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Measuring Deformation Performance of Geogrid Reinforced Structures using a Terrestrial Laser Scanner

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ABSTRACT: Geogrid Reinforced Structures (GRS) are inherently flexible and although the design for ultimate limit state is relatively mature, GRS are often defined by their deformation performance, in the serviceability limit state (Koerner and Koerner, 2013). Currently, serviceability design protocol does not determine or prescribe deformation limits for the built wall or slope, but rather imposes limits on the theoretical mobilised strain of geogrid reinforcement.

Current understanding of the principle mechanisms for GRS deformation is weak and often the only way to assess the serviceability of structures is by the observational method. Typically this has been done with external surveying instruments such as total stations or internally using strain gauges, extensometers and inclinometers. Laser scanning has previously been used to measure the serviceability performance of conventional geotechnical structures and slopes and provided useful information (Mechelke *et al*., 2007) but has not yet been used on GRS. This paper assesses the potential of a Terrestrial Laser Scanner (TLS) to rapidly survey GRS. This assessment covers a range of structures including a 6.5 m high steel mesh faced retaining wall and a 3.6 m wrap faced structure. The measured behaviour obtained from this range of structures demonstrates the importance of facing stiffness on controlling deformations. Terrestrial laser scanning has potential because it is unobtrusive, only requiring lines of sight to the face and does not use targets located on the GRS. The system can be used to measure the position of the GRS face to within a noise range of ±5 mm (Kersten *et al*., 2008), across a large surface area from a single observation point in minutes. This paper assesses the application of using TLS to measure deformations during construction and in-service and proposes a standard scanning procedure. It also details experience gained surveying GRS constructed with a range of face systems and discusses accuracy and repeatability issues. It concludes with possible implications of using the TLS method for routine monitoring of GRS.

Keywords: geogrid, terrestrial laser scanner, deformation

1 INTRODUCTION

Geogrid Reinforced Structures (GRS) are used as a solution to stabilise slopes. GRS prevent backfill from assuming its natural slope angle of repose, providing a potentially economically beneficial and more sustainable alternative to mass concrete and other conventional retaining structures (WRAP, 2010). GRS typically consist of several key components: geogrid reinforcement; reinforced soil fill; retained backfill soil; foundation soil and can include a range of optional facing components, providing local support to the reinforced soil fill (e.g. segmental blocks, concrete panels, wraparound etc.).

As a result of the need to reducing the excessively conservative nature of commonly used GRS designs (Bathurst *et al*., 2002), monitoring of GRS structures has been widespread since they started to be increasingly used in the 1990’s. Typically this has been undertaken using conventional geotechnical monitoring techniques such as strain gauges, inclinometers and assessing the face of the structure using conventional survey equipment.

Improvements in the scanning speed and mobility of TLSs have been made in recent years and they have been successfully implemented within several areas of geotechnical engineering. However, the authors are not aware of their use in the monitoring of GRS. There are many advantages of using this advanced form of surveying, not least their ability to measure large swathes of a structure in a short space of time, with minimal effort.

This paper presents the case for utilising TLS to measure deformation of GRS and includes the initial results of two monitored GRS, where the scanner has been used successfully to measure performance over a determined time period. Issues of accuracy and repeatability of measurements are discussed.

2 DEFORMATION IN GRS

GRS are, by their nature, flexible structures and as such they deform during their service life. This deformation can be defined as the action of changing shape and is typically measured relative to an outside point of reference.

Typically GRS are considered as 2-dimensional structures in plane strain, as in most cases these structures are laterally continuous, where strain perpendicular to the sloping face is often insignificant. GRS structures tend to deform outwards horizontally from the face as a result of geogrid strain, and vertically due to settlement, consolidation and the displacement caused by the aforementioned horizontal movement.

This particular paper focuses on the horizontal deformation of GRS. Deformation in GRS can occur horizontally due to three dominant mechanisms (Figure 1): GRS Displacement; typically caused by the pressure from the retained fill, resulting in the whole structure moving forward. Internal deformation; resulting from straining reinforcement, and face deformation; specifically bulging in wrapped faced GRS, resulting from strain within the facing element to resist the lateral earth pressure behind. Understanding this movement is critical in determining performance and improving design.

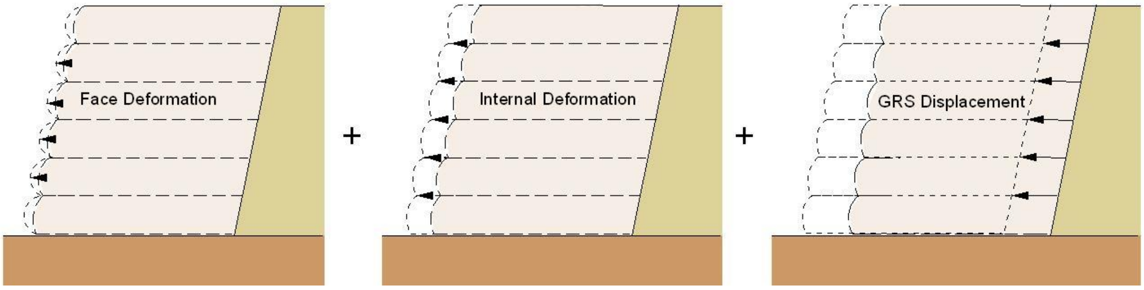

Figure 1. Horizontal Deformation Mechanisms in GRS.

3 GRS INSTRUMENTATION

Geotechnical engineering involves the interaction of complex soil and structural properties, which make design and performance measurement difficult and the sub-discipline of geosynthetics adds further complexity. The deformation of GRS has been measured since they were first used over 40 years ago, typically using: surveying techniques, extensometers, inclinometers and strain gauges. Generally, these can be used to measure deformation on the face (1), inside (2) or surrounding the GRS (3) as shown in Figure 2. Previous monitoring programs have focussed on implementing instrumentation at positions 2 and 3, whilst accounting for position 1 with traditional surveying techniques or extensometers.

This study presents an innovative use of a TLS, which is a form of surveying to monitor the face profile of two individual GRS. The advantage of profiling the face is that the data measured is the maximum movement acting through the structure, as it is a combination of face deformation, internal deformation and external deformation. Monitoring structures in this way, makes it difficult to trace the source of the deformation. However both GRS case studies featured in the report were monitored only in the short-term and both feature firm foundations and robust global stability, so the face deformation mechanism was expected to be the critical mechanism contributing to deformation observed.

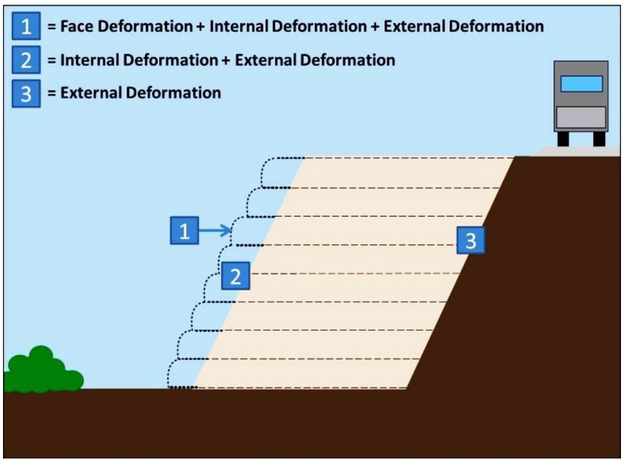

Figure 2. Typical Measurement Positions

3.1 *Surveying Techniques and the Development of Laser Scanning*

Surveying, using total stations, has been the traditional method for measuring civil engineering structures for the last 20 years (Bussert, 2012). However, one of the main limitations of surveying with total stations is that it is time consuming to manually reposition the scope to the next target. Although the data from these individual points can be used to assess individual profiles, it is often not viable to obtain more than a small number of accurate face profiles over a limited portion of the GRS and this is a problem in flexible structures such as GRS.

However, there are two alternative branches of surveying instruments that have developed significantly over recent years with the advance of computer technology. These are TLS and photogrammetry. This paper focuses on the assessment of TLS as a tool to measure GRS. Photogrammetry has not been considered in this piece of work because there are issues with establishing control points and accessing higher areas of tall structures as well as requiring complex photo stitching.

3.2 *Terrestrial Laser Scanning (TLS)*

A TLS is essentially an advanced form of a total station. Whereas a total station projects a single beam at a target using a phase shifted laser, a TLS uses a rotating mirror at high speed and moves automatically, allowing the device to scan a large field of view in a short time space, with minimal effort from the operator. Modern TLSs also contain on-board data loggers, human interfaces and on-board cameras, for ease of use and for post-processing visualisation.

Similarly to total stations, the TLS featured in this paper uses a time of flight laser scanner, where the distance to an object is calculated based on the time it takes for the pulse of light to reflect off an object and back to the scanner. The on-board computer logs its position in 3D space relative to the scanner. As it does this for the whole structure, it builds up a 3D representation of this data, termed a point cloud. This point cloud essentially contains thousands of individual coordinates equivalent to those obtained using total station surveys.

To the author's knowledge these devices have yet to be used to survey GRS but have begun to be deployed in other geotechnical area such as in embankment monitoring. Miller *et al.* (2008) proved the concept of monitoring deformation of two highway embankments using a TLS. The authors conducted two scans over a period of 6 months allowing them to successfully observe deformation between the two scans.

3.3 *TLS Equipment*

The laser scanner used in this assessment was *Leica's Scanstation 2* (see Figure 3). The device, although no longer the state of the art in laser scanners, was chosen to present the concept. A previous study by Mechelke *et al*. (2007) found this TLS to have a noise range of ±5 mm at a distance of 10 m. This level of accuracy is acceptable for the level of GRS deformation expected (>10 mm) by a typical wrapped faced GRS (Duijnen *et al*., 2012).

As with other surveying devices, accuracy and repeatability are dependent on a number of external factors such as weather, tampering and most importantly reliable control points, which are outside the area of influence of the engineering structure. High definition scanner (HDS) targets were chosen to locate these control points, as Kersten et al. (2008) had shown them to be more accurate (±3 mm) for the laser scanner, than black and white (±5 mm) or spheres targets (±5mm), over a distance of less than 50 m.

Figure 3. Typical Laser Scanning Equipment with HDS target in the background

4 SCANNING PROCEDURE

A scanning procedure was developed in a controlled environment at Loughborough University before applying this to active construction sites. Although based on the use of a particular laser scanner, the methodology is adaptable to most TLS. The work detailed in this paper was carried out between the June 2013 and February 2014.

The first activity to be undertaken when surveying a new structure is the setting up of a minimum of 3 reliable and stationary control points in the area around the proposed section of GRS. This study used the head of a nail in the top of a wooden stake, set in the ground away from the GRS as a control point. These control points should be protected to prevent tampering damage between surveys. These control points need to be accessible to allow tripods to stand vertically above the centre points. HDS targets, set up on these levelled tripods, allow the TLS to locate the control points. The distance of the temporary HDS target above the permanent control point in the ground should be obtained by using a tape measure. This value can then be used by the software to transpose the observed HDS target to the position of the permanent ground control point, removing the variable height of HDS target tripods.

The laser scanner should be placed on a levelled tripod within sight of the target face of the GRS at a perpendicular distance of at least twice the maximum height of the GRS. Upon start-up most modern scanners will calibrate themselves before measurement scanning.

An initial medium resolution image can be taken by the on-board camera to locate and acquire the control points. Once these control points have been acquired the TLS should be set to scan the GRS, making an effort to scan as much of the face as possible in a single scan at a uniform intensity. This is important as this will ensure complete coverage of the structure. The time required to scan a GRS is dependent on size of the target and intensity of the points measured, but the TLS was set to a scanning speed of 40 m^2/min, collecting up to 2,500 data points / m^2. Greater detail or scanning speed can be achieved by adjusting the intensity of points recorded. More data points allow the user to better statistically reduce any noise recorded and improve accuracy, but a compromise has to be found between detail and speed. At extremes, the TLS used are capable of scanning 500 m^2 / min or 1,000,000 data points / m^2.

After undertaking the scan, the control points should be checked again to ensure the TLS’s or target positions have not been disturbed during scanning. Once this is confirmed the laser scanning equipment can be dismantled, leaving only the reference points in their position.

Subsequent scans should follow the procedure outlined above, locating and acquiring the same control points. The laser scanner does not need to be in the exact position as previous scans, as long as it has a line of sight to the previously established control points. This procedure can be used as often as the surveyor wishes to develop a more complete assessment of changes in profile. Ideally, a GRS could be surveyed every lift height in construction and every month after construction, however, given the time and accessibility constraints of real construction sites, this was not possible for the two case studies featured in this paper.

5 SURVEYING GRS

5.1 *Loughborough Field Trial*

A field trial was conducted at Loughborough University to determine a suitable methodology for scanning GRS. The extent of the field trial involved a TLS being used to measure the position of a conventional retaining wall on the Loughborough University campus. The work was carried out in May 2013. After development of the procedure (Section 4), the TLS was taken to the two live GRS construction sites.

5.2 *3.6 m high GRS against Historic Wall*

5.2.1 *Background*

A GRS, was built to protect the base of a listed 400 year old harbour wall. Recent neglect required the wall to be repaired and shored to prevent it from collapse. To facilitate these works, a GRS was built in front of the wall, on top of which a light scaffolding frame was erected to allow access to the wall for repair.

The GRS has a maximum height of 3.6 m and runs alongside the wall for 40 meters (Figure 4). The structure was built using 7 wrapped layers, each 3.6 m long, of Polyester (PET) geogrid, with a short-term tensile strength of 35 kN/m. A fine-aperture geomesh was incorporated behind the wrap-around to retain the imported gravel fill used for the embankment. The wrapped face was constructed at an angle of 60 degrees, behind a moving single layer formwork system. Construction began in September 2013 and was completed in October 2013.

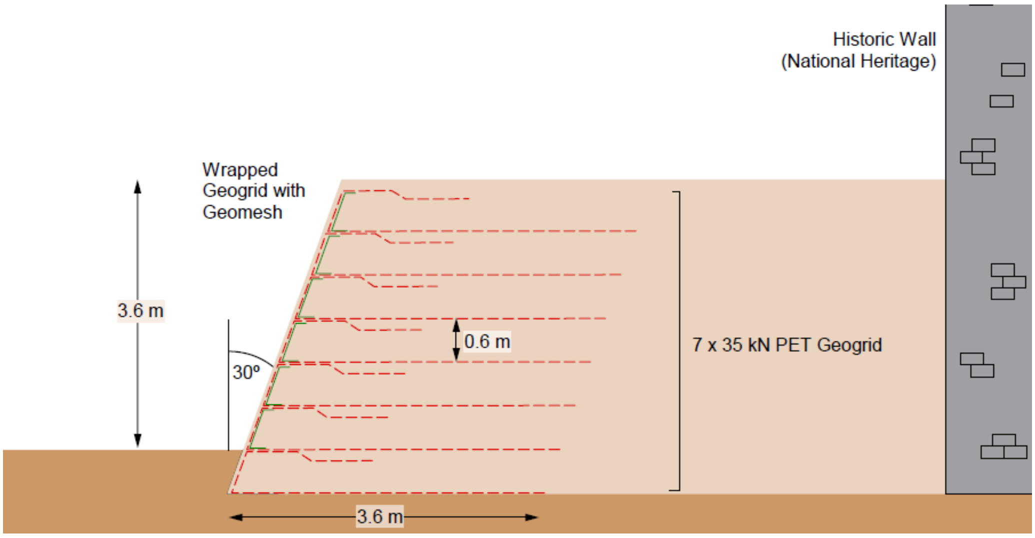

Figure 4. Historic Wall GRS Typical Arrangement

5.2.2 *Scanning Programme*

At the time of writing, two scans had been completed of this GRS. The first scan was undertaken in September 2013, during construction, when only 3 out of the 7 layers had been constructed. A further scan was undertaken 1 month after completion of construction in November 2013. In both cases, the scanner was positioned approximately 15 meters from the GRS.

Figure 5 presents a photograph of the GRS as well as an example of an intensively scanned section of the GRS. At this intensity the scanner is able to observe local deformation occurring across the wrapped layers and highlighted the problem that real deformations are non-uniform due to local soil conditions.

Figure 5. Historic Wall GRS photograph (left) and TLS scan output of point cloud defining the surface of the GRS (right).

5.2.3 *Results*

To compare the deformation in the GRS, cross-sections of the Historic Wall GRS were taken from the point clouds collected by the TLS, which had been overlaid using the control points and exported into MS Excel to produce profiles. The location of the specific cross-section was chosen by the user. Only the first 3 layers of the GRS have been compared. As shown in Figure 4, there is a further buried layer that is not visible to the laser scanner.

MS Excel was used to calculate the horizontal difference between the two profiles, surveyed during and after construction (Figure 6). Between the two scans, an additional 4 layers were constructed on top of the 4 already in place during the first scan. Based on a dry unit weight of 18 kN/m^3, these additional layers equate to a considerable additional overburden pressure of more than 40 kN/m^2. The largest deformations occurred at mid-height in the lowest layer observed of the structure, with a magnitude of up to 80 mm. A smaller peak deformation was recorded in the wrapped layer above. These strong peaks in deformation around the mid-height of the wrapped face, suggests the primary mechanism is face deformation, occurring due to an increase in vertical pressure. This deformation, is much greater than precision of the TLS (±5 mm).

Other deformation mechanisms: GRS Displacement and Internal Deformation were not evident from these cross-sections.

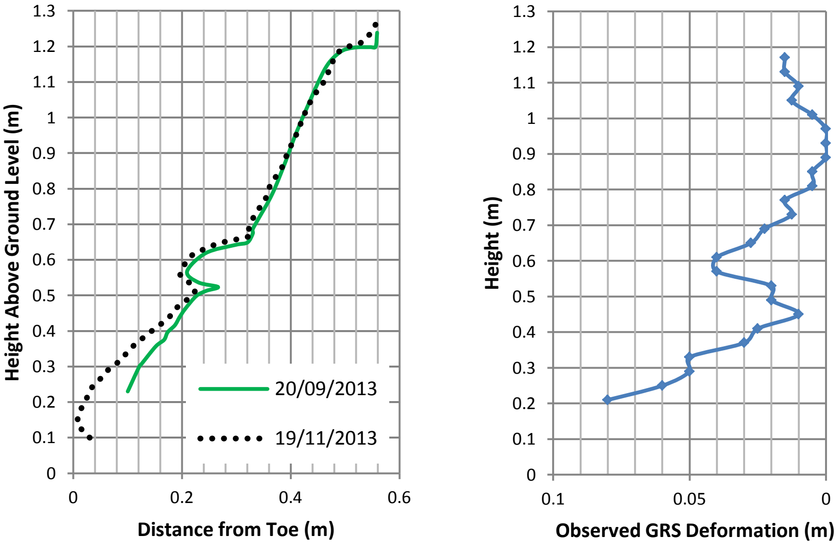

Figure 6. Sample profiles of historic wall buttress GRS taken from laser scanned point cloud (left) and calculated deformation between September 2013 and November 2014 profiles (right)

5.3 *6.5 m high GRS in a Former Quarry*

5.3.1 *Background*

The second laser scanned site is situated in a former limestone quarry which is currently in the process of being turned into a large housing estate. The GRS has a maximum height of 6.5 m and consisted of 13 geogrid layers of varying length with a spacing of 0.5 m (Figure 7). Two grades of PET geogrid layers were used in the GRS, with short-term tensile strengths of 35 kN/m and 55 kN/m. The layers were constructed using a sacrificial steel mesh formwork set at 80 degrees, behind which a small aperture geomesh was laid for local stability. The GRS extends against one of the quarry faces for a length of approximately 135 m, and is formed of a locally won high quality sand and gravel soil with a shear resistance of approximately 35°. The GRS was constructed between January and February 2014.

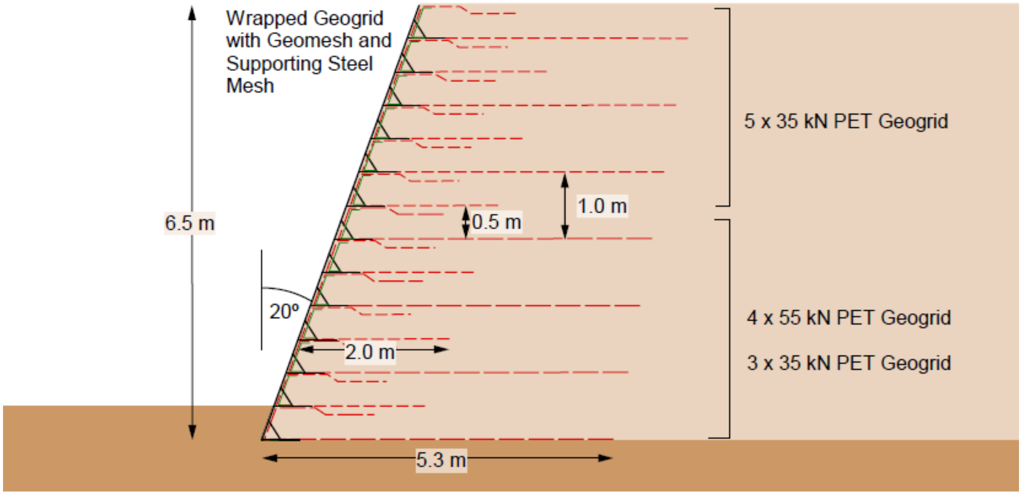

Figure 7. Former Quarry GRS Typical Arrangement

5.3.2 *Scanning Programme*

At the time of writing, 2 laser scanning surveys had been undertaken, The first scan (Figure 8) was undertaken during construction in January 2014. The TLS was positioned approximately 30 meters from the centre of the GRS. At this distance it was possible to scan a 60 m horizontal section of the GRS in a single scan. At this stage 10 of the 12 layers had been constructed. A follow up scan was undertaken in March 2014 approximately a month after the end of construction.

Figure 8. Former Quarry GRS: Photograph (left) and TLS Scanned Point cloud (right) obtained during construction.

5.3.3 *Results*

Figure 9 presents user-selected cross-sections through the former quarry GRS (left) and the resulting deformation (right), calculated in *MS Excel* from raw coordinate point data extracted using Leica’s point cloud software, *Cyclone*, which displays the data surveyed using the TLS. The comparison covers the lowest visible 9 layers of the structure, with an additional layer buried and obscured from the laser scanner’s view.

The two profiles, taken from during and after scanning, distinctly show similarity at the bottom of the GRS but gradually become separated with height. Overall the deformations recorded are much larger than with the smaller historic wall case study. The greatest deformations were featured in the higher layers of the structure, with a change of over 110 mm, recorded at 4.25 m above ground level. This large amount of deformation is likely to have been caused partly by an increase in vertical (approx. 20 kN/m^2) and horizontal pressure resulting from the addition of 2 further layers. The profile differences between the January and March scans suggest that a combination of deformation mechanisms are involved as deformation is not limited to mid-heights of reinforcement layers unlike in the previous case study. Further scans are to be undertaken to reinforce this result and monitor any further deformation occurring post construction.

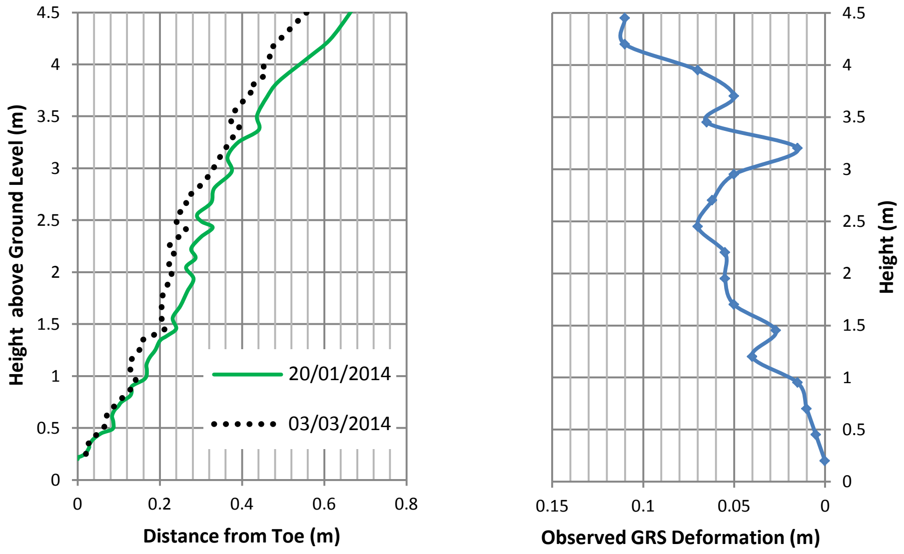

Figure 9. Sample profiles of former quarry GRS taken from laser scanned point cloud (left) and calculated deformation between the January and February profiles (right)

6 CONCLUSIONS

This paper has presented the case and a methodology for utilising the advanced surveying technique of TLS, to monitor deformations occurring in the facing profile of GRS. The case studies included in the paper have proven its effectiveness; allowing the user to collect extensive profile data about an entire GRS, with up to 20,000 data points measured in under an hour, unlike traditional forms of surveying which are restricted in collecting a number of pre-selected points. Although laser scanning GRS has a precision of ±5 mm (Mechelke, 2008) and features challenges common for all surveying methods such as requiring line of sight and control points, it is a valuable technique to assess deformation in GRS, which, as shown by the examples, can be as much as 100 mm, particularly during construction.

Although the data collected so far is limited to a pair of scans at two GRS, it is the intention of the authors to continue to monitor the case sites over time and to expand laser scanning to a range of other structures with alternative facing types and construction techniques, amongst other variables, in order to create a comprehensive database of GRS deformation, which can be used to consider design methods, with a view to reduce over-conservatism in design in the future.

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