Electrical resistivity as a tool to identify areas of progressive failure within UK infrastructure embankments.

R. Sellers[a]*, N. Dixon[a], T.A. Dijkstra[a], D. A. Gunn[b], J.E. Chambers[b], P. D. Jackson[b], P. Hughes[c]

[a] *Department of Civil and Building Engineering, Loughborough University, Loughborough, LE11 3TU*
[b] *British Geological Survey, Keyworth, Nottingham,NG12 5GG*
[c] *School of Civil Engineering and Geosciences, Newcastle University, Newcastle, NE1 7RU*
**Corresponding author email: R.Sellers@lboro.ac.uk*

Abstract

Although electrical resistivity has been used by the oil industry for more than 50 years to locate oil resources, the use of this method for geotechnical purposes has been limited. This is largely due to the non-unique nature of the values, the intricate interpretative process and a degree of scepticism related to the potential usefulness of this method.

Among the factors contributing to bulk electrical resistivity are water content and pore fluid chemistry. This paper introduces research that is currently underway into identifying whether non-intrusive electrical resistivity tomography (ERT) can be used to identify areas of significant soil moisture changes in UK infrastructure embankments. Many of these embankments are over 100 years old and constructed using over-consolidated clays.

Cyclic changes in soil moisture are indicative of failure mechanisms in infrastructure embankments. Temporal variations in moisture content could deliver valuable insights into the potential for failure of embankments

In order to test the methodology, the BIONICS test embankment facility near Newcastle has been instrumented with ERT arrays to enable time-lapse imaging on two cross

sections through the embankment. In addition, a monitoring network of sensors, including temperature, moisture content and suction, have been installed within the embankment. These data will be used, along with other geotechnical properties and relationships from laboratory work, to create numerical models capable of describing the temporal variations of moisture content inside the embankment.

Initial findings indicate the ability of the ERT array to detect important physical property differences inside the embankment, including the location of lifts generated during the construction of the embankment. Temperature variations inside the embankment appear to be considerable with fluctuations occurring at depths as large as 4m. ERT is sensitive to variations in temperature and further research is required to appreciate the importance of these variations for the relative interpretation of multi-temporal arrays. Laboratory work is being undertaken using a modified compaction mould into which compacted samples of representative clays can be placed. This will enable the assessment of the sensitivity of ERT to small variations in key parameters and the development of a suitable model that can be used to assess the long term condition of infrastructure embankments in a quantitative way.

Introduction

Research is in progress to bring together information obtained during a resistivity survey and the factors which affect the measured values in order to aid investigations into long term progressive failures in infrastructure embankments.

Electrical resistivity is a measure of how much a material resists the flow of electrical current (Schippan, 1997). The electrical current flows through the movement of ions. The more ions and connected pathways present in a bulk material the greater the flow of current and the lower the resistivity. Electrical Resistivity has been used since the early 1940’s to indicate the presence and quantity of oil reserves in offshore deposits (Archie, 1942). This technique used a vertical arrangement of electrodes to measure the resistivity of the geological strata. The oil has a significantly higher resistivity to that of the surrounding unsaturated or sea water saturated rock (Archie, 1942), so that the difference between the two materials is clearly identifiable.

With developments in technology both in the instrumentation and the processing of the gathered data, the applications for which resistivity can be used as a subsurface investigative tool has expanded. Resistivity has been used in a 2D and 3D configurations to allow mapping of large areas (Carpenter *et al.*, 1991; Suzuki *et al.*, 2000). It has at present been mainly used to identify areas of contamination in an aquifer such as sea water ingress (Abdul Nassir *et al.*, 2000; Whittecar *et al.*, 2005). Also it can be used to track voids in a karst environment (Ahmed and Carpenter, 2003; Zhou *et al.*, 2000). In a soil material the primary control on the resistivity value is the amount of moisture in the material, other factors shown to affect the resistivity readings, include temperature, pore water chemistry and clay mineral content (Bryson, 2005; Fukue *et al.*, 1999).

Slope failures are occurring in some of the Victorian age railway embankments. There are failures that occur unexpectedly and in areas previously not showing signs of deformation. This type of failure can cause massive disruption to rail services and lead to closures while the failure is treated. This kind of disruption is both bad for the company economically but also it portrays a poor image to the public. The embankments that are particularly susceptible are those that were constructed using overconsolidated fine grained soils and which have a large amount of swelling clay minerals present (Palmer and Rice, 1973). The failures occur when the material undergoes repeated cycles of shrinking and swelling caused by the clay absorbing water and increasing in volume and then drying out and decreasing in volume. This process builds up irreversible plastic strains within the soil and this weakens the soil reducing shear strength until the forces acting on the slope are greater than the resisting forces. The reduced shear strength occurs in zones, starting in general at the toe and progressing up into the body of the embankment (Leroueil, 2001). There is a moisture content change across the shear zone (Skempton, 1964). The identification of this zone and subsequent quantification of the change in moisture content will enable a better use of stakeholders resources in preventing failures that cause disruption to passengers, and will lead to a more planned management system.

Infrastructure embankments stability

Large infrastructure embankments were constructed during the Victorian period from 1850 to 1900 for the expansion of the rail system and also in the 1950's and 1960's for the road construction. The soil used to construct the embankments was often won locally from cuttings or tunnels on the same stretch of line or road (MacDonald, 2005). This acquisition of soils leads the embankments to reflect the local geology and therefore vary across the country. Embankments constructed during the two periods have different physical properties due to the technology and knowledge available at the time. Figure 1 shows the difference between the two different construction methods.

The railway embankments were generally constructed using an end tipping method (Figure 2). In this method the soil is carried by cart either horse drawn or steam driven to the end of the constructed area and the carts emptied to form the structure (Skempton, 1996). The soil was not compacted as part of the construction method and only underwent compaction through the trafficking of passing vehicles and subsequent layers of soil. This method was employed as it was the most cost effective at the time, as the storage of soil from the nearby cuttings and tunnels was expensive so the material had to be placed in the embankment at the same rate that it was being won (Skempton, 1996).

The more recent motorway embankments were constructed to the specifications and standards in place at the time. This meant that they were constructed using suitable soils that were compacted in layers of known thickness and to achieve the maximum strength available for the material. An example of this specification is Design Manual for Roads and Bridges (1994).

The type of failures that are being identified in the older railway embankments can be caused for a number of reasons and one of these is repeated cycles of wetting and drying. This failure method is termed progressive failure and was first identified as a mechanism by Terzaghi and Peck (1948) and Taylor (1948). The soils that fail through this method generally contain clay minerals that have the ability to absorb water onto their surface and in between layers to increase their volume (Mitchell and Soga, 2005). When the water is removed through drying the material shrinks. This process causes shear stress to increase and hence shear strains (Lambe and Whitman, 1999). It is possible for the accumulated shear strains to be mobilised (Figure 3, point B). Once the peak has been reached the soil element can no longer support all the shear stress and this is transferred onto adjacent soil particles. This process is repeated throughout the soil until a zone of soil particles with post peak and possibly residual shear strength (Figure 3, point C) is formed. Once the zone of soil at a post peak shear strength can no longer can retain an equilibrium state then failure of the slope will occur. At the time of failure zones of soil in the shear zone can exist in three states, those that are at a post peak state (Figure 3 point C), those that at are peak stress (Figure 3, point B) and those yet to reach peak stress (Figure 3, point A).

Potts et al. (1997) showed through modelling of a cutting that it can take a large number of cycles for strain of 20% to build up (Figure 4). Also the strain does not form a continuous shear zone, but originates at the toe and retreats in to the slope with repeated cycles. The rate at which this propagation occurs is dependant on the range of moisture content change and the physical properties of the soils. This method of failure was monitored and identified through field observations in an Oxford clay cutting by Burland et al (1977) and in a test site in Gault Clay by Cooper et al. (1998). This mechanism may result in an embankment that has remained stable for over 100 years beginning to show signs of shallow deformation or possibly more significant deep rotational failure. When an embankment is constructed it undergoes stress release when the construction material is removed from the ground it then undergoes compaction, this creates a reduction in pore pressures. When placed in the embankment the soil will absorb water to return this reduced pore pressure to equilibrium values. When this occurs it reduces the shear strength of the material and the embankment slopes may no longer be able to withstand the destabilising forces.

ERT for soil moisture assessment

Electrical resistivity is considered to be a suitable technique to assess the moisture content changes within an embankment as it is a relatively non intrusive technique and resistivity is sensitive to changes in moisture (Fukue *et al.*, 1999). The resistivity equipment can be set up to be a permanent installation logging on a pre-programmed time series or equipment can be taken out to site and measurements made when required.

Understanding of the factors that affect resistivity in soil are key to being able to use it as a tool for assessments of moisture content changes that occur in an embankment.

Numerous investigations have been undertaken to investigate the effects of different soil parameters on resistivity readings. The parameters include moisture content, temperature, clay size particle content, clay mineral type, pore water chemistry and concentration, and compaction. Table 1 provides a summary review of the key research in this area and indicates the relative focus given to each of the above parameters .Resistivity sensitivity is different to each parameter and therefore needs to be considered separately, however the parameters and sensitivities may be interrelated. The soils that are more susceptible to fail by progressive failure are the formations with large amounts of swelling clay minerals (Palmer and Rice, 1973). These materials are often not quantified in laboratory studies due to the added complexity and cost of the tests and because they change volume during moisture content changes and absorb water into the interlayer space. The investigation of these soils and their resistivity is crucial to understanding the long term progressive failures within UK infrastructure embankments.

Research programme

To achieve an understanding of soil resistivity behaviour and integrate field and laboratory behaviour a combination of field monitoring and laboratory testing is being utilised. The field work is concentrated on the full scale test embankment BIONICS (BIOlogical and eNgineering Impacts of Climate change on Slopes). This embankment was constructed during 2005 to investigate the effect of climate change on infrastructure embankments. The site is managed by Newcastle University with a number of other institutions running long term experiments on the site. The embankment is 90m long, 6m high with a crest width of 5m (Hughes *et al.*, 2008). The soil used to construct the embankment was a locally won glacial till (Hughes *et al.*, 2008). The embankment is orientated with the long axis aligned east-west. There are two sections with differing compaction, one is compacted to existing highway specifications for earthwork construction, the second area was not actively compacted, with compaction coming from the trafficking of vehicles during the construction process (Hughes *et al.*, 2008). This is to represent compaction practice consistent with older railway embankments. In collaboration with the British Geological Survey the embankment was retrofitted with a number of instruments to aid the interpretation of resistivity values. A resistivity array was installed in each of the different compaction zones. These were orientated perpendicular to the long axis of the embankment. The electrodes were spaced at 0.5m across the entire section a total of 32 electrodes on each array. The arrays are set to record once every 24 hours with arrays monitored one after the other, to reduce the possibility of interference.

In addition to resistivity arrays, 14 combined temperature and moisture content probes were installed in the less compacted section close to the resistivity array (Figure 5). These probes are set to log once every 30 minutes, this data is then downloaded to the onsite computer by radio transmission from the logging boxes. The combined probes were installed at varying depths below the surface along the length of the section to enable interpretation of temperature across the embankment including the effect that orientation has on the temperature, as this is crucial in allowing a quantitative assessment of the resistivity readings. In addition, 5 suction probes were installed at depths up to 1.0m on the southern flank to monitor the drying of the shallow material where the propagation of desiccation cracks is identified (Barnfather, 2009). These probes also log on a 30 minute cycle and are downloaded in the same way as the combined probes. To identify how the embankment responds and in turn how the instruments respond to weather changes two air and shallow soil temperature probes, have been installed on the north and south flanks. The data gathered from these probes will allow for long term monitoring of the temporal and spatial changes in the embankment. At present there is approximately 10 months of data. The data gathered from these instruments will allow the testing of relationships between resistivity, moisture content and temperature formed through the laboratory work and used to identify whether an economically viable method could be developed for assessing infrastructure.

Laboratory work

The laboratory testing programme is designed to relationships between the various soil parameters and resistivity. The tests are carried out in a purpose built testing rig, to control the parameter variations. Compaction of the soil is identified in previous work as important (Abu-Hassanein *et al.*, 1996) and so the ability to control the amount of compaction used to form a sample and the repeatability of this compaction is crucial. It was decided to use an existing compaction process as set out in the British Standard (1990) and the Proctor mould compaction method was selected. The process requires soil to be compacted using a weight of specified mass, dropping from a specified height for a specified number of blows. The material is compacted in this way in 3 or 5 layers and using 2.5 kg or 4.5 kg hammers (British Standards Institute BS 1377, 1990).

The mould used is made from metal and so not suitable for resistivity measurements and therefore a modification was designed. The soil sample is extruded directly from the compaction mould into a plastic pipe of equal internal diameter. This allows stresses created in the sample to be retained. To retain the moisture within the sample during testing the sample is waxed in a similar way to the preparation method of a U100 sample (British Standards Institute BS 5930, 1999). Wax is non-conducting and will not interfere with the resistivity readings.

To measure resistivity readings of the cylindrical soil samples specially designed end caps were constructed that are slightly smaller diameter than the plastic pipe. The pipe has an internal diameter of 105mm, with the end caps having a diameter of 100mm (Figure 6). These caps were designed to allow current flow through the entire sample and not just a small section, as has been used by previous researchers. It will provide an average value for the entire sample. This will allow a similar measurement to the ones made in the field as the electrodes are installed perpendicular to the compaction layers. This method of reading allows for the averaging out of the slight difference in compaction that could be present across the sample (Figure 7). The caps are designed to input current into the system and record the changes in voltage. This is done by arranging stainless steel screws in a grid formation in a sturdy plastic circular disk. The screws penetrate through the plastic disk so the threaded ends are in contact with the soil. The screws that are providing the current are wired together and the screws that are measuring the voltage are wired together. This procedure is completed to form a pair of caps on each sample (Figure 7). The caps are then pushed into the top of the soil sample inside the plastic pipe and the remaining space in the top of the pipe is filled with wax to prevent moisture loss from the soil and to protect the operator from the electrical current. The samples are then placed into a Fisons FE610T climate chamber, that will maintain the temperature of the samples during testing and allow the samples to be subjected to a range of temperatures representative of current and an expanded range through the future climate predictions of UKCP09 (Murphy *et al.*, 2009)). The apparatus used to input current and record the voltage difference is a Terrameter SAS 4000. The current is put in to the sample at both cap locations and the voltage is also recorded at each cap.

The testing programme will include reworked embankment material mixed to a range of moisture contents to represent the different moisture contents measured within the field environment. During testing, the soil samples will be retained within the temperature controlled chamber. This is important as temperature is seen as a significant factor in the bulk resistivity value of soil (Besson *et al.*, 2008; Samouelian *et al.*, 2005).

Research results

The results gathered from the field work at the BIONICS test site have identified that temperature changes occur throughout the embankment. The variation is greatest at a shallow depth which is as expected (Figure 8). The variation in temperature measured at 0.5m below ground level is 6.5°C (9.7 -16.2°C) between May 09 and September 09, for the same period on the same flank (southern) of the embankment at 3.0m depth the temperature variation is 3.1 °C (8.3 -.11.4°) (Figure 8). The north side of the embankment also shows a general trend of being cooler than the southern slope of the embankment, which is again as expected as the southern side will receive more direct sun rays than the northern flank. The temperature range at 0.5m bgl on the northern flank is 8.5 – 15.1°C between May and September 09, which is approximately 1° C lower than the southern flank (Figure 9). Winds coming from the north are generally colder than winds from other directions and the southern flank is protected from these cooling winds. A difference to the expected results is that the crest of the embankment has shown to be warmer than the southern flank through the summer months of June and July. This may be due to the thermal properties of the ballast.

The resistivity array results can be presented to show both the absolute resistivity and the changes in resistivity from a base reading taken on the 14th March 2009 (Figure 10 and 11). Showing change rather than a bulk value identifies zones of change, rather than the underlying structure of the embankment that is shown in the bulk resistivity reading.

The values of resistivity identified vary from 10 to 542Ωm. Initial resistivity plots obtained 14th March 2009, 1st May 2009 and 1st June 2009 show how the data is presented from interpretation undertaken by the British Geological Survey (Figure 10 and 11) for the compacted and uncompacted sections For comparison the change in resistivity plots are shown in figures 10 and 11 with 14th March 2009 as the base survey from which the variation is calculated. The highly coloured zones to the base of the plots are developed through the processing method and are not representative of the physical attributes of the embankment.

The colours at the warmer end of the spectrum (red, orange, yellow), indicate higher resistivity that could mean a reduction in moisture content, cooler areas as these are factors that could result in an increased resistivity value. The cooler colours (blue and green) represent areas of lower resistivity, that could be a result of higher temperatures, higher moisture contents.

Summary and further work

The results obtained to date show the importance of including temperature in any field resistivity interpretation. Without a correction for variation in temperature at the time of recording, any results presented are not reliable for use in moisture content change determination. The temperature recorded within a cross section of the BIONICS embankment shows that the orientation of the embankment plays a significant role in creating temperature variations both spatially and temporally. This signifies that a temperature correction based on a single generic site temperature is not appropriate and a correction based on a thermal contour correction is a more accurate method.

The resistivity plots show the ability of the technique to identify change within the embankment. The most significant change is located within the shallow material. This is primarily due to the proximity to the air, which will produce the most sudden and significant response. The further from the surface the small and slower the responses.

Research into the response of resistivity to changes in moisture content within an embankment are on going. A range of tests will be undertaken within the laboratory to investigate the response of resistivity to changes in the key soil parameters including temperature data. The relationships will enable the quantification of resistivity survey data with respect to moisture content. This approach will allow for the identification of possible zones of deterioration in constructed embankments slopes

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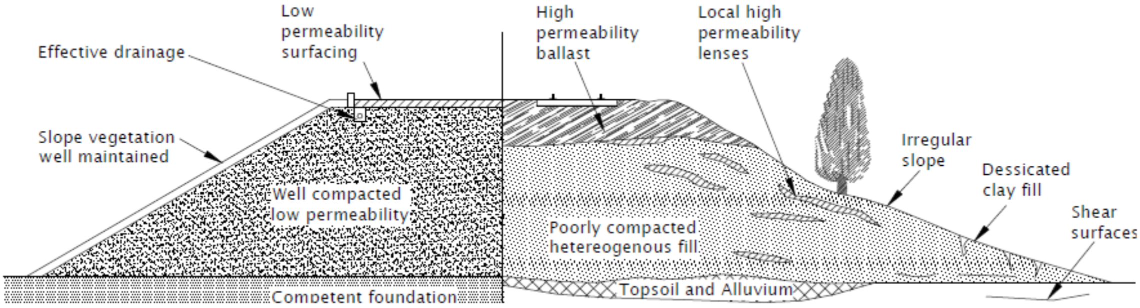


Figure 1: Variation in physical properties between modern highway embankments (on left) and Victorian railway embankments (on right) (after O'Brien, 2007)

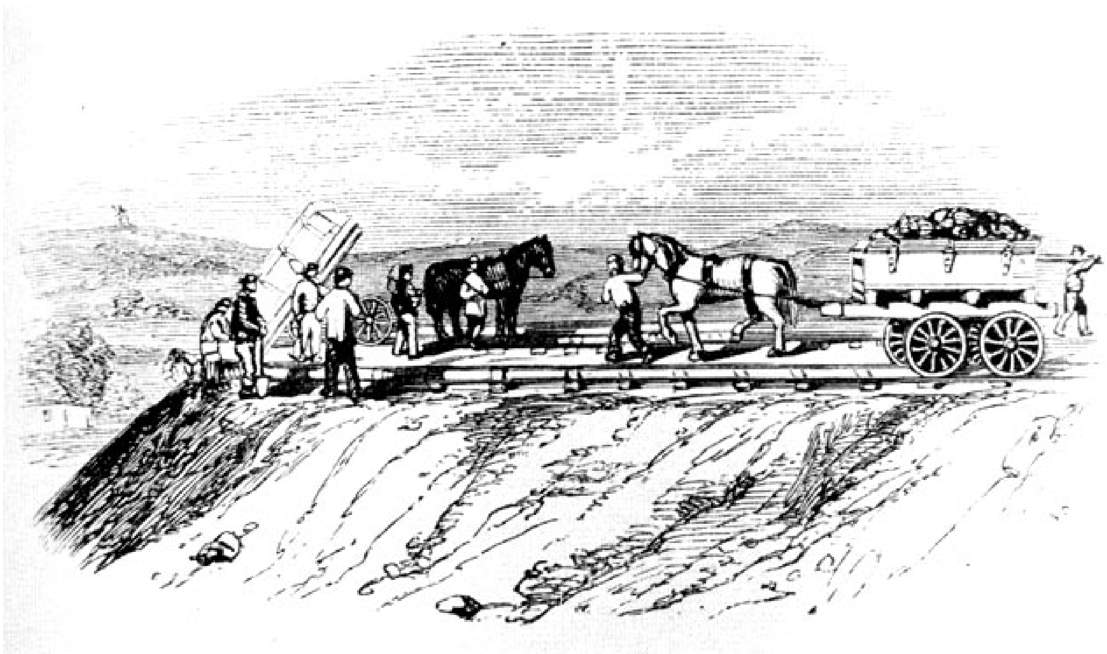


Figure 2: End-tipping on the Birmingham- London railway during 1830's (Sullivan, 1983)

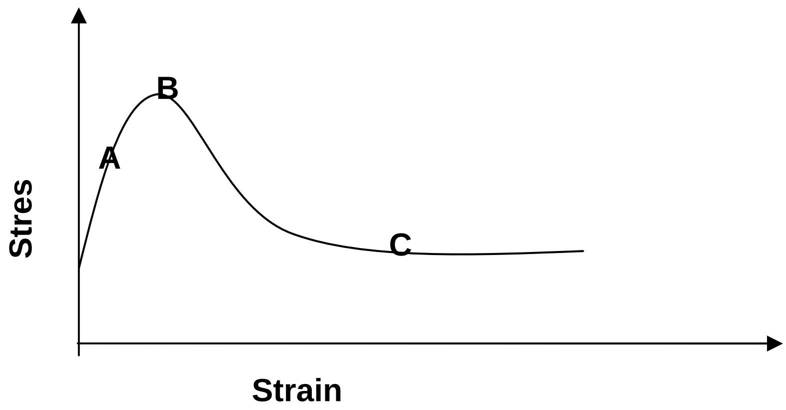


Figure 3: Mobilised shear strength in soil zones during progressive failure.

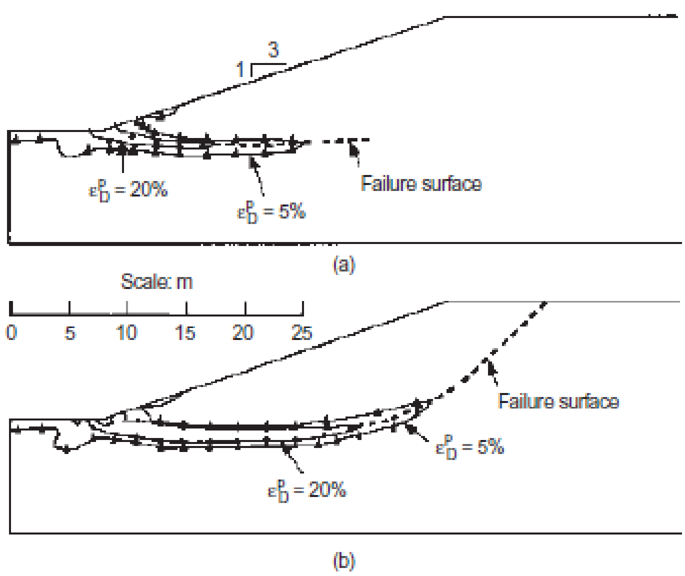
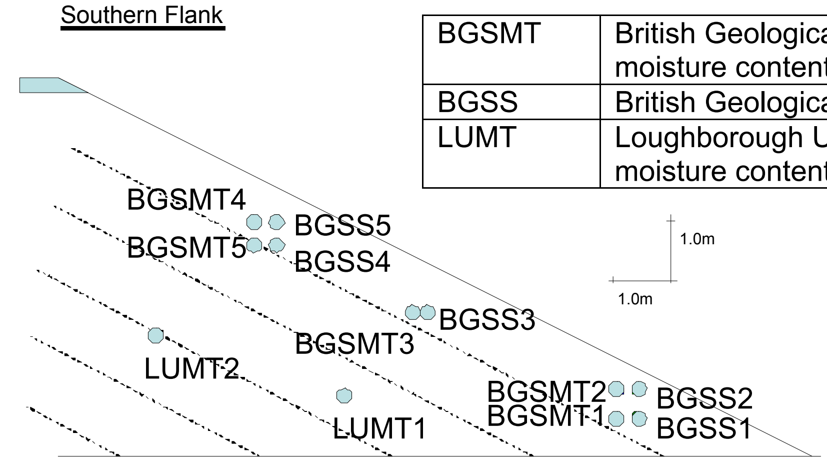


Figure 4: Propagation of strain a number of years after construction a) 9 years after b) 14.5 years after (after Potts *et al.*, 1997)

Key

BGSMT	British Geological Survey combined moisture content and temperature probe
BGSS	British Geological Survey suction probe
LUMT	Loughborough University combined moisture content and temperature probe



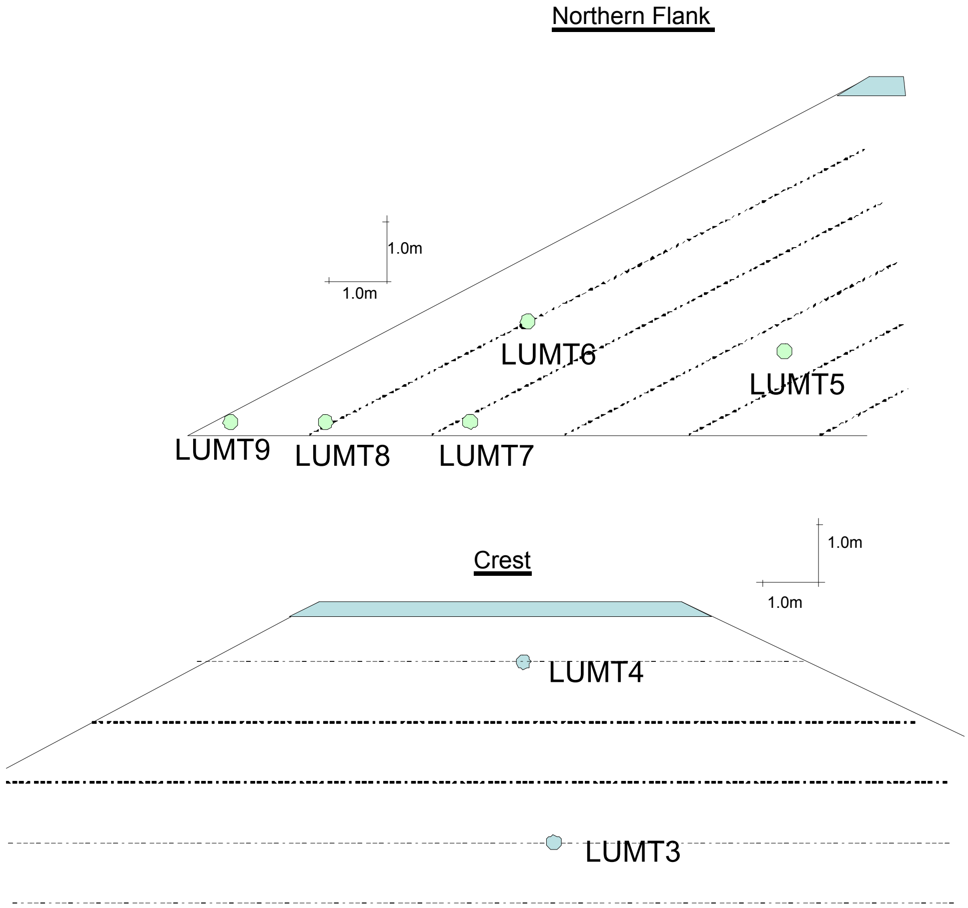


Figure 5: Location of combined temperature and moisture content, and suction probes within the BIONICS embankment installed by British Geological Survey and Loughborough University.

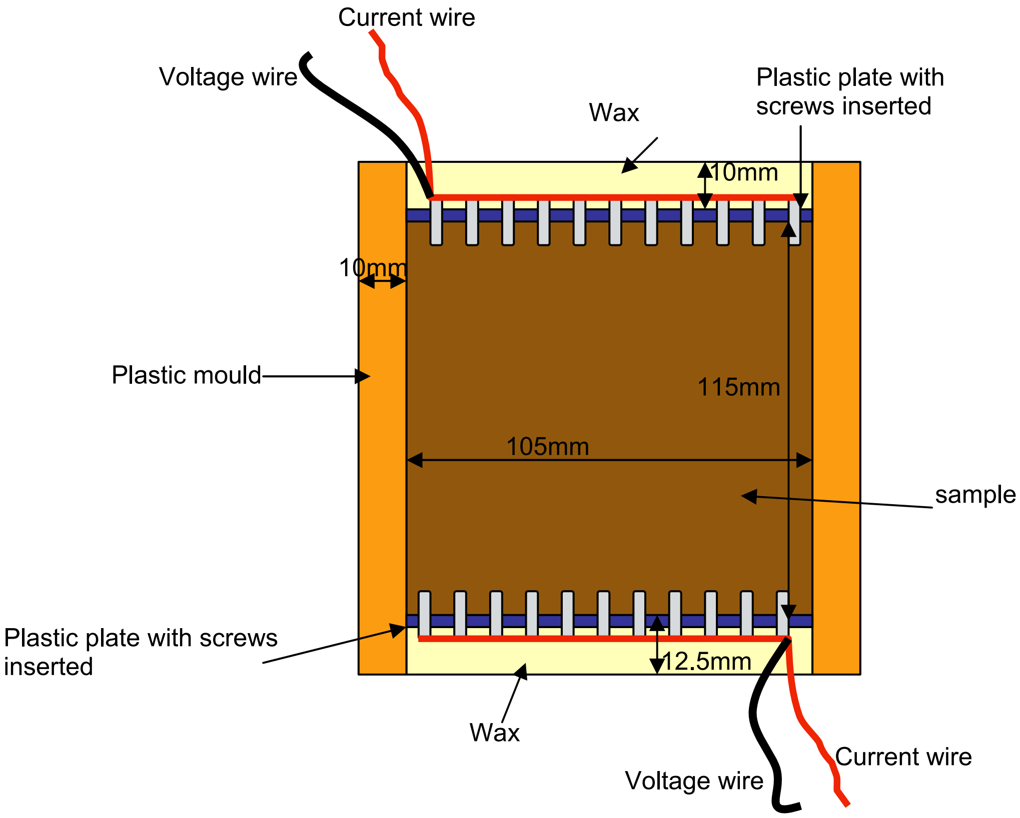


Figure 6: Sample setup for laboratory resistivity testing.

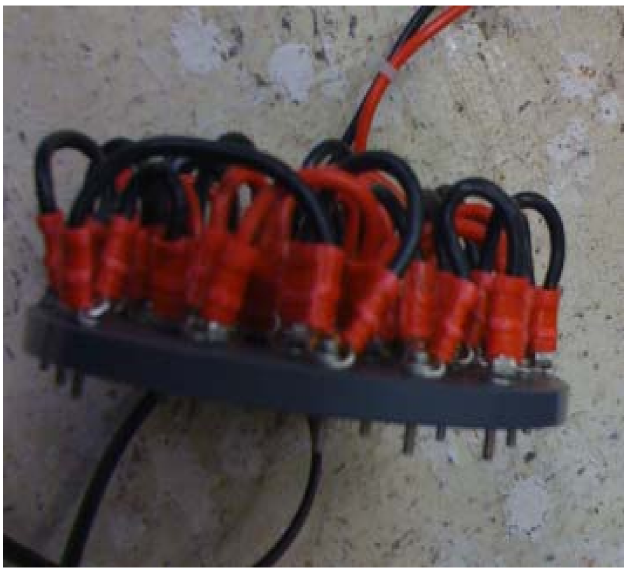


Figure 7: End cap construction for laboratory testing with screw electrodes at 10mm spacing.

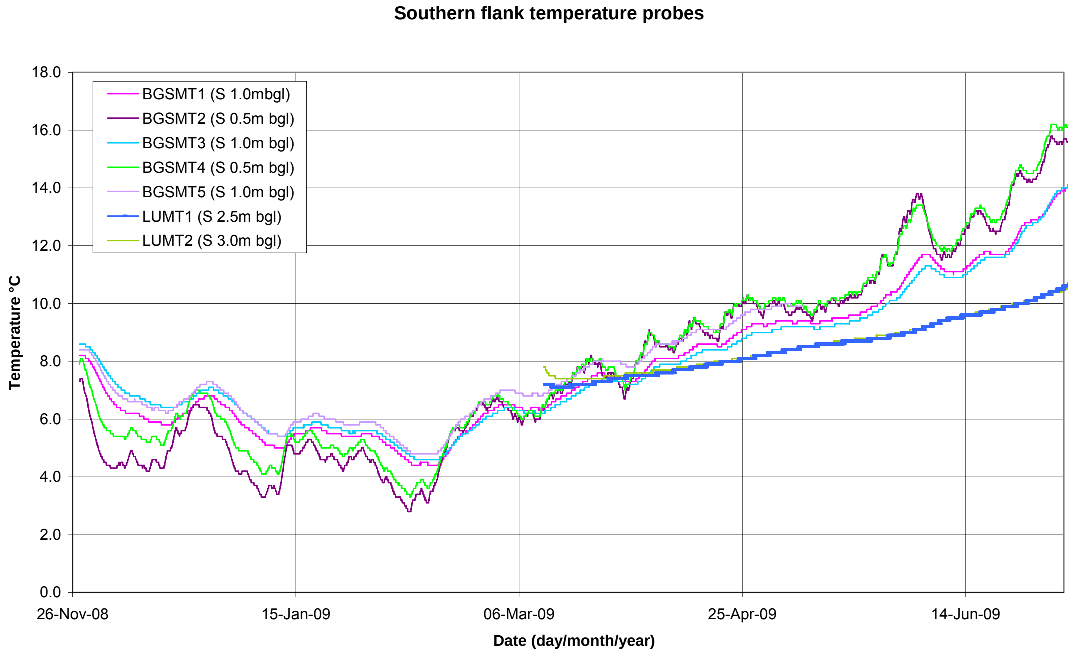


Figure 8: Variation in temperature on the southern flank of the BIONICS embankment.

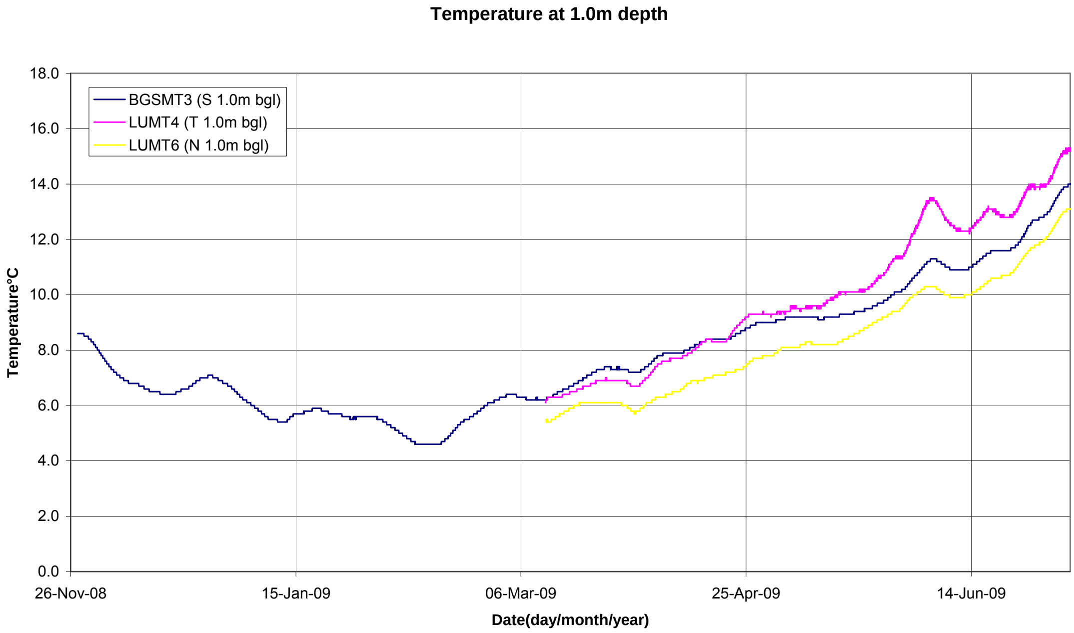


Figure 9: Variation in temperature at 1m depth on the south, top and north locations at BIONICS

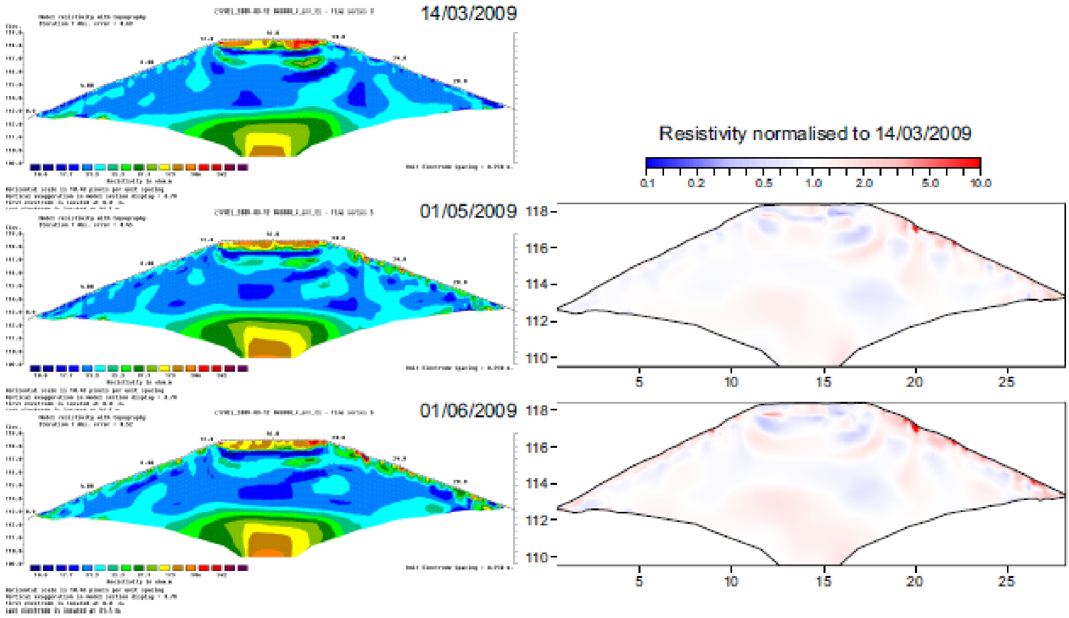


Figure 10: Resistivity and resistivity plots for the uncompacted section of the BIONICS embankment. (Image courtesy of the British Geological Survey)

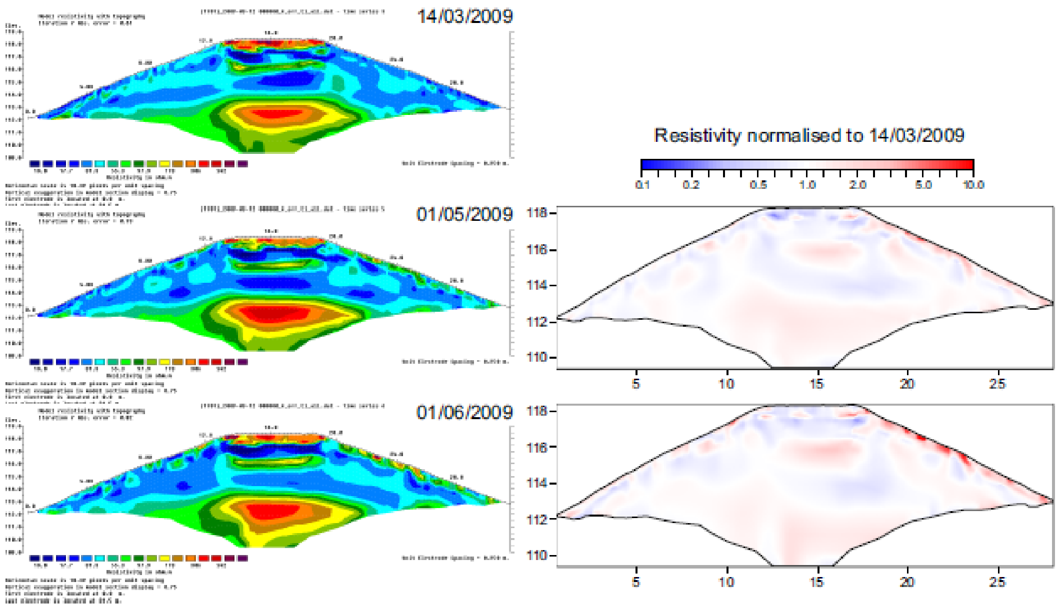


Figure 11: Resistivity and resistivity difference plots for the compacted section of the BIONICS embankments. Image courtesy of the British Geological Survey.

Paper	Parameters covered					
	Temperature	Compaction	Pore water Chemistry	Clay mineralogy	Moisture content	Particle size distribution
Determination of selected geotechnical properties of soil using electrical conductivity testing. (Bryson and Bathe, 2009)					■	■
Electrical Resistivity of Compacted Clays. (Abu-Hassanein *et al.*, 1996)	■	■		■	■	■
The temperature correction for the electrical resistivity measurements in undisturbed soil samples. (Besson *et al.*, 2008)	■				■	
Evaluation of Geotechnical Parameters using Electrical Resistivity Measurements (Bryson, 2005).	■	■	■	■		
Electrical resistivity survey in soil science: a review. (Samouelian *et al.*, 2005)	■		■	■	■	■
Effects of liquid-phase electrical conductivity, water content and surface conductivity. (Rhoades *et al.*, 1976)			■		■	■

The electrical resistivity characteristics of compacted clays. (McCarter, 1984)		■			■	
Estimating water content of soils from electrical resistivity. (Kalinski and Kelly, 1993)			■		■	

Table 1: A summary of current work on soil parameters and their effect on resistivity.