6 could not be observed at all. As expected, the results of the network optimisation of the remaining observable lines of sight clearly demonstrated that the existing survey control network was completely compromised and that acceptable results could not be achieved using the original total station methodology.

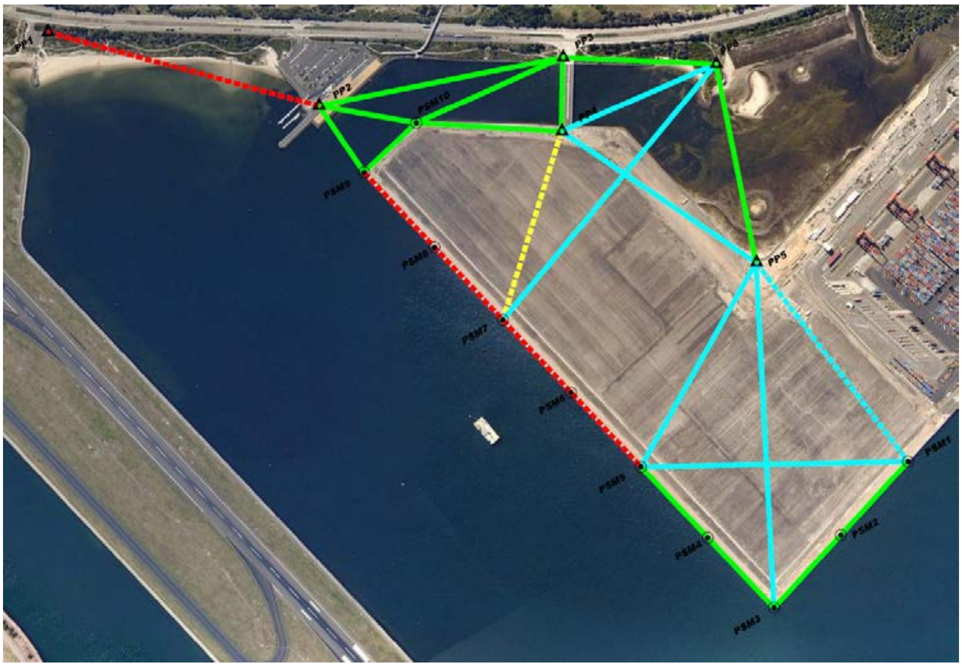

Figure 6: Phase One lines of sight at time of Epoch 4.

It was at this point that NSW Public Works advised the client that a new approach needed to be developed. An in-depth investigation into a new methodology that utilised a combination of the geometrically-sound braced-quadrilateral geometry and the CORSnet-NSW network of permanent Global Navigation Satellite System (GNSS) reference stations (Janssen et al., 2011; LPI, 2014) was commissioned.

4.3.1 Relative Position – Braced Quadrilateral Network

Whilst a variety of geometric configurations, including a single braced quad, had been used in the Phase One total station survey control network, once stockpiles started to grow and plant and materials arrived on site, the sightlines that crossed the site were now compromised. A variation to how the braced quads were implemented was developed. This involved a series of abutting braced quads that ran the length of the crane rail beams. However, the braced quads were now only the width of the two parallel crane rail beams, i.e. approximately 35 m wide. Sightlines were now limited to the relatively clear corridor afforded by the crane rail beams (see Figure 8). Consultation with the client and a review of proposed facilities plans indicated that these corridors would in fact remain relatively free of permanent obstruction, even when the port was operational.

Again, a network optimisation was run on this geometric configuration, and it was proven that this network was a strong and robust configuration best adapted to long narrow surveys (Anderson and Mikhail, 1998) that would support the monitoring of the settlement points into the future. From this network of braced quadrilaterals, the relative location of all crane rail settlement pins could be reliably measured using the total station methodology previously employed from the Phase One network. Whilst the network of braced quadrilaterals could effectively overcome the site obstructions, a total station-only propagation of control from the Foreshore Road baselines would still be plagued by the inherent weakness of a long network ‘hanging’ off a short baseline with a less than ideal connection across the Penrhyn Estuary. This connection was also to be further compromised by the erection of a continuous sound wall along the entire northern edge of the site proper. Consideration was thus given to the propagation of absolute control across the site using long-occupation GNSS techniques.

4.3.2 Absolute Position – Long-Occupation GNSS

Long-occupation GNSS, in particular utilising the CORSnet-NSW network of Continuously Operating Reference Stations (CORS), became a realistic consideration for the absolute positioning of the braced quadrilateral network. CORSnet-NSW would provide:

- A certified external reference frame for absolute positioning of the pillars within the Phase Two survey control network.
- A means of overcoming the geometrically weak link between the Foreshore Road control pillars and the site proper.

As the requirement for absolute position for this project was tight, the client was understandably cautious about adopting a GNSS methodology. A review of literature revealed that long-occupation GNSS had been successfully applied to similar monitoring activities previously, in particular:

- Eckl et al. (2001) estimated single baseline solutions of 12-hour observation sessions should yield accuracies of ±5.9 mm in Easting and ±4.8 mm in Northing. It should be noted that this evaluation used actual and not estimated satellite orbits.
- Wang (2011) reported accuracies of ±2.8 mm in Easting and ±5.1 mm in Northing under difficult conditions with a network of six reference stations, observing 6-hour sessions and processing a network adjustment, using actual and not estimated satellite orbits.

Furthermore, a review of available information on CORSnet-NSW (LPI, 2014) showed that observed daily coordinate differences for Port Botany CORS (PBOT) indicate a precision of approximately ±4 mm in both Easting and Northing.

While it is recognised that the precision of GNSS is dependent upon many factors, NSW Public Works could demonstrate to its client that several of these factors were under the control of NSW Public Works surveyors to ensure the highest possible precision:

- Session length and timing (day/night).
- Using a network adjustment methodology as opposed to single-baseline processing.
- Network geometry.
- Centring errors at survey stations.

NSW Public Works thus proposed that absolute horizontal control could be reliably propagated throughout the braced-quad network using long-occupation GNSS techniques and the CORSnet-NSW network as an external reference frame.

4.3.3 Observation of the Phase Two Network

Giving consideration to all of the site restrictions, availability of equipment, survey logistics, and a need to bench mark the proposed Phase Two methodology against the previously implemented Phase One methodology, the following survey specifications were developed and implemented for the observation of the GNSS component of the Phase Two network:

- Five CORSnet-NSW stations would be adopted as the external reference frame for absolute control: Villawood (VLWD), Chippendale (CHIP), University of NSW (UNSW), Port Botany (PBOT) and Waterfall (WFAL).
- 12-hour sessions at 30-second log rate continuous static observations.
    - ✓ Best balance between resolution of multipath, occupation time and survey logistics.
- Observations at night.
    - ✓ Best ionospheric conditions for GNSS observations.
- Two independent sessions.
    - ✓ Check on setup errors and detection of anomalies in GNSS that can occasionally occur and would be otherwise undetectable.
- GNSS observations at nine existing pillars with reasonably good prospects of clear sky in the future.
    - ✓ Distributed uniformly throughout the Phase Two survey network.
    - ✓ Some combinations of which would enable direct comparison of distances from both GNSS and total station between nominally stable pillars.
- All steps taken to reduce centring errors.
    - ✓ Same receiver at each pillar for each observational session.
    - ✓ Set up on precision carriages with trough bubbles and Leica adaptors.
    - ✓ All receivers to be orientated consistently.

Figure 7 illustrates the geometry of the CORSnet-NSW GNSS control network adopted for epoch 4 in relation to the Port Botany Expansion (PBE) site.

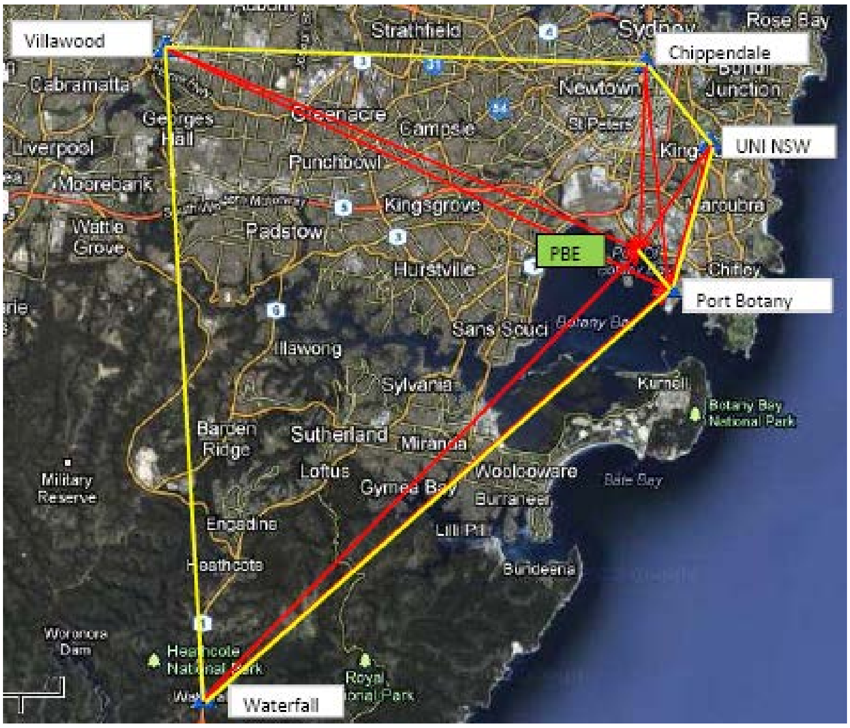

Figure 7: CORSnet-NSW GNSS survey control network adopted to establish control at PBE.

The distribution of GNSS stations throughout the braced quadrilateral network on site is shown in Figure 8. It can be seen that the north-south berth contained three main braced quad total station configurations, whilst the east-west berth contained one main braced quad, indicated by the yellow lines. GNSS receivers were placed at the stations denoted by blue circles.

Figure 8: Epoch 4 survey control network showing integrated GNSS and braced-quad configuration.

The braced-quad network for epoch 4 (January 2013) was observed from a selection of the removable steel pillars as well as temporary tripod stations which were set up on the inner crane rail beam. Being able to ensure that the observation of the survey control network could be repeated in the future was paramount when it came to the design of this new system. With construction activity to continue for the next two years, followed by the site being transformed into an operational port, it became necessary to develop a field methodology that was repeatable yet flexible enough to cope with unforeseeable obstructions that were undoubtedly going to emerge over time and yet still maintain the overall geometric integrity of the control network. The exact location of the temporary tripod stations can be varied to a degree (to accommodate temporary obstructions) without an adverse effect on the overall network geometry. The obstructions included cranes, container stacks and temporary site buildings. Maintaining the geometric integrity was essential to the accurate reporting of horizontal movements of the settlement pins. The additional temporary tripod stations also afforded much greater redundancy in sightlines should any settlement pins be unable to be radiated from the steel pillars only, as had previously been the case.

4.3.4 Processing Phase Two Observations

The processing methodology for the combined GNSS/braced-quad survey observations has a number of checks built into it to ensure the reliable reporting of settlement pin movements. The procedure developed for processing the observations for Phase Two was as follows:

1. GNSS field deployment and data collection, then:
   - A. Process all baselines in the GNSS network (approximately 90) using Trimble Business Centre (TBC) software.
   - B. Adjust GNSS network with four outer CORSnet-NSW reference stations held fixed and solving for PBOT.
     - ✓ Checks integrity of GNSS for that session.
     - ✓ Checks integrity of baselines between GNSS receivers on site that could otherwise distort the network.
   - C. Introduce PBOT into the network adjustment as fixed and solve for Map Grid of Australia (MGA) coordinates for the nine site pillars.
   - D. Compare and average results of two independently processed GNSS sessions.
   - E. Transform GNSS-derived MGA coordinates for all nine site pillars into Port Botany Plane Survey Grid (PBPSG). PBPSG is the datum within which all results are reported.

   Note that steps A, B and C are all done independently for each GNSS session.

2. Total station braced quadrilateral network field deployment and data collection, then:
   - A. Run a ‘freenet’ Compnet adjustment of control network observations.
     - ✓ Enables identification of any observational errors or compromised observations free of any distortion introduced by potentially noisy GNSS data.
   - B. Introduce PBPSG coordinates of pillars occupied with GNSS as ‘weighted control’ in Compnet adjustment of control network.
     - ✓ Yields PBPSG coordinates for all pillars and temporary tripod stations in the Phase Two network.

3. Total station radiations to settlement points:

   Adjust radiations from pillars and tripods to settlement points in Compnet adjustment with PBPSG coordinates for all pillars and temporary tripod stations in the Phase Two network (from 2B above) held fixed.
   - ✓ Extremely large number of observations with some potentially compromised to some degree, e.g. long shots low over concrete.
   - ✓ Ensures any compromised observations to individual settlement points do not distort the overall control network.

4. Presentation of results:

   Results of this processing and the comparison of each epoch to the previous epoch is presented to the client in Excel spreadsheet format, with full disclosure of control network survey repeatability, comments against potentially compromised measurements and high-quality plans to aid in the interpretation of the data by third party consultants.

5 RESULTS

Despite being situated in the early stages of a long-term monitoring effort, the initial results of the Phase Two network methodology are encouraging. This paper does not offer any public presentation or opinion of the movements detected in the settlement pins. That information is owned by the client and is not discussed here. However, it can be stated that importantly it was possible to migrate to the new methodology without any erroneous ‘spikes’ or noise in the monitoring data and as a result the client has retained a high level of confidence in the survey integrity despite numerous site challenges having to be overcome. Some of the more significant challenges and notable outcomes of the most recent Phase Two monitoring surveys are detailed in this section.

5.1 Epoch 4 Results

An element of the epoch 4 (Phase Two) network was an ability to compare distances measured by GNSS directly against those measured by total station as a means of benchmarking the Phase Two methodology, and easing some of the client’s concerns about the migration to the new methodology. Table 1 shows the comparison of distances measured between several pillars by both GNSS and total station. This comparison of distances yielded results that were within expectations, given the adopted survey and processing methodology.

Table 1: Comparison of distances measured by GNSS and total station.

Line	Distance (m)	Difference (mm)
PP2 → PP3	538.7	3.0
PP3 → PP4	160.4	2.7
PP2 → PSM9	174.8	1.2

As noted previously, the construction activities occurring on site required concrete safety barriers (jersey kerbs) to be placed along half the length of the north-south berth. These barriers were inadvertently placed almost directly under the lines of sight between the steel pillars in this part of the site, effectively reducing the ground clearance for some lines of sight. During processing it became evident that some of these lines were affected by refraction, with larger than normal residuals being observed. The impact upon the line of sight can be seen in Figure 9.

Figure 9: Jersey kerbs reducing effective ground clearance of total station observation.

However, and as expected, the redundancy afforded by the use of a network of braced quadrilaterals meant that in the instances where the observation between steel pillars was compromised by the jersey kerbs, it was relatively simple using Compnet to identify the offending observation and apply a statistical weighting that would effectively eliminate this observation from the dataset without any significant impact on the overall quality of the control network.

The use of CORSnet-NSW as an external reference frame also enabled not only the verification of the Foreshore Road baseline of pillars but it also enabled the detection of what appeared to be a small disconnect between the Foreshore Road control network and the site proper in previous epochs. The GNSS network of baselines was both denser and geometrically better-conditioned than anything that could be observed previously with the total station. As a result, a small, unresolved anomaly in the propagation of control across the Penrhyn Estuary in previous epochs was able to be resolved in epoch 4.

5.2 Epoch 5 Field Deployment

In mid-2013, the request came for the next scheduled monitoring survey, epoch 5. This request now provided NSW Public Works with the opportunity to put the repeatability of the methodology to the test, with the nature of the site completely different again from the last deployment, epoch 4, in January 2013. Planning for epoch 5 began with a site inspection and another series of inductions and accreditations that were required to allow surveyors access to areas of the site now under the separate control of various operators and contractors. Epoch 5 has recently been completed, with the field deployment undertaken during November 2013. Prior to epoch 5, some of the gantry cranes had been delivered to the site, large areas of concrete pavement had been laid and 3 m high sound walls had been erected along the north-eastern perimeter of the expansion site (Figure 10).

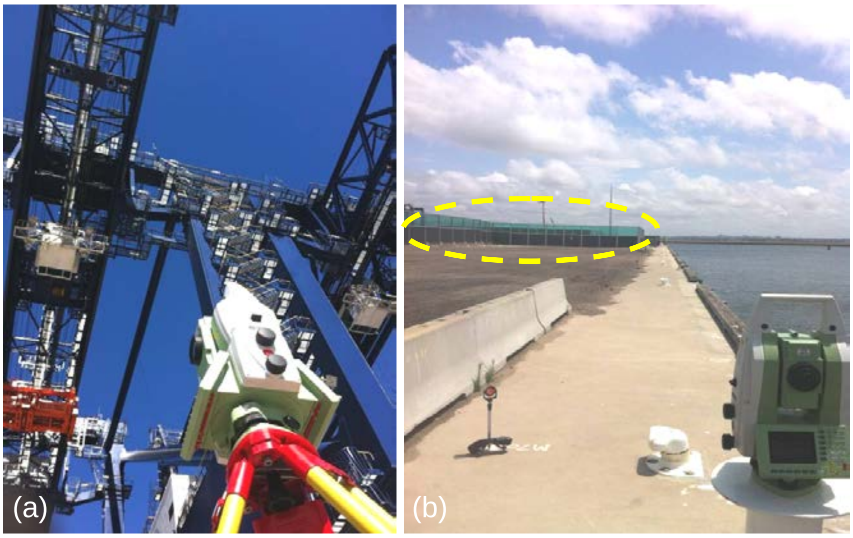

Figure 10: (a) Gantry crane and (b) sound wall in the background.

The erection of the sound wall in particular permanently ‘broke’ any total station-only connection of the site proper to the Foreshore Road control pillars. Although the site had changed appreciably in some ways, the survey methodology was surprisingly unaffected. This was due mainly to the in-built rigour and flexibility of the integrated GNSS/braced-quad system. Only some minor adjustments to the locations of the temporary tripod stations were required due to obstructions caused by the new cranes, temporary site sheds and items associated with the construction and commissioning of plant.

One change to the CORSnet-NSW GNSS control network between epoch 4 and epoch 5 was the omission of Chippendale CORS (recently decommissioned) and the subsequent inclusion of Fort Denison CORS. This change had little effect on the network geometry. At the PBE site, nine GNSS receivers were again deployed across the site, with some changes made to the stations that were occupied in the previous epoch 4 to better accommodate local sky obstructions.

Again, the integrated GNSS/braced-quad methodology was deployed across the site to obtain coordinates of both the control stations and the settlement pins to facilitate reporting on horizontal movements of the crane rail beam settlement pins. Vertically, precision levelling of all settlement pins continued in a manner similar to previous deployments.

5.3 Epoch 5 Results

Now that two repeat surveys have been completed with almost identical methodologies, it is prudent to look at the results obtained. The results have shown that excellent repeatability has been achieved between the epoch 4 and epoch 5 GNSS surveys, independent of the total station observations. Table 2 shows the variation in coordinates derived for the nominally stable control pillars that have been coordinated in epoch 5 when compared to epoch 4. Survey Pillar PP3 was also coordinated for another unrelated additional survey activity using essentially the same GNSS observation and processing strategy – the results of its comparison to epoch 4 are also shown in Table 2.

Table 2: Comparison of pillar coordinates against epoch 4 coordinates for nominally stable pillars.

	Additional Survey - PP3 Only (07/13)		**Epoch 5 (11/13)**	
Pillar	**ΔE (mm)**	**ΔN (mm)**	**ΔE (mm)**	**ΔN (mm)**
PP2			1	0
PP3	-2	-2	-1	-1
PSM9			0	-1
PSM5			-1	1

A truer indication of the repeatability of the entire methodology will only be realised after the completion of several more epochs of GNSS observations covering a wider variety of GNSS constellations and conditions such as ionospheric activity – given that the initial GNSS epoch was observed during a period of maximum solar activity (Janssen, 2012).

Also, if examining the braced quad network independently, the results comparing these surveys have also shown excellent repeatability. It is expected that the next repeat survey will be undertaken mid-2014, again deploying the outlined methodology with good results.

6 CONCLUDING REMARKS

Now that two repeat surveys have been completed under essentially the same conditions and using the same Phase Two methodology, NSW Public Works has been able to derive a number of conclusions over a range of topics. Foremostly, this project has been a good example of the rigour and reliability afforded by the CORSnet-NSW network. CORSnet-NSW has been used in a challenging and dynamic environment to provide precise absolute survey control across a site where construction activities tend to compromise lines of sight required by total station. The CORSnet-NSW network also has the benefit of being a legally traceable external reference frame, alleviating concerns about the stability or otherwise of primary control networks that may be potentially compromised by the very construction activities that they are intended to be used in the monitoring of.

In a geometric sense, it is important to highlight the flexibility afforded by the braced quadrilateral network which allowed NSW Public Works surveyors to effectively overcome the difficulties of a dynamic environment without compromising rigour and geometric integrity. By its very nature, a monitoring survey demands a stable foundation for the survey control network. This site in particular is not stable: it is dynamic and currently affected by construction activity which brings many issues to the fore. Into the future, this site will be an operational port and it will therefore continue to be a dynamic environment that will present challenges for the execution of precise monitoring surveys, but the integrated CORSnet-NSW/braced-quad solution provides the stability, redundancy and flexibility that is required to achieve high-quality results that can be relied upon by the client now and into the future.

This project has shown that by applying lateral thinking and integrating a combination of reliable survey techniques and software, new methodologies can be developed to overcome dynamic and challenging environments to achieve high-quality precision results. With assistance from Land and Property Information (LPI) colleagues, NSW Public Works surveyors have been able to research and develop alternative methodologies that provide reliable and high-quality results to the client in order to help them meet their obligations by the most efficient and accurate means.

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REFERENCES

Anderson J.M. and Mikhail E.M. (1998) *Surveying: Theory and practice* (7th edition), McGraw-Hill, 1200pp.

Eckl M.C., Snay R.A., Soler T., Cline M.W. and Mader G.L. (2001) Accuracy of GPS-derived relative positions as a function of interstation distance and observing-session duration, *Journal of Geodesy*, 75(12), 633-640.

Janssen V., Haasdyk J., McElroy S. and Kinlyside D. (2011) CORSnet-NSW: Improving positioning infrastructure for New South Wales, *Proceedings of SSSI Biennial Conference (SSSC2011)*, Wellington, New Zealand, 21-25 November, 395-409.

Janssen V. (2012) Likely impact of the approaching solar maximum on GNSS surveys: Be alert but not alarmed, *Proceedings of Association of Public Authority Surveyors Conference (APAS2012)*, Wollongong, Australia, 19-21 March, 66-82.

LPI (2014) CORSnet-NSW, http://www.corsnet.com.au/ (accessed Jan 2014).

Wang G. (2011) GPS landslide monitoring: Single base vs. network solutions − A case study based on the Puerto Rico and Virgin Islands permanent GPS network, *Journal of Geodetic Science*, 1(3), 191-203.