Assessing the Planarity of Containment Liner Systems Using a Terrestrial Laser Scanner

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ABSTRACT: Conventional stability analysis approaches assume Containment Liner System (CLS) slopes to be planar surfaces, i.e. a straight line on a cross section drawing. This paper explores the variability of data collected on the planarity of CLSs, which was collected using Terrestrial Laser Scanning (TLS). Four landfill containment lining systems in the UK were scanned as part of this study including a temporary capping system, a vertical expansion (piggyback) landfill liner, a permanent capping system and side slope landfill lining system.

Keywords: Laser Scanning, Surveying, Lining Systems, Wrinkling, Planarity

1 INTRODUCTION

Conventional stability analysis approaches assume slopes to be planar surfaces, i.e. a straight line on a cross section drawing. Little consideration is given during these analyses to the out of plane construction tolerances of a Containment Liner System (CLS). Designers can place specifications on construction tolerances based on maximum heights above or below a lath, however, these are seldom a high priority for quality assurance engineers, and for capping scenarios, irregularity of subgrade is inherent, even after regulating layers are placed. This paper explores the variability of data collected on the planarity of CLSs, which was collected using Terrestrial Laser Scanning (TLS). The relationship between the planarity of CLSs and the associated slope stability is addressed through applying limit equilibrium methods. Figure 1 presents a cross section through a schematic CLS with small and large scale variations in slope shown. This study is focussed on Marco asperities within the slope, from causes such as settlement, poor construction and poor subgrade.

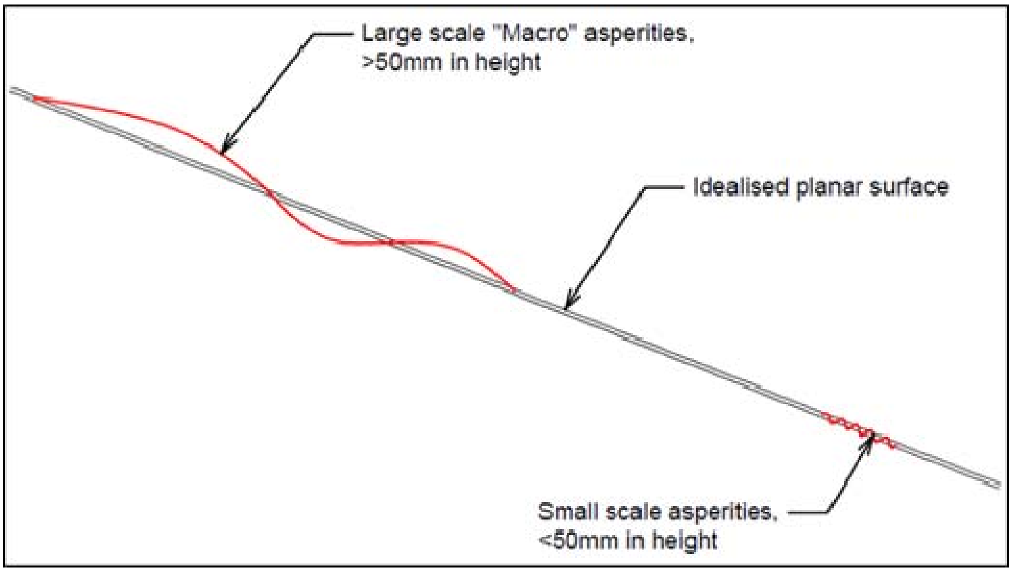

Figure 1 Macro asperities with a containment slope lining system

2 METHODOLOGY

The first objective of this study was to quantify the planarity of CLSs. This section outlines the data acquisition, using TLS, and post processing carried out in order to quantitatively assess and compare the planarity of a number of CLSs.

2.1 *General*

Four landfill containment lining systems in the UK were scanned as part of this study. To obtain a good range of data from varied types of CLSs, the data was collected from the following:

- A temporary capping system, covering waste approximately four years old, at a landfill site in eastern England;
- A vertical expansion (piggyback) landfill liner at a landfill site in eastern England. The liner represents the interface between historic and new municipal solid waste;
- A permanent capping system, covering a mix of municipal solid waste and inert soils, at a landfill site in central England. The cap analysed represents the lower bench of a 72m waste mass as reported by Fowmes and Zamara (2014);
- A sideslope landfill and raw point cloud data that had previously been collected by Zamara *et al.* (2012).

Table 1 gives a summary of the four slopes including geometry and materials present. It should be noted that the "scanned surface" relates to materials which were present at the time of scanning, and additional drainge material was to be placed on the vertical expansion and cell sideslope, and restoration soils on the permanent cap.

Table 1 Charateristics of the Four CLSs Scaned

Slope	1 Temporary Cap	2 Piggyback Lining System	3 Permanent Cap	4 Sideslope Lining System
Slope angle (°)	12.2	20	21.8	21.8
Subgrade	Recent Municipal solid non-hazerdous waste	1980's co-disposed hazerdous and non hazerdous waste with 300 soil cover	1990's and 2000's municipal solid waste and inert fill.	Engineered glacial till bund.
Slope Height (m)	6	10	18	12
Containment system	1mm LLDPE geomembrane	2mm HDPE geomembrane with cuspated geocomposite drain above	1mm HDPE geomembrane with protection geotextile below	2mm HDPE geomembrane with non woven proction textile above
Scanned surface	Geomembrane	Geocomposite	Geomembrane	Non-woven Geotextile

2.2 *Terrestrial Laser Scanning (TLS)*

TLS has become the standard 3D measurement technique for surveying and civil engineering applications (Barnea & Filin, 2008). TLS involves the use of a laser beam to measure distances to a series of three dimensional points on the surface of an object. The scanner logs the 3D co-ordinate points in the on-board computer in 3D space relative to the scanner. The resolution and area of interest is specified by the user and the laser beams collects three dimensional measurements. As more points are measured, a 3D representation of the whole structure is built up, called a point cloud. This project used a time of flight TLS (see Figure 2), which calculates the distance to an object based on the time a pulse of light takes to reflect off the object and back to the scanner (Vosselman & Maas 2010). This device has a scanning range of up to 300m (Leica Geosystems 2007), and previous work by Mechelke *et al.* (2007) found this particular TLS to have an accuracy of 2mm up to 100m. The authors were initially concerned regarding the angle of incident of the material, however, Mechelke *et al.* (2007) stated the effects of the angle of incidence and also object colour were understood to be negligable.

Figure 2: Leica Scanstation 2

The TLS can be used to take multiple scans of structures to assess movement or additional development, with the scanner position calibrated each time through the use of control points, however, for the assessment of planarity in this study a single scan of each slope was required and therefore, control points were not necessary. The time taken to scan the CLS was dependent on the size of the slope and intensity of points measured. By adjusting the intensity of the scans, greater detail or scanning speed could be achieved. More data points allow for any recorded noise to be statistically reduced, thus improving the accuracy (Scotland *et al.* 2014); despite this a compromise between the detail and speed had to be found. Furthermore, this paper is considering macro asperities within CLSs. Therefore, a scanning intensity of 10mm was deemed acceptable for the scanning procedure. The raw point cloud data obtained for the cell side slope from Zamara *et al.* (2012) was scanned at an intensity of 5mm. Figure 3 shows the raw point cloud data for each of the four sites.

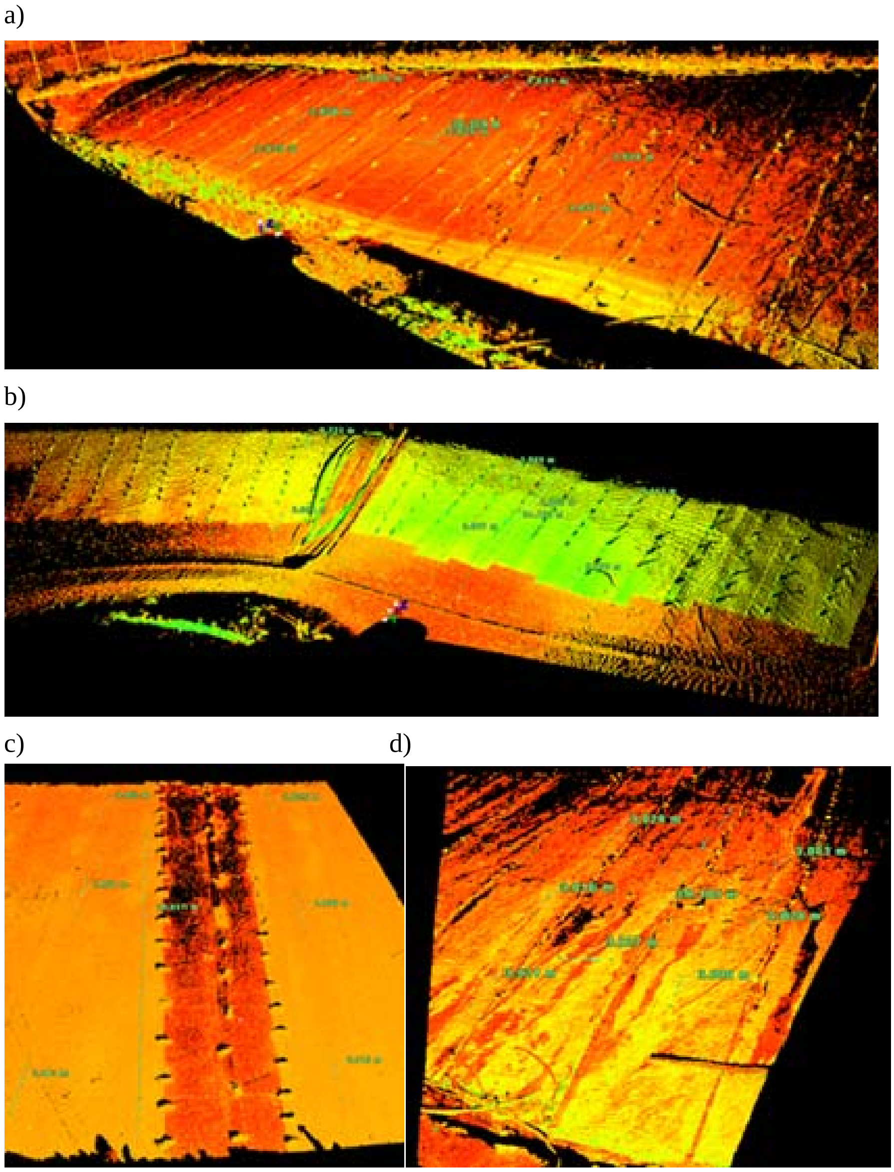

Figure 3. Point clouds obtained from a) temporary cap b) piggyback lining system, c) permanent cap and d) a cell sideslope lining system.

2.3 *Processing and Analysing the 3D Point Cloud Data*

Raw data was processed using HDS Cyclone v7 to enable sections to be taken. Two dimensional sections were cut through the point cloud data to facilitate more manageable analysis. Deciding on the quantity and location of sections was dependent on the quality and amount of data obtained from each CLS. Cyclone provided inadequate tools to analyse the section lines created, therefore, AutoCAD was used to analyse the section lines. In order to quantify the planarity two analyses were carried out:

- The changes in slope angle along the length of the slope were assessed by considering the slope angle of each discrete 0.5 m length of slope.
- Localised irregularities were analysed by the use of laths digitally constructed along the slope

2.4 *Slope angle analysis*

From the two dimensional section lines produced in HDS Cyclone, the slope was discretised into 0.5m lengths and slope angles were taken for each 0.5m length, defines as the $A_{0.5}$ value. 0.5m lengths were taken to avoid localised irregularities and whilst still retaining sufficient resolution for analysis. Trials of shorter gauge lengths were carried out, but these resulted in anomalously high number of steep readings thought to be due to wrinkling of the geosynthetics. Figure 4 shows the variation in slope angle compared to the design slope angle plotted against distance from the slope crest for each of the four slopes.

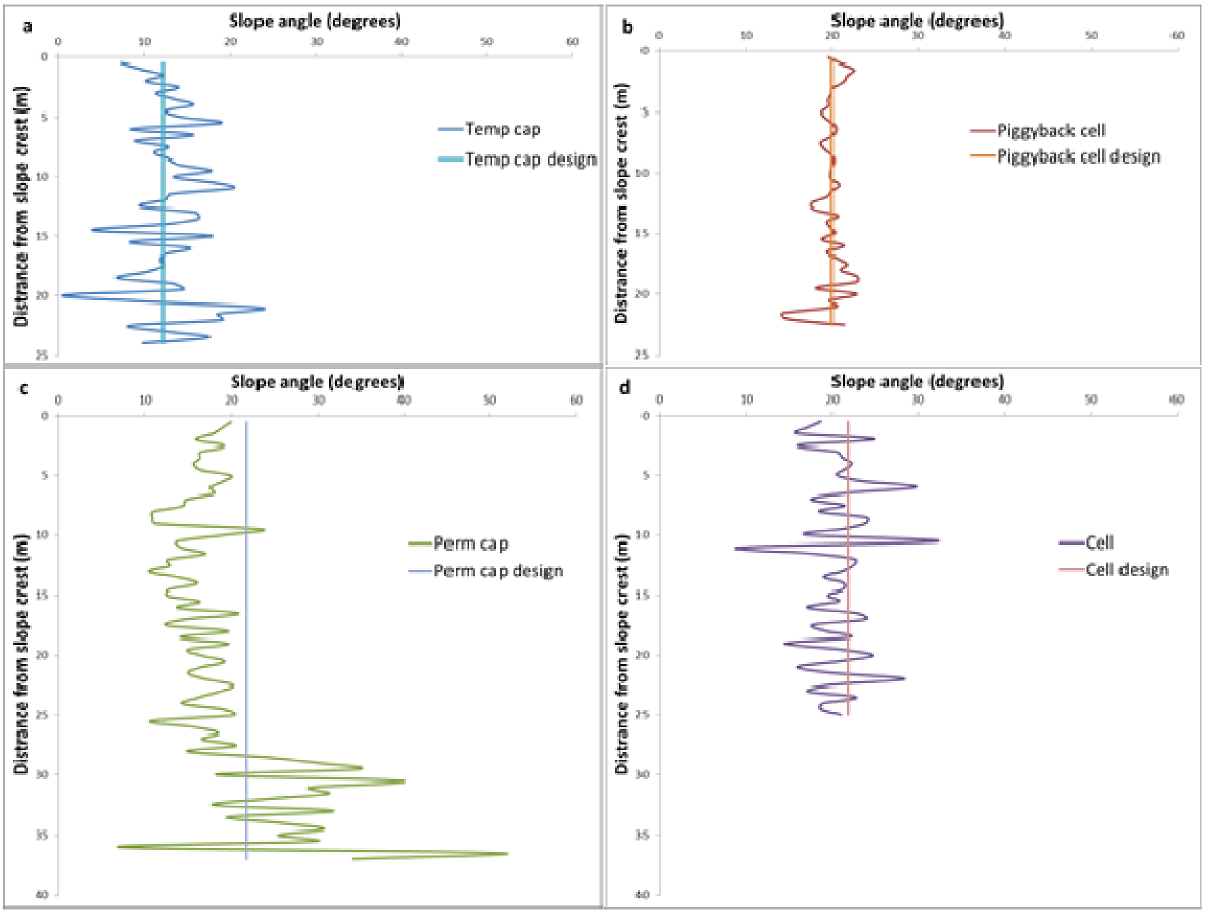

Figure 4 Variation in $A_{0.5}$ for a) Temporary cap b) piggyback lining system, c) permanent cap and d) a cell side-slope lining system.

The data indicates that even the cell side slope with an engineered subgrade has significant variability in the slope angle, with maximum slope angle recorded of 32.2°, 10.4° steeper than the design slope angle. The piggyback lining system had the most planar slope with a standard deviation on $A_{0.5}$ of 1.8° and a maximum of 22.9°, only 1.1° greater than the design slope angle. The permanent capping slope had the widest variability of slope angles, with a steepened toe of the slope as a result of over-tipping of the temporary waste slope. The localised extreme $A_{0.5}$ values (>50°) are due to a drainage ditch near to the base. The temporary waste slope had a waste subgrade, thus making the regrading work challenging, and irregular macro asperities more likely to be formed.

This data has been collated into 1 degree increments and is presented as a histogram in Figure 5. And the slopes are compared in a cumulative plot in figure 6. Summary statistics are given in Table 2.

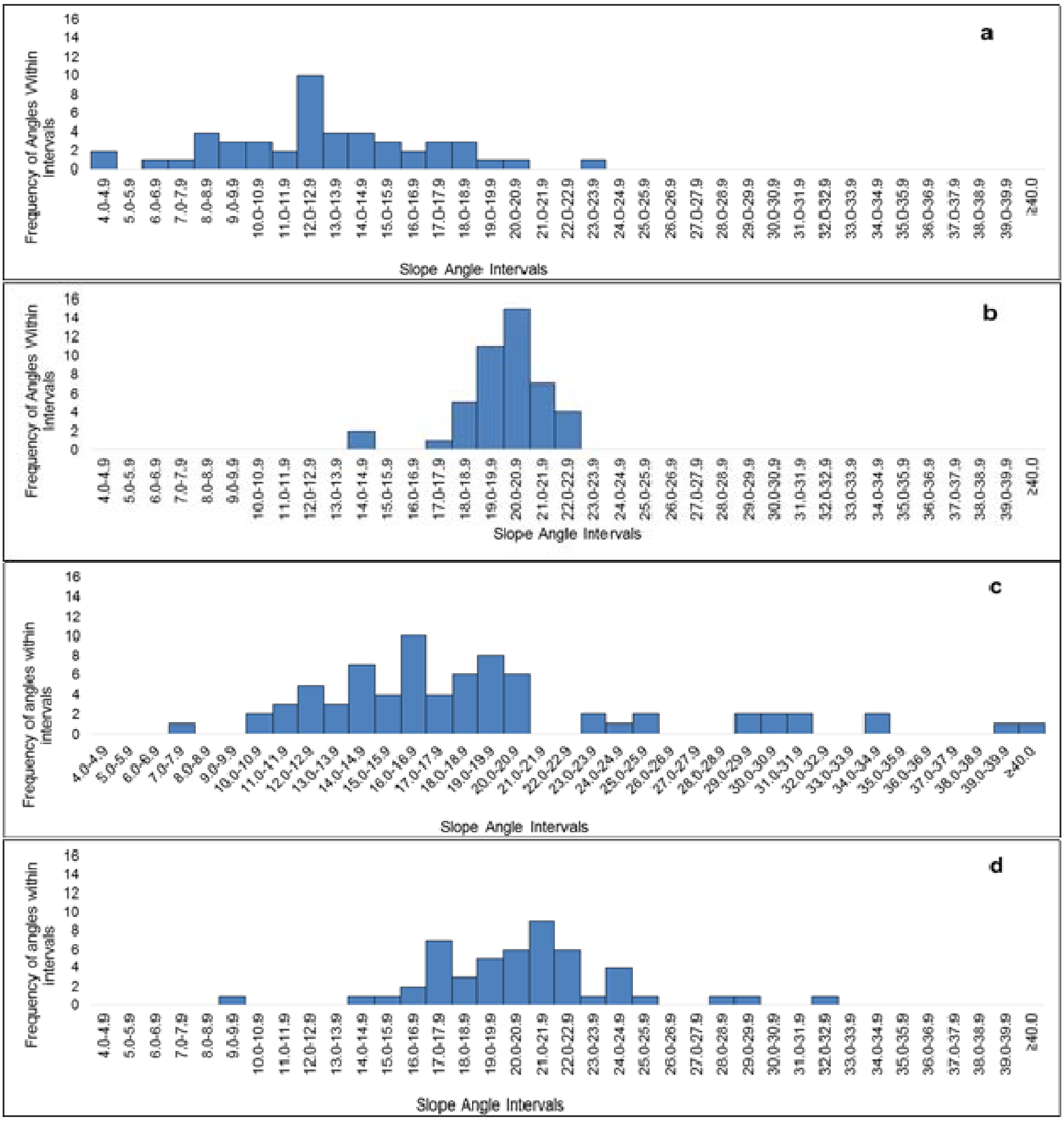

Figure 5 Histograms showing the distribution in $A_{0.5}$ for a) temporary cap b) piggyback lining system, c) permanent cap and d) a cell sideslope lining system.

Table 2 Statistical data from TLS containment slopes

Slope	Temporary Cap	Piggyback Lining System	Permanent Cap	Sideslope Lining System
5th percentile	6.9	17.7	10.9	15.8
50th percentile	12.7	20.0	17.1	20.8
95th percentile	19.0	22.8	32.9	27.2
Standard deviation	4.3	1.8	7.4	3.8

The statistical data and histograms pose a powerful tool for analysis of large quantities of data. Whilst this data has been processed for a single slice through the point cloud, this process could be coded and automated to include many section lines and give far greater spatial representation of the slope behaviour than currently available. This would facilitate risk based design whereby designers may quantify the probability of failure based on a distribution of slope angles.

2.5 *Measurement using electronic laths*

In addition to assessment of slope angle, 3m laths were constructed electronically along the slope to determine the deviation in slope length along a 3m length. The deviation from the design slope was given in terms of a H_{max} value and areas above and below the lath (see Figure 6), to define the deviation from the slope angle of the lath.

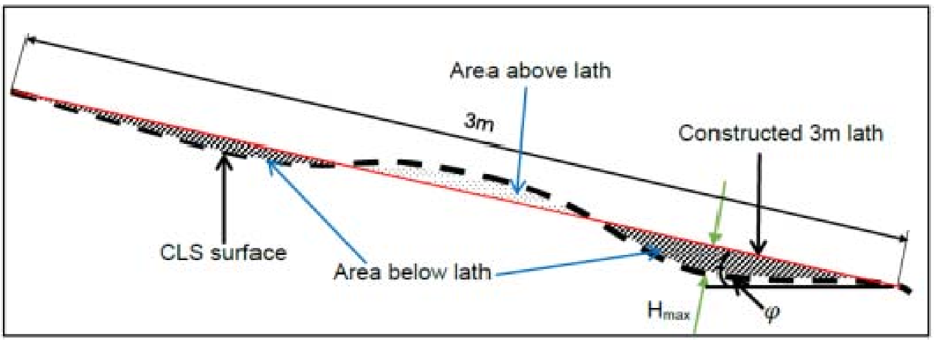

Figure 6. Construction of a 3m lath through the section lines.

Seven laths were assessed on a systematic grid pattern on each slope. The grid selected laths parallel to the slope at two locations in the upper, central and lower thirds of the slope, with an additional horizontal lath also selected. The "least planar" results for planarity are presented in Table 3.

Table 3 planarity of the CLSs based on lath method.

CLS	H_{max} (m)	Area below 3m lath (m^2)	Area Above 3m lath (m^2)
Temporary Cap	0.029	0.012	0.025
Piggyback	0.017	0.017	0.009
Permanent Cap	0.046	0.017	0.048
Sideslope Lining System	0.031	0.012	0.020

The analysis again shows the permanent cap to have the least planar slope, displaying the highest values on each of the indicator criteria shown in Table 7. The laths were manually selected and analysed using AutoCAD, however, there is again potential to automate this process, thereby considering a greater number of section lines, to better define H_{max} and areas above and below the laths.

3 CONTAINMENT LINER SYSTEM SLOPE STABILITY

3.1 *Containment system stability analysis*

Current commercial practice in designing CLSs typically involves applying limit equilibrium methods, such as those proposed by Jones & Dixon (1998), and for more complex problems, numerical modelling techniques are used, such as the approach proposed by Fowmes et al (2008). It is not uncommon to construct a tapered cover soil profile on capping systems, which is when the cover soils become thicker from top to bottom. Since the bottom and top surfaces of a tapered soil profile are not parallel to each other, Zhang *et al.* (2012) proposed a method for tapered cover soil profiles considering seepage. This approach determines a horizontal submergance ration (HSR) and modified parallel submergence ratio (MPSR) to facilitate the geometry of the tapered profile as the flow net is no longer parallel to the CLS surface. However, all of these limit equilibrium techniques assume a perfectly planar surface with a single slope angle.

For this study, in order to give an appreciation of the variability in factor of safety that can occur due to a non-planar slope a simplistic infinite slope model has been considered for this analysis, as a worst case assessment of the impact of increased slope angle over the length of the slope. This analysis is not intended to give an overall assessment of the slope stability of a non-planar slope, but rather is intended to indicated the magnitude effect of localised changes in slope angle on the stability of each 0.5m segment of the slope, thus highlighting the potential impact and if the measured values are of significance to warrant further study.

The analyses are carried out for each of the cell side slope and piggyback lining system considering the veneer sliding of 300 mm of drainage soils from the upper geosynthetic with an upper interface friction value of 35 degrees. The results are presented in Figure 7. The permanent cap has a more complex tapered soil veneer, and assessments of the stability of these slopes are ongoing. The temporary cap has a shallower overall slope angle and no veneer cover therefore analyses of sliding are not appropriate.

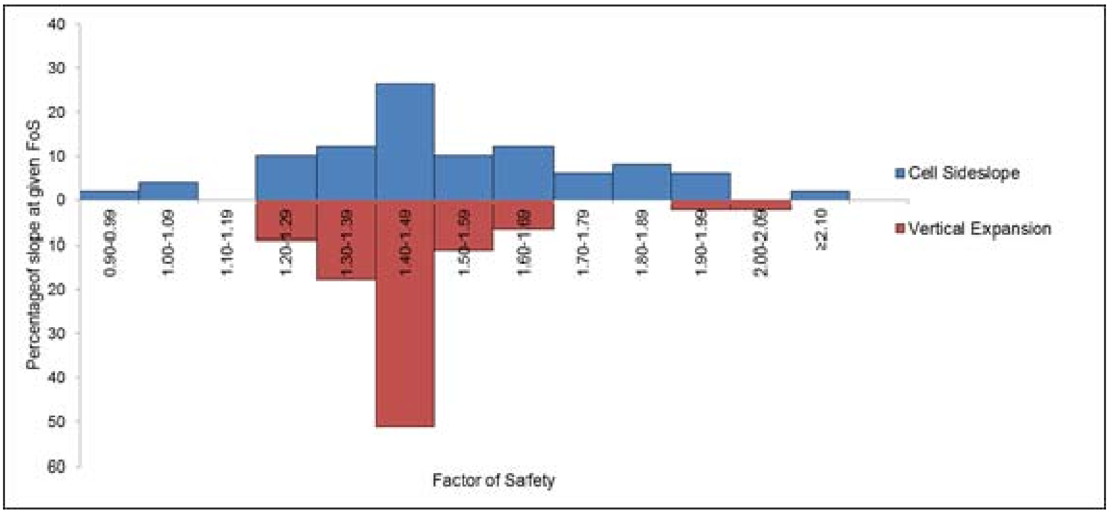

Figure 7. Factor of safety distribution on cell side slope and vertical expansion

The infinite slope analyses show that there is potential for localised instability in both slopes, especially the cell subgrade where locally steeper areas were recorded. Whilst the overall slope remains stable, it is not desirable to have any 0.5m section intrinsically unstable and reliant on the soil around it for stability. Further work is ongoing to better understand the impact of the slope variability on the stability of the whole slope. In addition to the stability, integrity can be comprised by non-planar slopes (Fowmes et al., 2007) as changes in slope angle can cause stress concentrations and differential movement in either protection, drainage or barrier layers.

4 FURTHER WORK

TLS provides a tool for quality and performance assessment of lining systems. The techniques of defining $A_{0.5}$ slope angles and H_{max} could be automated to interrogate the full slope, rather than discrete sections through the slope. This would build a greater statistical database around the slope structure and allow researchers and designers to better analyse the critical criteria for slope stability.

The stability analyses carried out to date are simply to show that changes in slope angle are of significance. The analyses can be expanded beyond the scope of this project to better understand the impact, either detrimental or beneficial, of non-planar slopes. Advanced modelling may be required to determine if a slope needs to shear or dilate around a macro asperity, thus providing additional resistance to sliding, or if the local increase in slope angles causes detrimental effects on stability.

Wrinkling has been studied by several authors (e.g. Take et al 2012). TLS could be utilised to analyse the intimacy of contact between the subgrade and geosynthetic layers by carrying out scans before and after material placement.

5 DISCUSSION

The following conclusions were established from the data obtained and its subsequent interpretation:

- TLS has been demonstrated as a tool for rapidly assessing the planarity of a containment lining system. The technology provides sufficient range and resolution to produce point clouds from which the slopes can be quantitatively analysed.

- The vertical expansion (piggyback) proved to be the most planar CLS, followed by the sideslope. The permanent capping system was the least planar.

- Basic stability analyses show that the magnitude of variation in slope angle can significantly affect the local factor of safety against failure. However, further analysis is required to better understand the impact of this variability on the overall slope.

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