Determination of moisture content and soil suction in engineered fills using electrical resistivity

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ABSTRACT: Integrated geophysical-geotechnical sensor systems are being developed to monitor ground moisture and associated geotechnical property changes. Therefore, it is essential that the relationships between electrical resistivity, water content and suction are more fully understood. This paper presents a study to resolve these relationships for a remoulded glacial till taken from a test site in Northumberland, United Kingdom, comparing laboratory and field data. Electrical resistivity was investigated using BS 1377-3:1990, whilst soil suctions were derived from moisture data using a suitable SWRC. To simulate seasonal effects, samples were allowed to dry and subsequently "re-wet" over the course of the testing program. Results indicated an inverse power relationship between resistivity and moisture content; suction was observed to increase with increasing resistivity. It was also observed that samples which fractured during testing had higher resistivities than those which remained intact. Trends observed in the laboratory could be seen to be repeated in field data.

1 INTRODUCTION

1.1 *Effects of climate change*

The concept of climate change as a consequence of anthropogenic activities has been broadly accepted (IPCC, 2007), with climate change projections suggesting a move towards warmer, drier summers and milder, wetter winters in the UK (Forestry Commission, 2010). It is well understood that ground moisture decreases soil strength, therefore a considerable change in atmospheric conditions would certainly affect the parameters which control slope stability.

Estimations that 10% of the UK has "moderate to significant" landslide hazard potential (Dijkstra & Dixon, 2010) are based largely on nationwide distributions of volume-sensitive clays (e.g. London clay) which are susceptible to shrink-swell behaviour. In these soils, the destabilising effect of water can be further exacerbated by annual wetting and drying cycles which cause shrink and swell displacements of the soil, resulting in desiccation cracks. These cracks then permit the rapid infiltration of rainfall, leading to elevated pore water pressures in the near-surface of clay slopes (Clarke & Smethurst, 2010), thus reducing the effective stress of the soil. It has been shown that these seasonal cycles can cause strain-softening, whereby an accumulation of shear strains and a corresponding loss in shear resistance result in progressive slope failure (Smethurst et al, 2006, Vaughan et al, 2004) as this reduced strength along shear zones leads to the development of shallow translational or deep rotational shear failures. If climate change projections are correct, then these annual wetting and drying cycles will have greater magnitudes. Correspondingly, the effect of reducing shear strength in natural and engineered slopes will be more severe, and the occurrence of landslides significantly more widespread. As such, the development of a viable system capable of assessing slope stability on a large scale is of vital importance.

1.2 *Currently available monitoring techniques*

There are many geotechnical sensors available that can be used to monitor slope conditions, including moisture content, pore water pressure and ground displacement. These sensors can to a certain degree provide indications of impending failure in unstable slopes. However, a number of weaknesses exist in the use of this type of equipment, the main ones being a) recording of point measurements rather than large-area coverage; and b) relatively high installation and maintenance costs. Point sensors are largely incapable of providing sufficient spatial sampling density for monitoring geotechnical property changes prior to slope failure in heterogeneous soils (Chambers et al, in press), meaning that they are often unable to detect the precursors to slope failure.

1.3 *Geophysical methods*

Resistivity imaging techniques such as electrical resistivity tomography (ERT) rely on using groups of relatively closely-spaced electrodes and therefore have the potential to provide far higher resolution geotechnical information. These techniques work on the principle that high soil resistivities are caused mainly by a lack of ground moisture, and vice versa, and can therefore be used to infer the distribution of ground moisture, which acts to decrease soil shear strength. For this reason, and due to the fact that it is also sensitive to lithology, two-dimensional ERT has been well-established as a means of subsurface hydrogeological investigation (e.g. Yamakawa et al, 2012, Zhou et al, 2002). Although there is a wealth of on-going research into three-dimensional ERT (using electrode arrays) as a means of monitoring slope stability (Chambers et al, 2011, Friedel et al, 2006), relevant geophysical-geotechnical relationships require further validation. As elevated moisture contents and a corresponding reduction of soil suction are associated with shear failure, their interaction with soil resistivity is key to the development of a slope stability assessment system.

2 METHODOLOGY

2.1 *Laboratory testing*

For the purposes of this research, the decision was made to investigate the moisture content-suction-resistivity relationships of the test soil for one initial drying/re-wetting stage, at twenty discrete gravimetric moisture contents (GMCs) between 22% and the residual GMC. Initial sample densities and moisture contents were based on average in-situ field site properties. The test soil – "Nafferton clay" is a remoulded glacial till taken from a test site in Nafferton Farm, Northumberland, and has very similar properties to London Clay. The site itself consists of a purpose-built embankment for studying the effects of climate on slope stability.

2.1.1 *Sample preparation*

Bulk Nafferton clay was passed through a 20mm sieve and allowed to air dry for 24 hours. The dried soil was then crushed using a mechanical crusher with a 3mm plate separation, and passed through a 2mm sieve. De-ionised water was added to the processed soil in order to bring it to a GMC of 22%. After a homogenisation period of 24 hours, 38mm diameter by 76mm length cylindrical soil samples were prepared using a steel mould filled by tamping after the addition of each of four approximately equal layers. 173.5g of soil was weighed out per sample, corresponding to dry and bulk densities of 1650kg/m^3 and 2010kg/m^3 respectively. The samples were then allowed to homogenise for a further 24 hours. Following preparation, those samples intended for the drying stage were allowed to air-dry until their masses corresponded to the target GMCs. Those intended for the re-wetting stage were air-dried to their residual GMC, and then placed in a "humidity chamber"; an insulated, sealed box with a mister submerged in de-ionised water, and "wet up" to their target GMCs. All samples were again left to homogenise for 24 hours. A total of forty cylindrical samples were prepared; twenty per each of the initial test stages.

2.1.2 *Resistivity*

Resistivity testing of the samples described above was carried out in accordance with the procedure as described in BS 1377-3:1990 chapter 10.2, with the following changes to procedure:

-no test container was used to encase the sample whilst testing; moisture loss was deemed negligible.

-a conductive grease was applied to either end of the samples to ensure good contact between the sample and the disc electrodes.

Samples which fractured over the course of the test program were retained and are treated separately in the results section of this paper.

2.1.3 *Gravimetric water content*

All GMCs carried out for the purposes of this study were undertaken in accordance with BS 1377-2 1990 chapter 3.2.

2.1.4 *Suction*

Fredlund & Xing (1994) curve parameters were fitted to moisture-suction data (gathered using the filter paper method) from Shehu (2011), to create a soil-water retention curve (SWRC) for the initial drying and wetting stages of Nafferton clay. This SWRC was then used to yield suctions corresponding to GMCs on both the drying and the wetting stages.

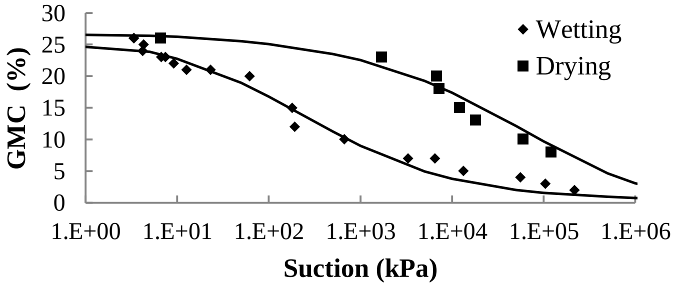

Figure 1.Soil Water Retention Curve. Data points from Shehu (2011).

2.2 *Field testing*

Since 2008, a series of probes embedded at depths of 0.5m and 1.0m have been in place at the field test site, recording various parameters which include volumetric water content and soil suction. Resistivity probes were installed in November 2012. For all of the above parameters, a sampling period of 30 minutes is used.

3 RESULTS

3.1 *Laboratory results*

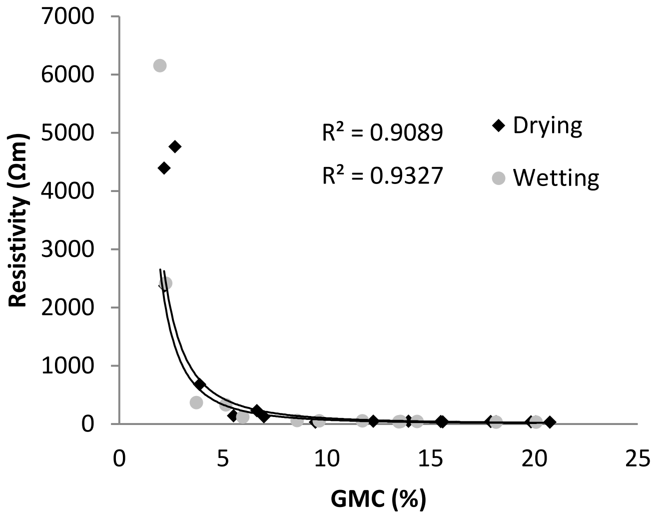

Figure 2. Laboratory-derived resistivity-gravimetric moisture content relationship for initial drying and re-wetting stages.

Figure 2 illustrates an inverse power relationship between resistivity and gravimetric moisture content, such that resistivity decreases with increasing moisture content. Little indication of hysteresis between the drying and wetting phases is evident.

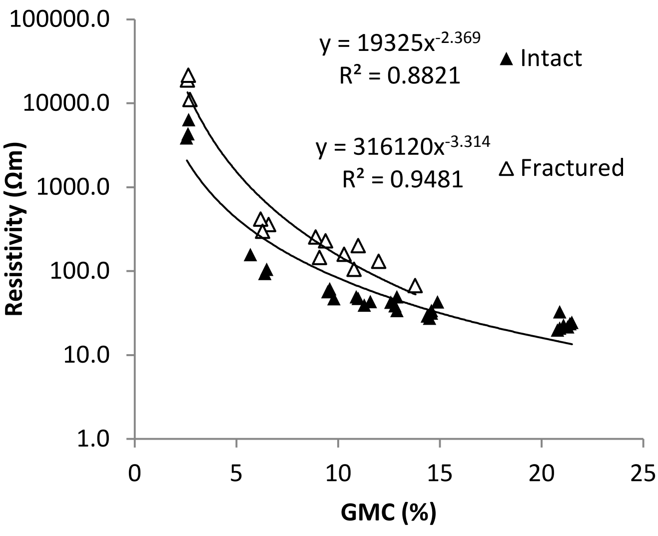

Figure 3. Laboratory-derived resistivity-gravimetric moisture content relationship for both intact and fractured samples. Resistivity data is shown on a logarithmic axis.

From figure 3, it is evident that fractured samples demonstrate significantly higher resistivities than intact samples of equivalent moisture content. As before (Fig. 2), an inverse power relationship between resistivity and gravimetric moisture content is observed.

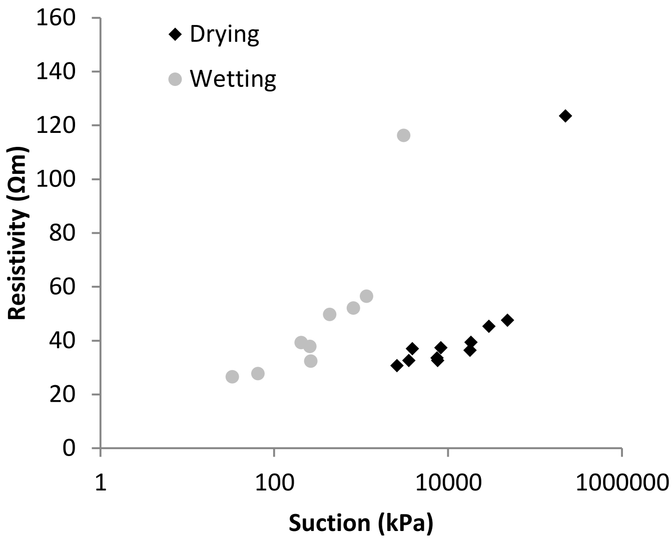

Figure 4. Laboratory-derived resistivity-suction relationship for initial wetting and drying stages.

Figure 4 shows soil resistivity to increase with increasing suction, for both drying and wetting stages. Higher suctions are achieved for samples during the drying stage than during the wetting stage, however, there is little change in the resistivities observed between the two stages.

3.2 *Field results*

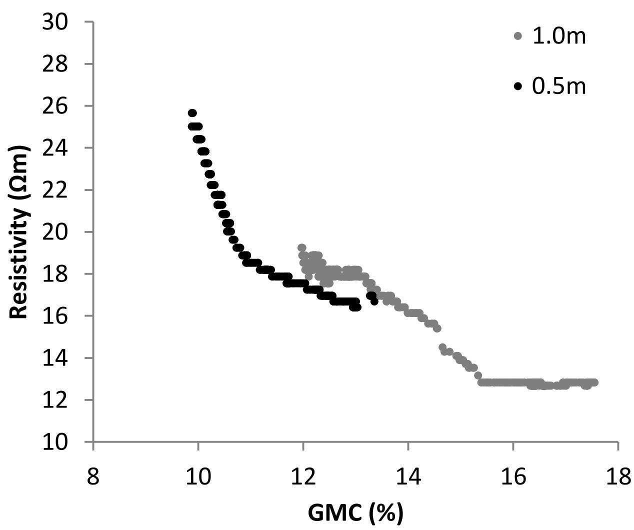

Figure 5. Resistivity-gravimetric moisture content relationship for drying stage only (summer 2013). Presents sensor data from

two discrete locations on the southern flank of the test embankment at 0.5m and 1.0m depths respectively.

From figure 5, it is apparent that field resistivity decreases with increasing gravimetric moisture content. Over the course of the summer 2013 period, higher GMCs were observed at 1.0m metres depth than at 0.5m, such that GMC ranged from a maximum of approximately 18% (1.0m) to a minimum of 10% (0.5m). GMCs of between approximately 12% and 13.5% are recorded on both sensors such thatthere is an interval of overlap; there is close agreement between the resistivities measured at both depths across this interval.

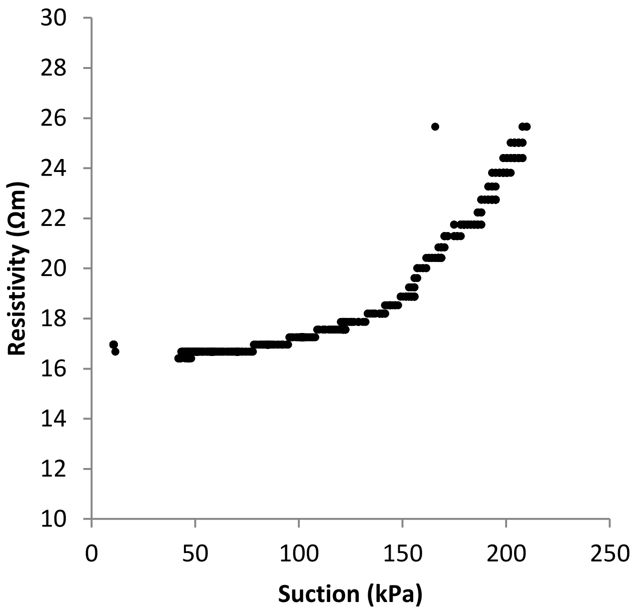

Figure 6. Resistivity-suction relationship for drying stage only (summer 2013). Presents sensor data from one location on the southern flank of the test embankment at adepth of 0.5m (same sensor as in figure 5). Suction data is shown on a logarithmic axis.

Figure 6 illustrates a clear exponential relationship between field resistivity and suction, such that resistivity increases with suction. Suctions increased from approximately 10kPa to 210kPa over the course of the summer 2013 drying period, with a corresponding change in resistivity from approximately 17Ωm to 26Ωm.

4 DISCUSSION

Both the laboratory and the field results have been successful in resolving a clear relationship between resistivity and gravimetric moisture content (Figs 2, 5). Whereas the laboratory data indicate an inverse power law, this cannot be fully inferred from the field data due to the limited range of moisture contents sampled at the test site (a function of the weather conditions since the installation of the resistivity sensors).This directly corresponds to a far narrower range of resistivities observed at the field site than in the laboratory. Weather conditions permitting, it may be possible over the course of the coming year(s), to extend the range of moisture contents recorded in the field, potentially supporting the concept of an inverse power law. Considering only the range of GMCs sampled in the field (approximately 10-18%), then resistivities are observed to range between approximately 13Ωm and 26Ωm in the field, and between 30Ωm and 60Ωm in the laboratory. Although there may appear to be a considerable difference in these resistivity ranges,it should be noted that both data sets show resistivity to approximately double over the same GMC interval. This difference can most likely be attributed to a difference in temperature of the sample soil, with field temperatures ranging between 12.3°C and 20.5°C, and laboratory samples of approximately 20°C. Additional laboratory work would be required to quantify the effect of temperature on resistivity.

Although initial stages of both drying and wetting were investigated in the laboratory, there is no clear evidence that the resistivity-GMC curve follows a different path depending on the stage. However, samples at lower resistivities (and correspondingly, higher GMCs) do indicate some degree of hysteresis, but this requires further investigation. It is well understood that the SWRC is different for drying and re-wetting stages (Fredlund & Xing, 1994), thus it is reasonable to expect that suction-moisture-resistivity relationships may be hysteretic for repeated cycles of drying and wetting. From figure 3 it can be observed that fractured samples demonstrate significantly higher resistivities than intact samples of equivalent gravimetric moisture content. This can be explained by the presence of fissures impeding current flow within the samples. This supports the concept of hysteresis within suction-moisture-resistivity relationships as repeated cycles of drying and wetting are likely to cause desiccation cracking of the soil, as explained above.

Both the field and laboratory results show resistivity to increase with increasing suction (Figs 4, 6), which is as expected as both low resistivity and low suction are associated with high moisture content. The field data indicate an exponential relationship, which is difficult to compare to the laboratory data due to the difference in the suction range. It is important to note that the range recorded from the laboratory data does not correspond to suctions which were directly measured; they are a function of the SWRC (Fig. 1) chosen to describe the suction of the test soil at discrete moisture contents. Given the excessively high suctions which correspond to high resistivities in the laboratory, it would be advantageous to directly investigate suction as a function of moisture content and resistivity, and modify the SWRC in order to more fully represent the laboratory-derived resistivity-suction relationship. This could be achieved in the laboratory by execution of a test program which directly measures soil suction using either the filter paper method or a tensiometer, and using these to create a new soil SWRC which could then be compared to the field-derived relationship.

Although figure 4 does show a different path for the resistivity-suction curve for the drying and re-wetting stages, this is again a function of the SWRC chosen, and although a hysteretic relationship is probable, this would need to be verified in the laboratory. As a result of the weather conditions since the installation of the resistivity sensors at the field site, only data pertaining to a drying stage is shown (Fig. 6). Over the course of the coming year(s), these data will be collected for subsequent wetting and drying stages.

This study has been successful in resolving the nature of the relationships between soil moisture content, suction and resistivity. Although there is some evidence of hysteresis, further investigation is required to fully develop how these relationships evolve with seasonal wet-dry cycles. If ERT is to be successfully deployed for the monitoring of slope condition, then it is essential that the integrated geophysical-geotechnical systems used must account for hysteresis in the relationships between moisture content, resistivity and pore water pressure.

5 CONCLUSIONS

From this research, the following conclusions have been drawn:

- An inverse power law exists between resistivity and moisture content which was successfully resolved in the laboratory; further investigation is required to confirm this relationship from field data.

- The nature of the relationship between resistivity and suction in the field is exponential; a testing program which involves direct suction measurement is required to fully resolve this relationship in the laboratory.

- Differences between the range of resistivities achieved in the laboratory and the field were attributed to temperature differences as well as a limited moisture content range in the field as a result of atmospheric conditions.

- There is an inference of hysteresis with seasonal cycling of the moisture content-suction-resistivity relationships from laboratory data; further validation of this from both field and laboratory testing is essential to fully resolve these relationships.

- The success of ERT has a means of slope stability monitoring relies on fully resolving geophysical-geotechnical property relationships which account for hysteresis as a result of seasonal cycling.

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