High-Productivity, High-Efficiency, Wide-Area Ground Subsidence Monitoring: A Blended Technique

Brady Rengger
Geodata KODA Australia
Brady.Rengger@geodatakoda.com
Steven Garlinge
Geodata KODA Australia
Steven.Garlinge@geodatakoda.com
Craig Roberts
School of Civil and Environmental Engineering
University of New South Wales
c.roberts@unsw.edu.au

ABSTRACT

With tunnelling forming a crucial backbone to Sydney's transport future, unique and challenging demands are imposed on surveyors to accurately measure and detect ground settlement from tunnelling activities. In one section of a recent mega-project, a wide zone-of-influence caused by groundwater drawdown required daily measurements from a distant, stable reference. Existing levelling methods were questioned, and alternatives were sought. To adapt to these requirements, a unique One Person Levelling method was created to fulfill client requirements and satisfy resource constraints. One Person Levelling is a high-productivity, high-efficiency total station levelling technique designed primarily for ground settlement monitoring. Monitoring performance of the method is to a high standard of accuracy and a high level of reliability. Originally written as an undergraduate thesis for a Bachelor of Surveying / Civil Engineering at the University of New South Wales (UNSW) with support from Geodata KODA, which received the Excellence in Surveying and Spatial Information (EISSI) University Student Project Award 2021, this paper is a condensed outline of the One Person Levelling method, containing more recent results since the original submission. Details on further testing and improvements to the technique are also discussed.

KEYWORDS: *Ground subsidence monitoring, groundwater drawdown settlement, One Person Levelling, precision levelling.*

1 INTRODUCTION

Tunnelling is an important augmentation in shaping infrastructure in large cities. It forms a crucial alternative path for traffic flow around cities. Sydney is one example of a city that is transforming its infrastructure utilising motorway and metro tunnels. A key concern by both community stakeholders and contractors during tunnel excavation is the issue of ground settlement. As specialists in measurement, surveyors play an important role in measuring and reporting on such ground movement. Numerous examples of current tunnelling projects in Sydney are presenting challenges for monitoring engineers. The ability to accurately detect and report on significant ground settlement was tested, leading to a realisation that innovation was necessary to transform existing methods into something more suitable for the task at hand.

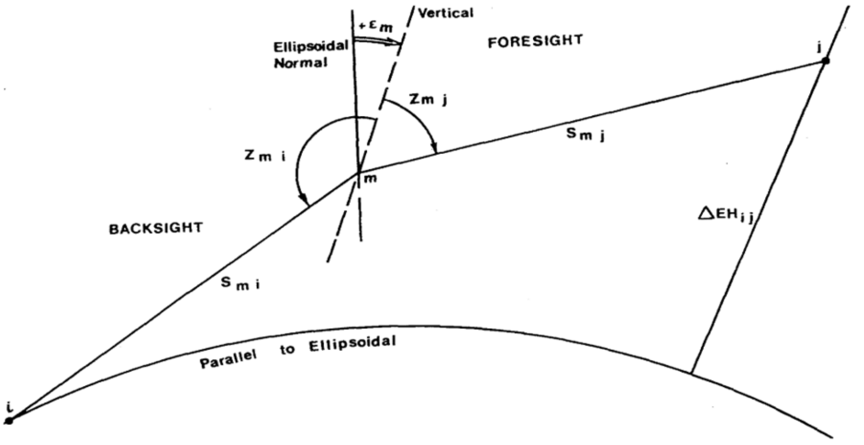
To address this issue, a unique One Person Levelling method was created to provide a high-productivity, high-efficiency total station levelling technique designed primarily for ground settlement monitoring. Originally undertaken as an undergraduate thesis for a Bachelor of Surveying / Civil Engineering at the University of New South Wales (UNSW) with support from Geodata KODA, which received the Excellence in Surveying and Spatial Information (EISSI) University Student Project Award 2021, this paper outlines this new approach, shows that monitoring performance is to a high standard of accuracy and reliability, incorporates more recent results and discusses details on further testing and improvements to the technique.

2 BACKGROUND

The unique monitoring requirements prompted the deployment of uncommon levelling techniques such as Total Station Differential Levelling (ICSM, 2020). A combination of wide-area ground subsidence from groundwater drawdown and levelling sections consisting of very steep topography necessitated the use of these techniques. Monitoring of building movement using purpose-built reflectors was an additional requirement of the project, which is well suited to this method.

2.1 Total Station Differential Levelling (TSDL)

Total Station Differential Levelling (TSDL) is one of the methods of precise Electronic Distance Measuring (EDM) height traversing outlined by Rüeger and Brunner (1981, 1982), which combines measured zenith angles with slope distances to a fixed height pole. Using these measurements, the height difference between two points can be calculated. Backsight and foresight differences are minimised as per traditional levelling. An instrument operator aims the total station at an assistant who holds the reflector pole plumb on top of a survey point (often a nail or change plate, bipod recommended). Measurement sequences and workflows follow conventional precision levelling. The principle is illustrated in Figure 1, with the corrections for the deviation from the vertical (*DE*), earth curvature (*CU*) and refraction (*RE*) shown. *R* is the radius of ellipsoid, *k* is the coefficient of refraction, and ε is the deviation from the vertical.



$$\Delta EH_{ij} = S_{mj} \cos Z_{mj} - S_{mi} \cos Z_{mi} - DE + CU - RE$$

$$DE = \epsilon_m (S_{mj} \sin Z_{mj} + S_{mi} \sin Z_{mi})$$

$$CU = \frac{1}{2R}\{(S_{mj} \sin Z_{mj})^2 - (S_{mi} \sin Z_{mi})^2\}$$

$$RE = \frac{1}{2R}\{(S_{mj} \sin Z_{mj})^2 k_{mj} - (S_{mi} \sin Z_{mi})^2 k_{mi}\}$$

Figure 1: Principle for measuring a height difference using TSDL (Rüeger and Brunner, 1982).

2.2 Wide-Area Subsidence from Groundwater Drawdown

Both due to human-induced and natural causes, the theory of effective stress in soils states that as the water level changes in the soil, so does the effective stress from the change in pore water pressure, therefore resulting in the heave or subsidence of the soil (Terzaghi et al., 1996). In certain geotechnical environments, a drop in the water table (from tunnelling or other external causes) can lead to widespread ground settlement. When water retreats from a soil medium, known as 'pore water loss', soil particles consolidate (squeeze closer together). Since there is no water between particles, the soil medium shrinks in size, leading to settlement. This is known as the process of soil consolidation.

Groundwater drawdown is expected by geotechnical engineers during tunnelling because excavation exposes saturated rock, which leads to water seeping into the freshly cut tunnel. Most of the time, seepage derives from rock layers that do not cause settlement, therefore 'volume loss' settlement may be the only concern.

2.3 The Need for an Alternative

Tunnel construction progress and design require many points over a large area to be measured daily (Monday to Sunday). With existing methods, the time taken for measuring points was lengthy and caused capacity constraints for monitoring deliverables. This created a need for a high-productivity, high-efficiency levelling method that could still deliver on client requests, but also alleviate resource constraints.

The need for an alternative was recognised and supported by the project. The existing, robust levelling network allowed for innovation to be explored with a fallback should any complications with the alternative arise. This alternative formed a 6-month research and experimentation opportunity for an Honours research thesis at UNSW and a path for Geodata KODA to advance a technique suitable for unique monitoring circumstances. The solution was a levelling technique, which blends existing total station differential levelling with purpose-built processes requiring only one surveyor.

3 THE ONE PERSON LEVELLING (OPL) TECHNIQUE

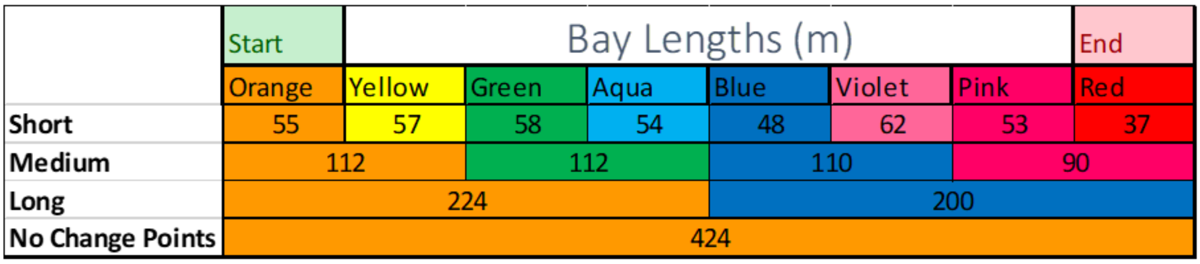
The One Person Levelling (OPL) method takes inspiration from the TSDL principles and augments this with permanent reflectors mounted to structures (telegraph poles in most cases) to mimic an assistant holding a reflector pole over a nail to act as a change point. Any monitoring points (often cats-eye reflectors glued to ground and building structures) were then delegated as intermediate sights.

During this project, OPL networks for monitoring were kept simple, holding all measurements fixed against their respective starting points. These starting heights were applied to specifically chosen stable benchmarks, well outside the zone of settlement influence. These starting benchmarks were in turn connected to far-field established survey marks external to the zone of influence, enabling far field check surveys to be undertaken with conventional TSDL. A closing benchmark at the end of an OPL line allowed for a misclose check to be recorded for all rounds of measurements. On occasion, when these points were also affected by far-reaching settlement, check surveys were required to calculate corrections for closing benchmark points.

3.1 Loseby Park Test – A Preliminary Investigation

Prior to applying the method in a monitoring scenario, a test site was set up to examine the quality of the method as a simple height transfer technique. The site chosen at the time was Loseby Park. It was a long, open, straight stretch of road with similar, urban conditions to the future area of application. Each levelling bay was defined by power poles along the eastern side of the road. These would serve as objects to mount spigot prisms for the experiment. As shown in Figures 2 & 3, different bay lengths were measured so that their overall misclose quality can form a basis behind the design of a monitoring OPL network. The different colours indicate the unique bays.

Figure 2: Plan view of the Loseby Park / Bowral Hospital site, with each of the bays represented by a different colour and an approximate distance shown (imagery obtained from Nearmap).



	Start	Bay Lengths (m)						End
	Orange	Yellow	Green	Aqua	Blue	Violet	Pink	Red
Short	55	57	58	54	48	62	53	37
Medium	112		112		110		90	
Long	224				200			
No Change Points	424							

Figure 3: Different bay lengths for the four separate experiments (colour coding indicates the different bays).

On each power pole, two 11R2-40W wall bolts were drilled into them so that the prisms could be attached. One was placed at eye height (approximately 1.7 m from ground level) and the other was placed at about ground height to highlight any ground proximity effects (about 200 mm above the ground surface, i.e. high enough not be obstructed by grass). L-bar mini prism reflectors were chosen as the four permanent start and end benchmarks. Examples of the reflectors used are shown in Figures 4 & 5.

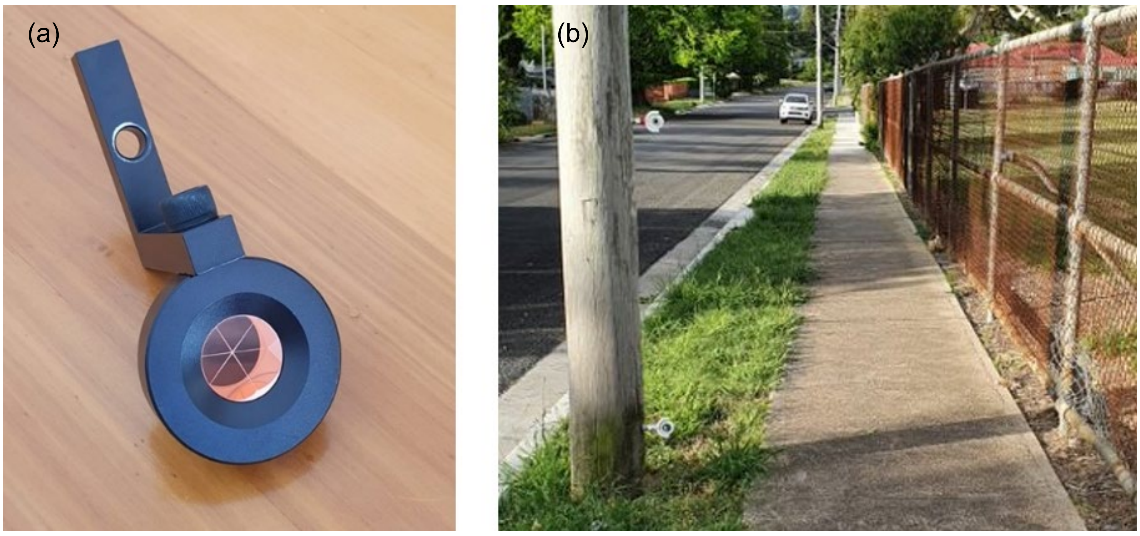


Figure 4: (a) L-bar mini prism (the reflector chosen for the start and end benchmarks), and (b) example of two spigot prisms attached to a pole at both eye and ground height.

Figure 5: Spigot reflectors mounted to a power pole. The spigot screws into a 'wall plug' that rests firmly inside a hold drilled into the pole. The reflector can turn freely on two axes in any direction, allowing measurements of the same point to be taken from both sides.

The instrument used was a Leica Nova TS60 0.5" total station, chosen for its precise angular measurements and rapid telescope transitioning with its piezoelectric motors. The A'B'B"A" measurement sequence in the 'measure sets' application was used at each setup to measure the four points, i.e. the eye-height backsight, the ground-height backsight, the ground-height foresight and the eye-height foresight, respectively. It should be noted that eye-height measurements and ground-height measurements were taken on two separate sets of measurements, with the instrument being relevelled between taking eye-height measurements and ground-height measurements. Each new day of taking measurements consisted of carrying out a check and adjustment (if required) of the instrument.

Before any OPL measurements were taken, a controlled levelling run using TSDL was carried out to measure absolute height differences between benchmarks. This formed the control height differences between benchmarks to be compared with any height differences between the OPL experiments.

3.2 Preliminary Test Results

Overall testing at Loseby Park took approximately 50 hours to carry out reconnaissance, install the points and observe. This was spread out over 7 weeks on 9 individual days. For a total length of 850 m (forward and backwards), the allowable misclose was 1.8 mm based on the 1st order levelling misclose of $2\sqrt{k}$ tolerance with k being the distance in km (ICSM, 2020).

Across all 40 sets of results, two had to be repeated due to two accounts of misdirected pointing of Automatic Target Recognition (ATR) during one of the sets of measurements. The affected surveys were a short bay-length run for eye-level prisms on 10 October 2020 and a medium bay-length run at eye-level on 23 September 2020. Both were re-taken on the last day of experiments (20 October 2020) to ensure a full set of results were achieved. The results for all measurements are summarised in Tables 1-4.

Table 1: Misclose summary for multiple arcs.

Misclosure - Short (mm)			Misclosure - Medium (mm)			Misclosure - Long (mm)			Misclosure - No Change Point (mm)		
Date	**Eye**	**Ground**	**Date**	**Eye**	**Ground**	**Date**	**Eye**	**Ground**	**Date**	**Eye**	**Ground**
23-Sep	-0.2	-0.9	17-Oct	0.4	-1.0	17-Oct	0.8	-2.3	17-Oct	-0.4	0.8
30-Sep	0.1	0.7	14-Oct	-0.3	-0.8	14-Oct	-0.4	-1.5	14-Oct	-0.3	1.1
10-Oct	0.1	-0.9	13-Oct	0.1	-0.1	13-Oct	-0.3	1.3	13-Oct	1.3	0.1
14-Oct	-0.3	-0.4	10-Oct	0.1	-0.1	10-Oct	0.1	-1.8	10-Oct	0.3	-0.1
20-Oct	0.4	-1.2	20-Oct	0.6	0.5	23-Sep	0.2	-0.3	23-Sep	0.0	0.3
std	**0.2**	**0.7**	*std*	**0.3**	**0.5**	*std*	**0.4**	**1.3**	*std*	**0.6**	**0.4**
average	**0.2**	**0.8**	*average*	**0.3**	**0.5**	*average*	**0.3**	**1.4**	*average*	**0.5**	**0.5**
max	**0.4**	**1.2**	*max*	**0.6**	**1.0**	*max*	**0.8**	**2.3**	*max*	**1.3**	**1.1**
min	**0.1**	**0.4**	*min*	**0.1**	**0.1**	*min*	**0.1**	**0.3**	*min*	**0.0**	**0.1**

Table 2: Summary of all measurements taken (eye- and ground-level measurements separated, including overall results).

	Eye (mm)	Ground (mm)	Overall (mm)
std	**0.4**	**0.9**	**0.8**
average	**0.3**	**0.8**	**0.6**
max	**1.3**	**2.3**	**2.3**
min	**0.0**	**0.1**	**0.0**

Table 3: Misclose summary for single arcs.

Misclose - Short			Misclose - Medium			Misclose - Long			Misclose - No Change Point		
Short	Eye	Ground	Short	Eye	Ground	Short	Eye	Ground	Short	Eye	Ground
23-Sep	0.0	-1.1	23-Sep	-0.2	0.5	23-Sep	-0.7	-1.4	23-Sep	0.4	0.2
30-Sep	-0.1	1.0	30-Sep	0.9	0.6	30-Sep	0.0	-1.0	30-Sep	1.9	0.3
10-Oct	0.5	-0.7	10-Oct	0.3	0.5	10-Oct	0.6	0.4	10-Oct	-8.4	3.2
14-Oct	-0.2	-1.1	14-Oct	-0.3	-1.6	14-Oct	0.7	-1.3	14-Oct	-0.9	3.3
20-Oct	-0.2	-1.2	20-Oct	-1.0	-1.4	20-Oct	-0.7	-6.7	20-Oct	-0.2	2.3
std	**0.3**	**0.8**	*std*	**0.6**	**1.0**	*std*	**0.6**	**2.4**	*std*	**3.6**	**1.3**
average	**0.2**	**1.0**	*average*	**0.5**	**0.9**	*average*	**0.5**	**2.2**	*average*	**2.4**	**1.9**
max	**0.5**	**1.2**	*max*	**1.0**	**1.6**	*max*	**0.7**	**6.7**	*max*	**8.4**	**3.3**
min	**0.0**	**0.7**	*min*	**0.2**	**0.5**	*min*	**0.0**	**0.4**	*min*	**0.2**	**0.2**

Table 4: Summary of all measurements taken, single two-face measurements only (eye- and ground-level measurements separated, including overall results).

	Eye (mm)	Ground (mm)	Overall (mm)
std	2.0	2.1	2.0
average	0.9	1.5	1.2
max	8.4	6.7	8.4
min	0.0	0.2	0.0

While a lot can be extrapolated from these results across all four tables, the key highlights are:

- Miscloses were tighter in eye-height prisms than in ground-level prisms, which can be explained by well documented ground proximity refraction.
- A notable decline in misclose quality can be seen in results for measurements not using any change points (longer distance, benchmark-to-benchmark height differences).
- When analysing results for single sets of two-face measurements (as opposed to averaging three in total), there is only a miniscule difference to the overall misclose quality. Having tested different bay lengths in the preliminary investigation and should the need arise, long sighting distances between backsights and foresights could therefore be integrated with an OPL monitoring network without considerable impact to result quality. Balancing foresight and backsight distances remains paramount.

4 APPLICATIONS TO SETTLEMENT MONITORING

Recall that the motivation for developing this method was to use it as a reliable way to measure ground subsidence in unique circumstances with large zones of influence and with fewer resource constraints. The Loseby Park data shows OPL to be a reliable method to transfer height accurately and precisely. This section outlines how the method was used in a monitoring scenario over a period exceeding 12 months and its success as a monitoring technique. Custom-built reflectors (Figure 6) were used as network change points. These reflectors have only 0.3 mm of separation between them but are uncalibrated. Since these prisms are used repeatedly in successive surveys, any absolute error is cancelled out in monitoring results. Once established, the system is monitoring for 'change' relative to a known reference state.

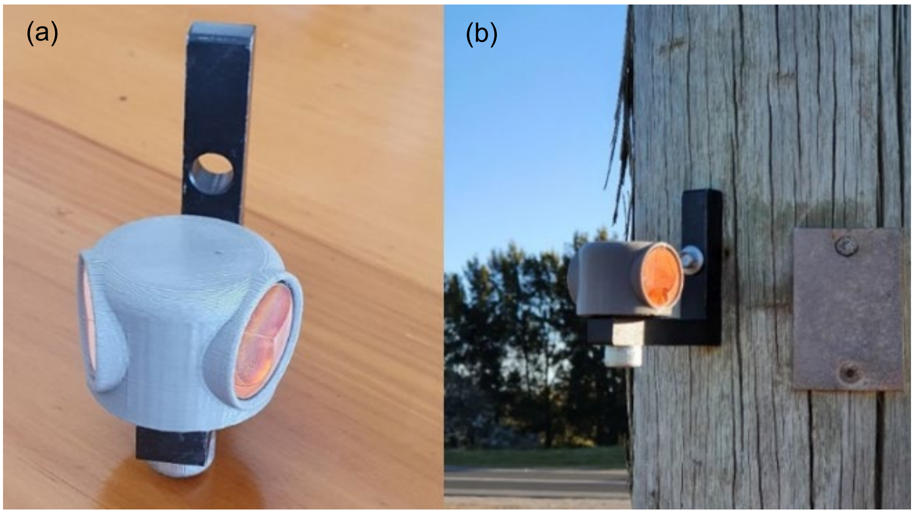


Figure 6: (a) Custom-made 3D printed housings with mini prisms glued into them for a 'back-to-back' fit, and (b) example of an L-bar prism mounted onsite.

Unfortunately, this does leave an OPL network vulnerable to these reflectors being vandalised or stolen, therefore requiring replacement. However, it is assumed that the error differences between each of these reflectors is marginal and hence has negligible impacts on monitoring quality. Figure 7 shows the reflectors used as intermediate sights for monitoring the ground surface.

Figure 7: (a) Cats-eye prism ground target glued to a footpath, (b) underside of a ground target, and (c) megapoxy glue used for installation of ground targets.

4.1 Benchmark-to-Benchmark Height Differences

Initially, an OPL line was designed to close on a ‘stable’ benchmark, which was assumed to be unaffected by the groundwater drawdown. Based on early measurements, this would act as a floating benchmark that would provide a quality check on the overall run based on a daily misclose onto this point. These miscloses were calculated based on the first ‘baseline’ survey of the line, setting the control survey tolerance of $2\sqrt{k}$ as a guideline for overall quality.

This benchmark misclose check later became redundant since the subsidence effect was wider than expected, therefore compromising this point as a stable check. Results were still useful, as it eventually stopped moving and could still be used for examining the overall change in height differences between the benchmarks. This could be further verified through its ties to the existing TSDL network via check surveys. As can be seen from Figure 8, the TSDL measurements followed the same trajectory as the OPL change in height differences. It is important to note that while the two methods agree, TSDL and OPL cannot be perfectly compared based on absolute height differences. This is due to the un-quantified errors from the minor prism separation in the purpose-built OPL reflectors. Therefore, comparing the two methods based on the change in height differences cancels out these errors.

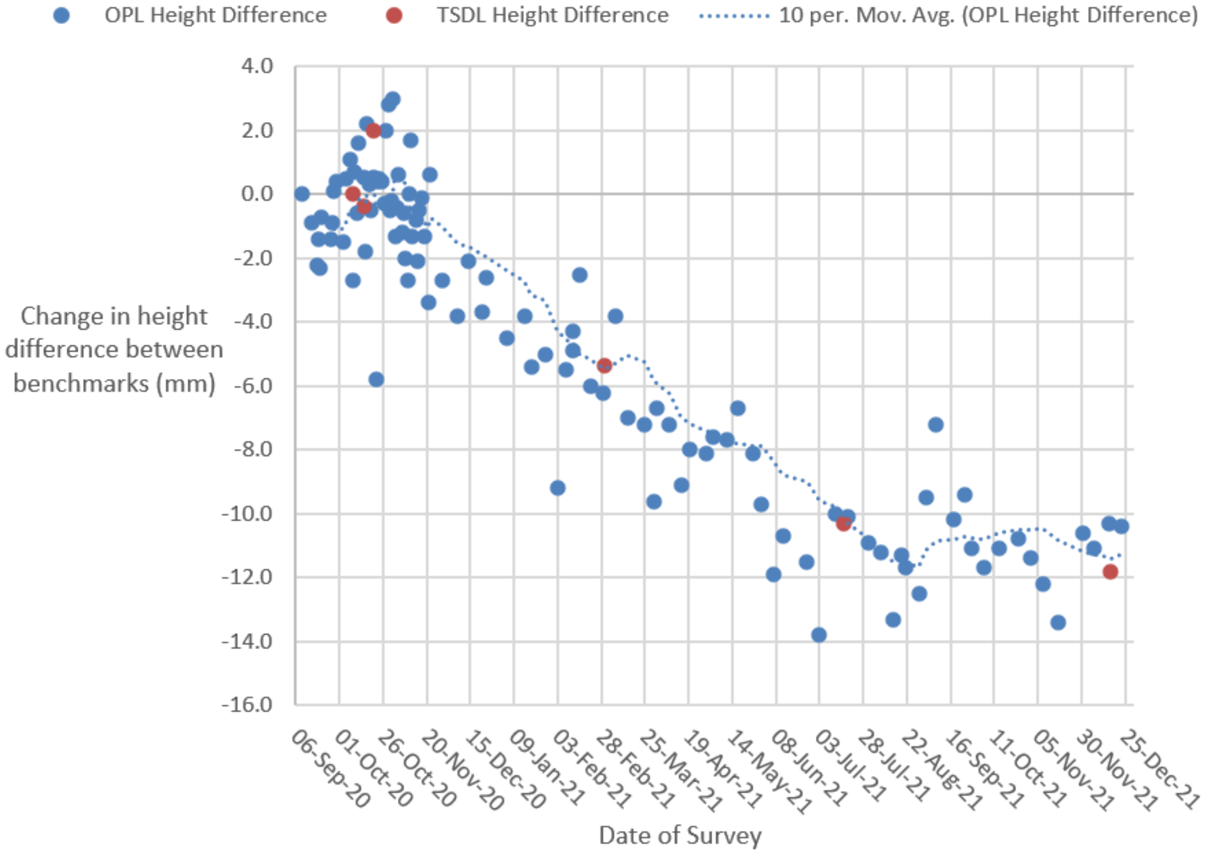


Figure 8: Overall spread of benchmark-to-benchmark height differences for all surveys at the monitoring site.

4.2 OPL vs. TSDL

A total of 14 check points were measured that could be referenced directly against TSDL. The point exhibiting the most movement has been chosen to demonstrate results. Figure 9 shows an example of how close the levelling nails were in relation to the cats-eye monitoring prism. For the most part, OPL monitoring was conducted daily, and then tapered off to a weekly schedule thereafter. TSDL check surveys were initially carried out weekly but were then reduced to a monthly schedule as per client requests.

Figure 9: Levelling nail (left) adjacent to a ground target (right) on the kerb, in close enough proximity to check if movements between the marks are consistent.

Figure 10 clearly shows that the monitoring results of the OPL technique were very accurate. The few check surveys conducted (in orange) closely follow the movement trajectory of OPL. It is quite clear that the TSDL measurements provided ‘smoother’ results, with OPL being fairly 'spikey' between successive surveys, with measurements jumping up and down by 2-3 mm in some places. Across the sample period, the same Leica Nova TS60 total station was used every day, including the TSDL check surveys. While the operator of the instrument varied depending on the day, this did not appear to have significant effects on the results. Both TSDL and OPL results were in strong agreement.

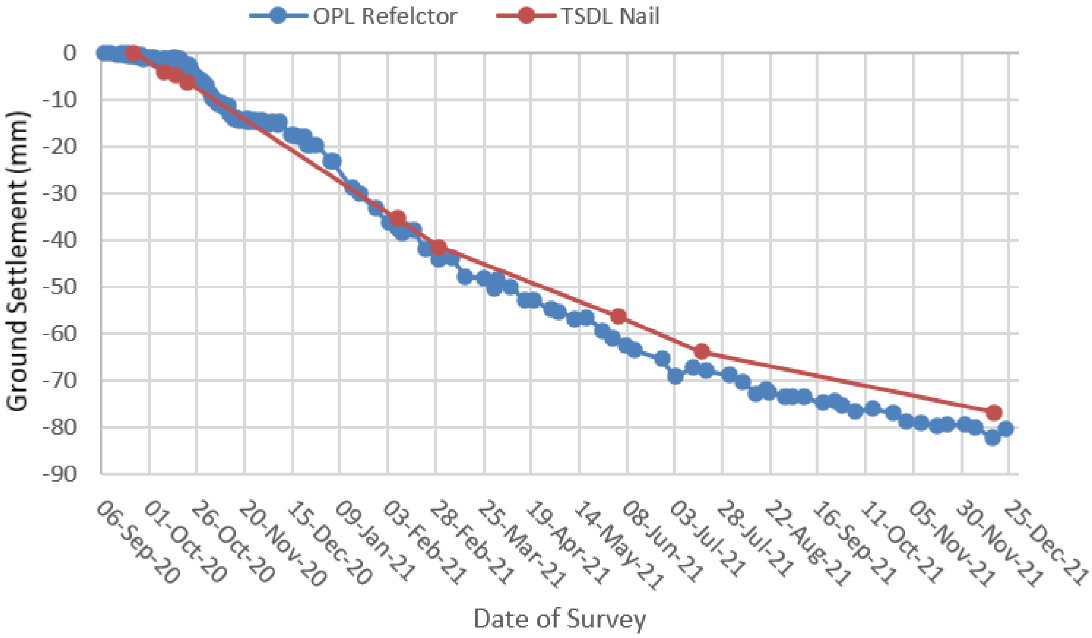


Figure 10: Movement of a specific point demonstrated by measuring with both OPL and TSDL.

It should also be noted that the 'spikiness' of movement vectors indicates the high susceptibility to errors. One characteristic of the simple network design is that if at any point a certain bay has low quality measurements, this gets propagated through to all measurements. As mentioned above, since measurements are from the same operator and instrument serial number, time of day and weather could be the main cause of inconsistency in measurements. Most measurements therefore would have been taken in the afternoon where temperature gradients are larger, hence leading to effects of refraction causing dips and spikes.

4.3 OPL vs. Digital Levelling

Often overlooked (or unspecified at the start of monitoring) is the criteria for 'closing out the monitoring campaign'. In this instance, a value of less than 1 mm/week of subsidence was designated as the basis for consideration of cessation of monitoring. Since OPL's repeatability is of that magnitude, digital levelling was incorporated into the measurement regime. It is worth acknowledging that OPL was proven to be successful using TSDL, not digital levelling. The growing engineering interest in the site's data and the monitoring team's interest in a comparison with the higher-precision digital levelling method led to these investigations. Therefore, to track slower rates of movement and an eventual zero movement, levelling points were installed adjacent to historical OPL points (Figure 11). These were then incorporated into the existing TSDL check network and measured with a digital level.

Initial measurements taken with a Leica LS15 0.3 mm accurate digital level showed that movements observed by the LS15 match the underlying movement measured by OPL. Figure 12 shows how closely aligned the two datasets are. Furthermore, the starting benchmarks for both OPL and digital levelling were maintained in close proximity (Figure 13), so that in the event of any change, the error will be present in both sets of results. Ideally, all measurements were to be observed on the same day for trueness, but this was not always possible. For digital levelling, a 2 m invar staff was used for all points, with the LS15 being calibrated by a two-peg test each day.

Figure 11: Levelling point glued just below the building mark reflector for OPL (including invar staff on right).

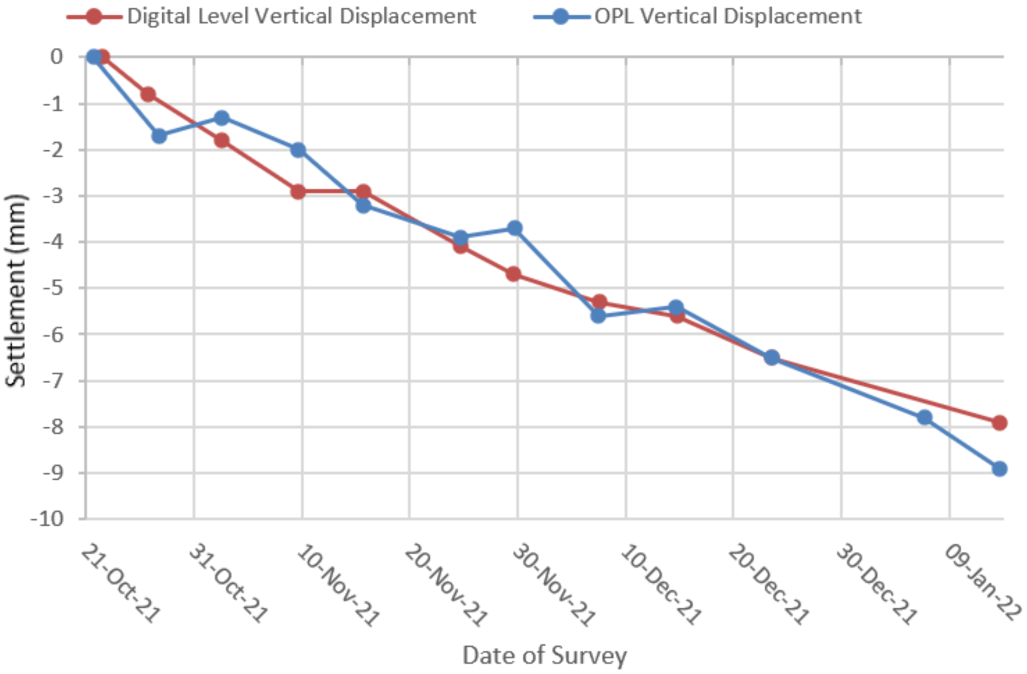


Figure 12: Movement chart comparison between OPL (blue) and digital level (red).

Figure 13: Close proximity of the starting benchmark reflector for OPL (left) and the starting nail for digital levelling below the 2 m invar staff (right).

5 DISCUSSION OF PERFORMANCE

The OPL method has provided impressive monitoring quality and has since been adopted along different areas of the project. While it is most suited for the unique conditions described earlier, more traditional methods of monitoring ground movement should always be used to check the quality of any OPL results. It is important to always incorporate a reliable control check for an OPL line. Having all measurements tied to one fixed benchmark makes data more vulnerable to compromised results, hence trusting a single starting benchmark is not sufficient to achieve high-quality OPL results.

5.1 Comparison between Levelling Techniques

Along a suitably flat and straight test line (approximately 400 m in length one-way), all three levelling methods were tested to analyse the time required to complete the measurement. Table 5 summarises the time taken to complete a double run with each of the three methods, and the respective number of setups. Times were from the first measurement to the last, where TSDL and digital levelling occupied exactly the same setups and where no intermediate sights were taken for either method. The digital level was taking an average of six measurements, and the TS60 was measuring three sets of two-face shots to each backsight and foresight. OPL is unique in this case due to the nature of having to place the special reflectors on power poles, and design setups around them. OPL only took one set of two-face measurements to each backsight and foresight for a double-run survey.

Table 5: Time and number of setups comparison between the three methods (measurements carried out along the same distance).

Method	Time (min)	Setups
TSDL	75	14
Digital Levelling	46	14
OPL	34	12

Based on Table 5, TSDL has an average setup time of 5.3 minutes, digital levelling is 3.3 minutes, and OPL is 2.8 minutes. With half a minute difference between OPL and digital levelling, this makes for a negligible time comparison. However, it is important to note that for both TSDL and digital levelling, two team members were required as opposed to only one for OPL. Therefore, OPL is reliable and efficient as a one-person operation. Data processing for measurements using the digital level is not needed because all heights are adjusted with the onboard firmware. Both OPL and TSDL require post-processing adjustments and calculations to determine results before they can be of any use.

5.2 Lessons Learnt for Future Use

When setting out future monitoring arrays where OPL is deployed, a few key take-aways have been identified. The first is to have a rigorous and robust far-field connection to stable height control. While a starting benchmark is intended to be outside the zone of influence of settlement, connecting this point to control further away is always suggested as it can verify any suspicious movement that may have occurred at this point. Furthermore, these check surveys should be neatly documented for traceability and record any adjustments that may need to be made to starting heights.

Secondly, having an efficient and reliable system for processing OPL results is necessary for good performance of the method. Initially, raw slope distances and zenith angles were exported in addition to measured 3D monitoring results. These raw measurements were used to calculate movement against the starting benchmark and to then adjust monitoring points and control heights for each setup manually. Since then, processing has improved, no longer requiring raw slope distances and zenith angles for post-processing adjustments. Results are now adjusted based on calculated height differences from the 3D exported measurement, where an efficient least squares processing spreadsheet uses these height differences to calculate their adjusted heights based on the starting benchmark. While processing has improved, an enhancement would be firmware that can execute all levelling calculations onboard the instrument, so that unadjusted point movement can be detected in real-time in the field.

6 CONCLUDING REMARKS

Tunnelling in urban areas is showing no signs of slowing. If anything, it is set to increase. With these projections, greater importance will be shouldered by surveyors to measure and report on accurate and consistent ground settlement as a result of tunnelling. The onus is then on surveyors to provide reliable deliverables to construction and design engineers. Anything less cultivates a distrust in the profession and hence the ability to innovate further. It is crucial for a monitoring engineer to have deliverables and workflows to assess monitoring data reliably and regularly against the project limits.

This paper has outlined OPL as a new approach, showing that monitoring performance is to a high standard of accuracy and reliability. OPL is one solution to a unique problem, with the potential to be progressed for other uses that are not yet realised. The method is used as part of a tailored monitoring campaign that skilfully balances resources against precision requirements during the different construction phases. Different rates of movement and overall magnitude will dictate the most appropriate method.

REFERENCES

ICSM (2020) SP1 Guideline for control surveys by differential levelling, version 2.2, https://www.icsm.gov.au/standard-australian-survey-control-network-special-publication-1-sp1 (accessed Mar 2022).

Rüeger J.M. and Brunner F.K. (1981) Practical results of EDM-height traversing, *Australian Surveyor*, 30(6), 363-373.

Rüeger J.M. and Brunner F.K. (1982) EDM-height traversing versus geodetic levelling, *The Canadian Surveyor*, 36(1), 69-88.

Terzaghi K., Peck R.B. and Mesri G. (1996) *Soil mechanics in engineering practice* (3rd edition), John Wiley & Sons, New York, 534pp.