

Construction and Post-Construction Deformations of an MSE Wall using Terrestrial Laser Scanning



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ABSTRACT

Terrestrial Laser Scanning (TLS) is a surveying tool that can create a 3D point cloud by shooting a web/mesh of laser points in different station locations in a 360° range of its surroundings. These scans can be registered to align itself from like surfaces, points, or objects and can be accompanied with pictures to create context and colour to the surfaces. The use of this technology can range from measuring dimensions of existing structure conditions for renovations, deformation monitoring of natural slopes, and risk management for rockslides on mountain sides. A laser scanner was used to measure settlements from the Mechanically-Stabilized Earth (MSE) wall abutments. The results were compared with the readings from a total station to determine its reliability and compatibility for applications in civil construction applications.

RÉSUMÉ

Le balayage laser terrestre (TLS) est un outil de mesure permettant de créer un nuage de points en 3D en réalisant une toile / un maillage de points laser dans différents emplacements de station sur une plage de 360 ° de son environnement. Ces numérisations peuvent être enregistrées pour s'aligner sur des surfaces, des points ou des objets similaires et peuvent être accompagnées d'images pour créer un contexte et une couleur pour les surfaces. L'utilisation de cette technologie peut aller de la mesure des dimensions des conditions de structure existantes pour les rénovations au suivi de la déformation des pentes naturelles, en passant par la gestion des risques pour les éboulements rocheux sur les flancs des montagnes. Un scanner laser a été utilisé pour mesurer les colonies à partir des culées murales en Terre stabilisée mécaniquement (MSE). Les résultats ont été comparés aux lectures d'une station totale afin de déterminer sa fiabilité et sa compatibilité pour des applications dans les applications de construction civile.

1 PROJECT BACKGROUND

The McOrmond-College drive bridge interchange in Saskatoon is a project that began construction in April 2018. The interchange was first proposed in order to help alleviate heavy traffic as the commuter population in that area has grown steadily over the years, causing more fuel consumption from the increased traffic delays (City of Saskatoon, 2017). The bridge interchange has 2 lanes of traffic for the 80km/h speed limit College drive roadway and 2 lanes for Northbound McOrmond drive and one lane for Southbound at 60km/h. The bridge has 3 lanes over the existing College drive. The bridge structure is supported by a total of 21 Cast-In-Place (CIP) belled piles. Approach fills for the bridge are approximately 8 to 9 m high and have an MSE wall face running parallel to College Drive.

The approach fills are supported by a total of 240 vibration-compacted stone columns (120 each at the North and South Abutments). The maximum estimated settlements for this structure is up to 55mm. The settlements were measured during construction through a combination of settlement plates and surveying of the MSE wall face. A study has been undertaken to determine if Terrestrial Laser Scanning (TLS) can provide a reliable and applicable surveying technique to measure movements in the MSE wall.

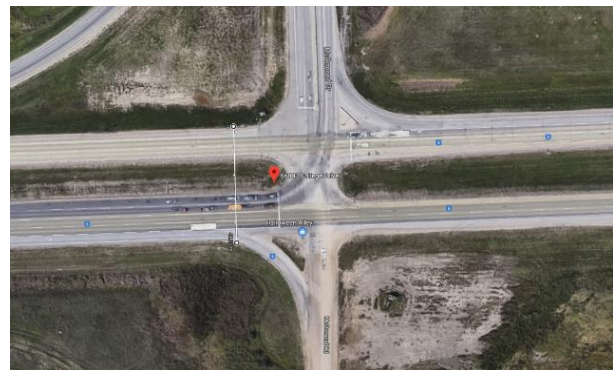


Figure 1 – Existing roadway conditions



Figure 2 Design Rendering Flyover Snapshot (courtesy of PCL)

2 TLS DETAILS

Terrestrial Laser Scanning is a surveying tool that can create a 3D point cloud by shooting a web/mesh of laser points in a 360° range of its surroundings in different station locations. Once points are collected, the laser scanner takes pictures of its surrounding area and overlays them onto the point cloud, colourizing the objects in the scan to create the environment during scanning. Multiple scans can be performed and registered together to create a large scale model of the area, also known as a “project point cloud”. These scans can be registered using like reference targets in paired scan views. The reference targets consist of cooperative targets like spheres and placards, and identifiable targets like the bridge structure and existing objects around the site (Knaak, 2017).

The laser scanner used in this project is the *FARO Focus X330* and the applicable software for data processing is *FARO Scene*. The scanner has a range of 330m with a ranging error of 0.3mm at 10m with 90% reflectivity. Registration of scans were completed by using Target and Cloud-to-Cloud registering. Target registration is when the program best fits the two scan point clouds together using manually selected paired targets. Cloud-to-Cloud registration is the software analyzing the scan points to determine its arrangement with reference targets, depending on user input parameters of subsampling distance, number of iterations, and search distance. Once registration is completed, a report pertaining to mean error, max error, and minimum overlap of the two registered scans is produced for quality assurance as shown in Table



Figure 3 – Project Point Cloud of North Wall on August 28

1. The mean and max point errors are associated with the amount of discrepancy between data points used to register scan point clouds, and the overlap is the percentage of how many data points will overlap during registration.

Table 1 – Registration Report

Scan Cluster	Connections	Mean Point Error (mm)	Max Point Error (mm)	Min Overlap %
004	2	6.0	7.7	54.3
002	2	6.5	7.7	53.2
001	1	5.3	5.3	53.2
003	1	4.2	4.2	80.3

After measurements are collected, registration errors can be taken into account to improve accuracy of results.

3 METHODOLOGY

The laser scanning occurred during construction and post-construction of the bridge to measure wall displacements as the backfill material was built up in lifts. Scanning the first row of panels was crucial to establish baseline position and determine all relative movements. During construction, scans can be performed after each row of panels is erected and monthly after wall completion (Scotland, 2014). Measurements during construction were performed during completion of the first row of concrete panel facings, completion of the last row, and in between (May 9, May 25, and June 2). Post construction, scanning was performed one month and two months after completion (July 5 and August 28), and there is another scan scheduled for May 2019 following the spring thaw, potentially another scan in August 2019 to measure traffic loading effects.

The laser scanner was set up with multiple reference targets that include spheres and targets. The laser scanner started at one end of the wall and completed multiple scans until the whole wall was scanned. For best results, each scan only contained data captured within an incident angle of 45° so bounce back error of the laser was minimized and therefore more scan locations may be required. Target layouts should include three reference targets to orientate



Figure 4 – Actual Photo of North Wall on August 28

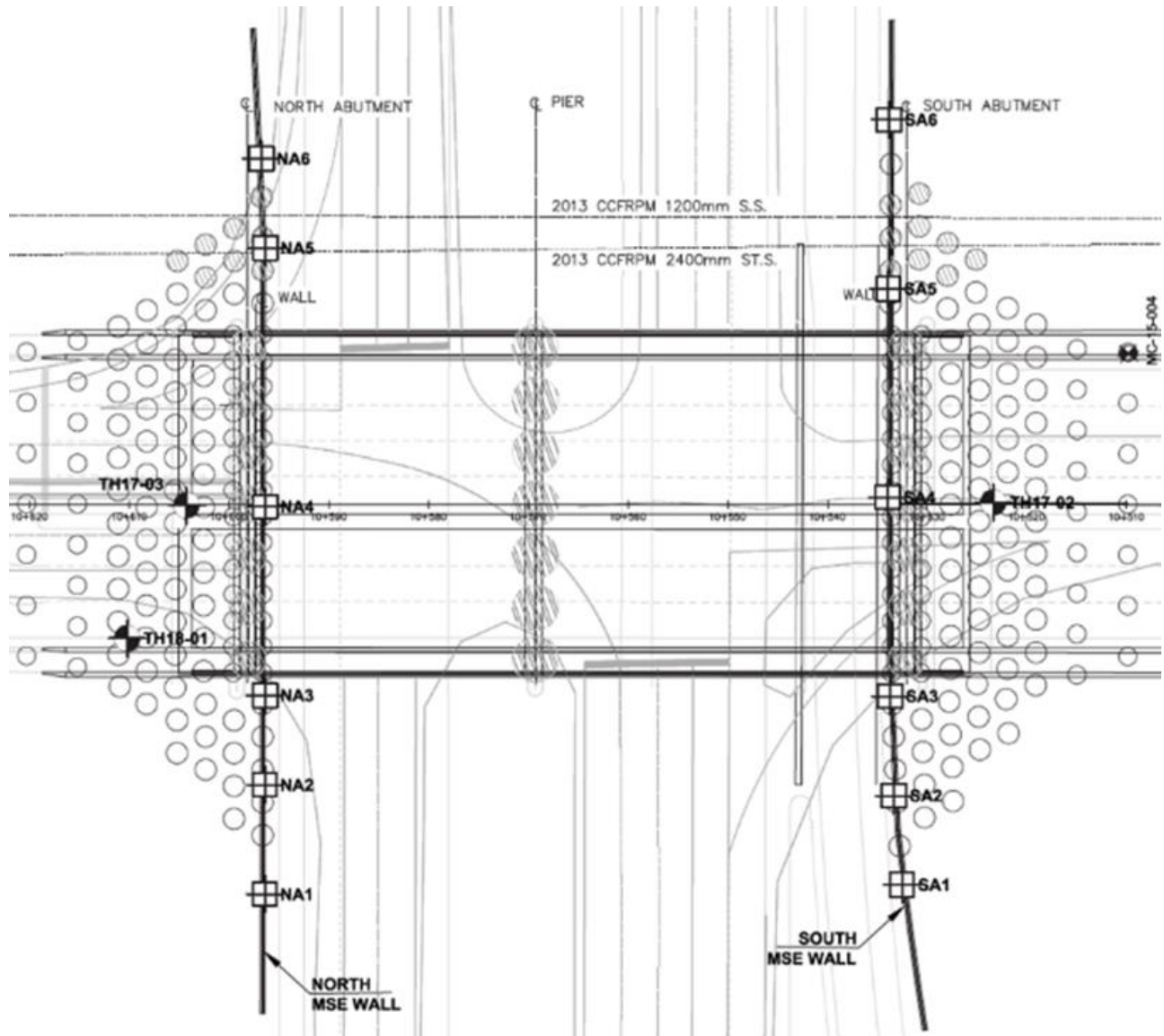


Figure 5 – Measurement Locations (provided by TREK Geotechnical Inc.)

the scans (Laefer & Lennon, 2008) and to try and avoid placing targets in a single line so that it will be easier to combine multiple scans (Knaak, 2017).

The laser scanner performance is compared with soil movements observed from settlement plates and total station measurements along the wall. The contractor on site, PCL Construction, was responsible for measuring the vertical displacements associated with the settlement plates and total station. These measurements were taken in 6 different locations along each wall, as shown in Figure 3, designated as NA1-6 and SA1-6. The laser scanner provided settlement measurements at these locations as well and were directly used for comparison of measurements.

4 SETTLEMENT ANALYSIS FROM TLS

As stated earlier, there were 3 scans during the construction phase of the wall with 2 more scans once the wall was completed. Each scan was set to a resolution of $\frac{1}{4}$ (44MPts) and quality of 4x. This was done to determine the influence of the wall construction lifts while post construction scans will determine the long-term settlement and influence of the erection of embankment lifts. Given that the bridge deck has minimal movements, it was selected for a reference target for registering subsequent point clouds to determine relative movements of the wall. The bridge deck is expected to have 20mm of total settlement (TREK Geotechnical Inc., 2017) and since it was constructed in the summer/fall of 2017, there could already be settlement that occurred before the wall was completed. The benchmarks on site to be used for surveying were established using Real-Time-Kinematic

Survey (RTK). RTK uses satellites to establish the location of the base station by setting up over a benchmark to be referenced for additional survey locations. A handheld rover then communicates with the base station to determine the coordinates of its location, the longer it is held stationary, the more accurate the measurement will be. Because of the variability in measurements, the errors can range from 5mm to 20mm or more. Due to this error variance, the assumption for the bridge deck reference is considered appropriate as a reference location.

For each scan point cloud, there were 4-6 scans performed at each wall. This allowed for areas of suspected large movements to be scanned as well as obtaining the entire profile of the wall. The observed movements from the TLS scans along with their respective rate plots are shown in Figures 6-9. The red dotted line placed on the rate plots depicts the date of completion for installing the concrete panels of the wall.

4.1 North Abutment Analysis

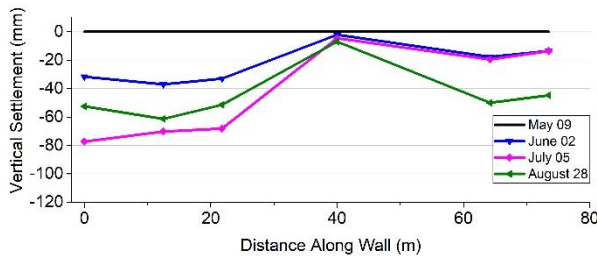


Figure 6 – North Abutment Terrestrial Laser Scanning Settlements

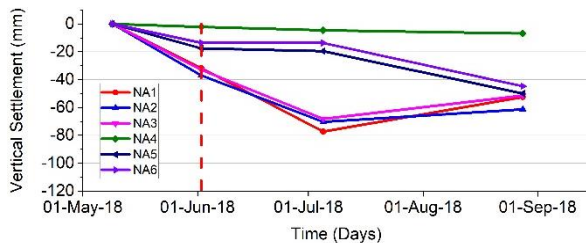


Figure 7 – North Abutment Terrestrial Laser Scanning Rate Plot

The North Abutment settlement profile resembles a 'W' pattern of displacements as shown in Figure 6 where the least settlement is in the centre and the most is at the outer sections. To note, the May 25th (16 days) settlement profile has been omitted as the data received from that comparison was out of error tolerance and did not exhibit the same behaviour as the rest of the scan dates. Looking at the overall profile, the maximum settlement was observed in the July scan with 77mm but looking at the rate plot, the wall is shown to move upwards from July to August on the left side of the graph (0 to 40m). This is due to registration error in the point clouds and more realistic this is an overestimation and the fact that the August 28 scan has a maximum settlement of 52mm gives reason to accept that the July settlement profile is likely an overestimation of the actual movement. The right side of the wall (Distance 40-80m along wall) shows that the July

scan is closer to June than August. This can be due to embankment buildup during construction between July and August and therefore there is the greater settlement in those time steps. A possibility behind this error is during registration of the targets, the wall may be tilted to best fit with its point cloud counterpart.

Looking at Figure 7, the rate and amount of settlement for both ends of the wall are similar to one another, which is good indication that differential settlement is not a concern as the criteria is set to a maximum of 1% along the wall.

4.2 South Abutment Analysis

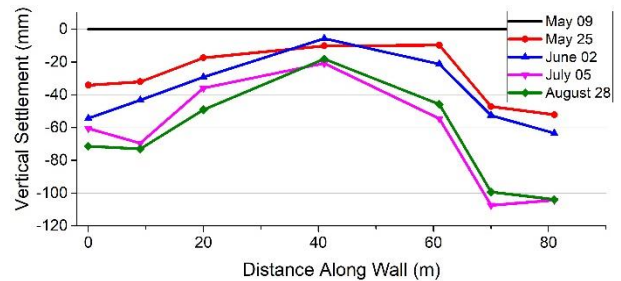


Figure 8 – South Abutment Terrestrial Laser Scanning Settlements

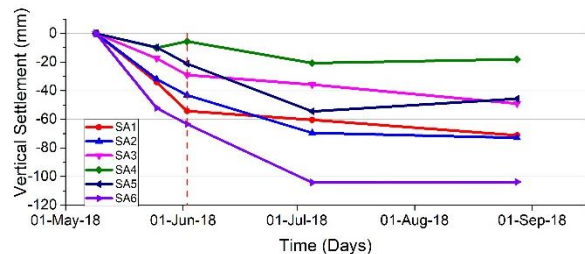


Figure 9 – South Abutment Terrestrial Laser Scanning Rate Plot

The South Abutment settlement profile resembles the same 'W' pattern of displacements as shown in Figure 8 similar to that in the North Abutment. A potential explanation for this pattern is that the centre of the wall is supported on the stone columns while the edges of the wall are not (as shown in Figure 5). Less settlement is observed along the edges of the wall where fill heights are lower. The maximum settlement exhibited on the graph is 107mm on July 5th, 2018. This is a few millimeters over the August 28, 2018 scan which can be attributed to some registration error associated between these two dates. The differences between the July 5 and August 28 profile can likely be attributed to measurement error as it appears that settlements are largely complete. This is evidenced by upward movement between the two surveys at select locations which is considered highly unlikely to have actually occurred.

5 SETTLEMENT MONITORING

The settlement monitoring on site has been performed by PCL in the way of settlement plates and total station. Due

to damage of the settlement plates that has occurred during construction and the amount of error in measurements, the settlement plate data are not being used and the total station measurements are relied upon instead. The total station data was made available by TREK Geotechnical Inc. in their instrumentation monitoring report summary (TREK Geotechnical Inc., 2019). The settlement profiles are shown in Figures 10 and 12. The rates of settlements are plotted in Figures 11 and 13.

5.1 North Abutment Analysis

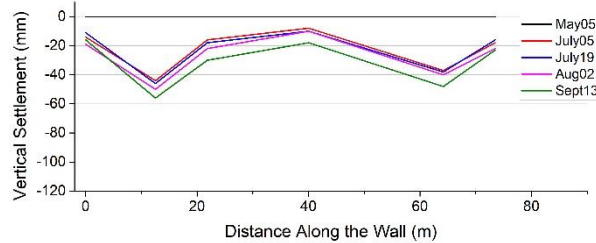


Figure 10 – North Abutment Total Station Measurements (provided by TREK)

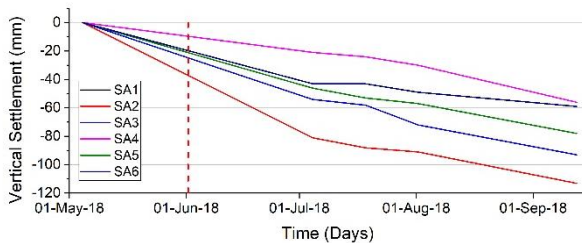


Figure 11 – North Abutment Total Station Rate Plot (provided by TREK)

The settlement profile for this abutment is defined in the 'W' pattern as exhibited with the TLS. The increments of settlement between each date are small with some deviations of negative settlement or upheaval, indicating some error in measurements. The magnitude of error is less than the TLS, the measurements are very similar to each other, and when referencing the long term settlement to January of 2019, the maximum settlement is 52mm. This confirms there has been small increments of settlement during construction and the measurement error is causing the small negative settlement.

5.2 South Abutment Analysis

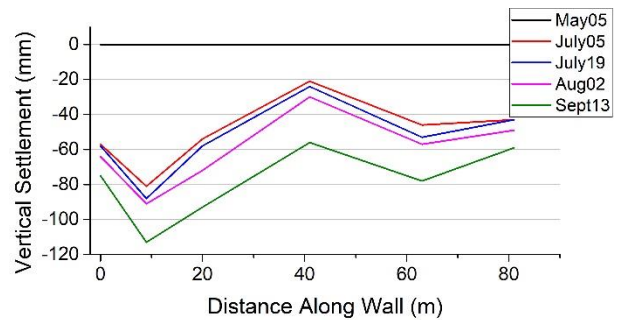


Figure 12 – South Abutment Total Station Measurements (provided by TREK)

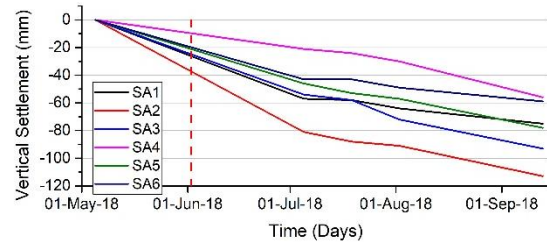


Figure 13 – South Abutment Total Station Rate Plot (provided by TREK)

The South Abutment shows a larger magnitude of settlement than the North Abutment and also shows increased settlement in the centre of the wall, between August 2 and September 13. This would indicate more overburden stress from the embankment. The maximum settlement measured by the total station is slightly higher than the predicted 55mm value.

6 DATA COMPARISON

As stated previously, the settlement plate data was not used so the total station measurements are used to determine the reliability and applicability of the TLS. Since the TLS and total station were not surveyed on the same dates (besides July 5), comparisons will be made using rate plots of the movement at each location. To simplify the analysis, it is assumed the settlement between measurement dates is linear. Table 2 and Table 3 represent the difference in settlement measurements between the total station and TLS, negative meaning TLS measures more settlement and positive meaning total station measures more settlement. To allow a visual comparison, the July 5th movements and August 28th/September 13th movements for each abutment will be compared on the same graph, as shown in Figures 14 and 15. When looking at the differences in measurement, the error in measurements should be addressed (Yang, Omidalizarandi, Xu, & Neumann, 2016):

- Surface reflectivity - The concrete panels are not a perfect surface and when that is combined with sunlight shining on the panels and the angles of laser bouncing off the wall, there will be some accuracy issues (Garcia-Fernandez, 2016).

- Scanning measurements - As previously noted, the ranging error of the machine is $\pm 2\text{mm}$ at 10-25m. Reference targets greater than 25m may be subject to larger errors and can decrease accuracy.
- Registration errors - This will be the bulk of the error. Errors can range from 2-10mm for all scan to scan registration, compounded with another 2-8mm error for point cloud to point cloud registration.
- Total station survey error - Only the final survey results were available. The total station will have a similar ranging error of $\pm 2\text{mm}$ with 2-10mm of error for referencing benchmarks to calculate station coordinates (Leica Geosystems AG, 2018). If benchmark coordinates were obtained from RTK, an additional 5-20 mm of error is assumed (Leica Geosystems AG, 2012).

6.1 North Abutment

Table 2 – North Abutment Differences

Date	NA1	NA2	NA3	NA4	NA5	NA6
09-May-18	0	0	0	0	0	0
02-Jun-18	-20	-17	-25	2	0	-7
05-Jul-18	-47	-20	-36	-12	18	-6
28-Aug-18	-35	-8	-25	8	-6	-20

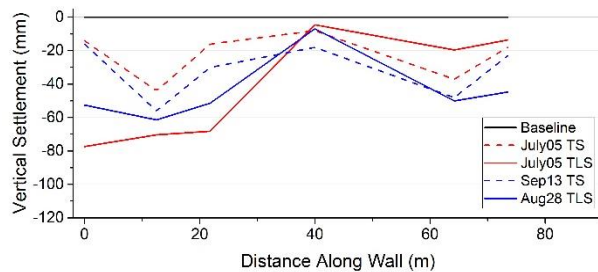


Figure 14 – North Abutment TLS vs Total Station

Looking at the table, the locations with the largest uncertainty were NA1, NA2 and NA3. This is understandable as the July scan at location NA1 and NA3 had maximum differences of -47mm and -36mm. The settlements in these locations can be discarded. The August scan does not fair as well, suggesting 35mm and 25mm more settlements for NA1 and NA2, respectively. The amounts of these settlements can be observed if there are large errors compounded from registering point clouds and RTK coordinates for benchmarks. Looking at the behaviour of pattern of movements for both methods, it is more reasonable to assume the total station is more accurate in relative settlement and that the TLS has overestimated the settlement, however the trend or behaviour of the settlement along the wall is similar and it is just the magnitude of the movement that is different. With differences of $\pm 20\text{mm}$ and less, it is fair to assume both methods are quite close to the actual settlement when referencing the range of errors listed in Section 6.

6.2 South Abutment Differences

Table 3 – South Abutment Differences

Date	SA1	SA2	SA3	SA4	SA5	SA6
09-May-18	0	0	0	0	0	0
25-May-18	-15	-6	0	-3	5	-35
02-Jun-18	-30	-8	-4	4	0	-43
05-Jul-18	-4	11	18	0	-8	-57
28-Aug-18	0	30	35	27	-25	-50

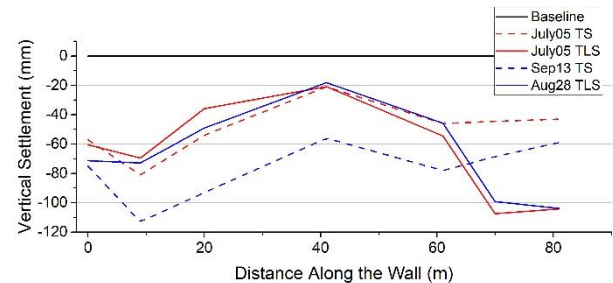


Figure 15 – South Abutment TLS vs Total Station

South Abutment has more of an even distribution of positive and negative differences, as evidenced by maximum values of -57mm and 35mm, respectively. The same problem outlined in Section 6.1, these values are too large to consider. The main concern is the August scan as they are mostly large positive values until location SA6 where it drops down to 50mm below the total station settlement readings. The location of SA6 and the August scan are all outside a reasonable acceptable threshold of 20mm, and should not be considered reliable. As stated with the North Abutment, the behaviour of settlement is similar while the magnitude of movement is different.

6.3 Recommendations

From the comparison of data, the settlement patterns are similar with the 'W' shape but the magnitudes of settlement are quite different as there are peak settlement numbers of -57mm and 35mm. Without knowing with certainty what the actual amount of settlements are, it is difficult to determine if all of the errors are on TLS or on total station.

The main advantage TLS has over the total station is the amount of data points it can collect in a 360° space. This allows for a better understanding of wall movement and can better identify outliers in the settlement measurements. A secondary benefit over the total station is that by using the project point cloud created from the scans, the designer can revisit the site without needing to leave the office and can make additional measurements within the point cloud space.

Observing the general trends of settlement over time for each instrument, the TLS has more variability in the results than the total station. Because the settlement of the abutments are in millimeters rather than centimeters, it is tougher for the TLS to accurately pick up the movement increments. Thus, the total station is a more suitable

instrument for this application while the TLS would be more suitable for when larger settlements are to be expected.

Upon reflection of if there was anything that could have been done to improve the measurements, more scans would have been set-up during the baseline reading (May 9) as the supports along the wall affected the line of sight for data points to collect on the panel face; as seen in Figure 16. Five scans were used for each abutment but this could be doubled to ten to improve the measurement.



Figure 16 – First Row of Panels Installed

7 CONCLUSION

The method of taking three scans during construction provides information on the initial settlement from the buildup of the retaining wall. The two post construction scans provide information on the longer term settlement behavior under the overburden stresses of the embankment and traffic loading to the rockfill column reinforced soft foundation. Comparing the TLS scan data with an already credible method of measuring settlements in retaining walls like the total station, determines the validity of TLS in the application of monitoring civil structures during and after construction.

When comparing the results between the TLS and total station, differences outside of 20mm may be regarded as too high in either measurement methods. Comparing the two methods, the TLS had more errors induced in its readings, Table 1 and 2 show the abutments had excessive settlements in NA1-NA3 and all of SA6.

TLS is an accurate method of determining movements and provides a new element of surveying by providing a 3D model in which the designer can navigate through without the need of being on site. However with the level of accuracy required, another survey method like total station is recommended to troubleshoot any discrepancies in data.

8 ACKNOWLEDGEMENTS

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