In-situ investigation of problematical soils

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Abstract

Problematical soils occur in many parts of the world, both naturally and as a result of man-made activity, thus making their behaviour a truly global problem. *In-situ* properties are often variable and difficult to predict, so effective site investigation is essential for the optimum characterisation and prediction of soil behaviour. Commonly, site investigations favour established techniques such as penetration tests, trial pits and boreholes. These provide useful but limited data, being obtained at discrete points on a site. Similarly, and as a consequence of disturbance, laboratory testing of soil samples often does not truly reflect the *in-situ* properties of the soil. The use of *in-situ* geophysical investigation is suggested as a possible solution to this problem. This paper highlights the potential of geophysics, with illustrated examples of recent work where geophysical methods have successfully assessed tropical red clay and brickearth soil properties. Information can be gained on both the general physical properties and the properties relating to failure of the soil (e.g. collapse or landslides), such as moisture content and presence of voids. It is also possible to assess the effectiveness of ground improvement engineering work undertaken on such soils. Geophysical investigations, characterising whole volumes of ground can be conducted rapidly and cost effectively, helping to provide the best approach to gain knowledge of *in-situ* collapsible soil conditions.

Introduction

There are several types of naturally occurring soils having potential to cause problems for a variety of reasons, including collapse, expansion, settlement, low bearing capacity and other factors that would cause difficulties for the civil or geotechnical engineer. Bell & Culshaw (2001) give an overview of problematic soils from a UK perspective, but the problems encountered are also a worldwide concern. There is a range of different types of naturally occurring problem soils, including expansive clays, peat, quicksand, glacial deposits and collapsible soils, as well as man-made problematic soils and fills. The specific problems posed by naturally occurring soils with potential for collapse under loading (for example by a building or during construction works) or wetting (such as during rise of groundwater) is an existing and on-going geological hazard, and represents a major area of concern when engineering work is planned, conducted or after it has been completed. Loess (sometimes termed 'brickearth' in the UK) is an example of a major type of collapsible soil and occurs extensively as a natural deposit worldwide and can often be found underlying areas of high population and major infrastructure works. Subsidence damage to buildings and other structures is a common result of collapse of loess.

Worldwide, billions of pounds are spent each year on prevention and remediation projects addressing the hazards caused by problematic soils. There exists a requirement to be able to rapidly identify and characterise areas where the ground underlying built areas, or areas with potential for future civil engineering works, are at risk due to the nature of the soil. Also, the ability to efficiently assess the effectiveness of ground improvement work undertaken on collapsible and other problematic soils is required.

For example, naturally occurring loess soil covers approximately 10% of the Earths entire landmass, and forms as a result of a long, high-energy process culminating in the transportation and deposition, by wind, of quartz silt sized particles. It is believed that current loess deposits were derived from areas where silt was produced by glacial action, prior to aeolian transportation. This wind blown silt deposition process has resulted in major loess deposits in North and South America, Europe, central Asia and China, including an almost continuous deposit from North China to south-east England. In the UK, loess deposits of greater than 1m thickness are only found in south eastern England, in Kent, Essex and Sussex, although lesser deposits can be found in other regions of southern, central, eastern and north-western England, and Wales (Jefferson *et al* 2001). The nature of the depositional environment results in a soil with high void ratio and low density. The resulting initial low (natural) moisture content and low dry density show high apparent strength, but on saturation problems arise as the soil undergoes structural collapse and subsidence (e.g. Rogers *et al* , 1994). The metastable texture of the soil collapses as the bonds between the grains in the soils fabric break down on wetting, collapse usually occurs rapidly, representing a re-arrangement of particles into a denser packing.

Another class of problematic soil is red clay soil, occurring throughout the tropics. The importance of such soils is increasing, as the development of infrastructure – rural, urban and industrial – requires knowledge of the behaviour of local materials (Hobbs *et al* 1992). They contain iron and aluminium oxides (which impart their red coloration), have distinctive clay mineralogies and are characterised by a porous soil fabric comprising 'bonded' aggregations, or clusters, of clay particles and finely disseminated iron oxide. Red clay soils behave in a different manner to loessic soils, and are not categorised as a truly ‘collapsible’ soil, but soil deformations due to moisture variations can cause equally serious issues to address. (See ‘Case Studies’ section for further details).

There is a range of options open to the geotechnical engineer to mitigate the effects of problematical soils, prior to subsequent site development. For example, Houston *et al* (2001) summarise the categories of techniques available to prevent collapse as including removal of soil, removal and replacement/compaction of soil, avoidance of wetting, chemical stabilization/grouting, pre-wetting, controlled wetting, specialised foundation design and dynamic compaction. Dynamic compaction, in which a mass is repeatedly dropped on the ground surface from height to compact and improve the strength of the ground, is a well established ground improvement technique. When used on collapsible soils, the technique has the dual action of improving the ground bearing capacity and also artificially ‘collapsing’ the soil structure, thus making collapse in the future (for example through inundation by water) less likely. Similarly, tropical red clay soils are compacted in place at carefully controlled moisture content conditions.

Soil characterisation

Problematic soil investigation

Houston *et al* (2001) observe that problematical soils, such as loess, have the greatest potential for damage when their existence and extent are not appreciated prior to the commencement of construction work. The identification and characterisation of collapsible soils and subsequent estimation of the collapse potential are extremely important factors, for example. Generally, the most commonly used method for reliable indication of collapse potential is that of a collapse test using a laboratory-based oedometer. However, it must be noted that despite this, even data from such an accepted test carry a degree of uncertainty and will not give accurate values for all field situations (Jefferson *et al*, 2001). Most laboratory tests use disturbed, re-moulded samples, and so do not measure actual *in-situ* properties. ‘Un-disturbed’ samples can be obtained, but this is a difficult and sometimes uncertain procedure.

Other laboratory geotechnical testing can be used to provide information about the engineering properties of the soil (e.g. strength, density, permeability, index properties), and can give some information about the collapse condition of the soil. Several criteria have been suggested for the direct assessment of collapse potential of soils using non-collapse laboratory tests, including moisture content, void ratio, initial dry unit weight, differences in sand and clay percentages and index properties (Rogers *et al* 1994, Northmore *et al* 1996, Basma & Tuncer 1992). Some relationships have been shown, but conclusions can sometimes be qualitative, and uncertain and misleading results can often be obtained.

The accepted non-laboratory approach to determining the possible degree of collapse is through *in-situ* field tests, normally consisting of a large-scale plate-loading test. There are disadvantages to such tests, there is often a non-uniform stress within the collapsing volume of soil, and subsequently there can be difficulty in determining accurate stress-strain relationships, for example. Unlike laboratory tests, large plate loading tests offer minimal sample disturbance and test large volumes of soil (e.g. Houston *et al* 1995).

***In-situ* ground investigation**

Once geotechnical information has been gained from laboratory or *in-situ* tests, the data can be integrated with the desk study and an *in-situ* ground investigation to fully characterise and understand the nature and extent of the problem faced by the ground engineer. Conventional *in-situ* ground investigation methods can include penetration tests, borehole sampling, trial pits, pressuremeters, vane shear tests, California Bearing Ratio (CBR) tests and other techniques for determining soil properties. Useful information can be gained concerning soil strength, thickness of layers and other geotechnically useful parameters by *in-situ* geotechnical site investigation tests. Work try to apply *in-situ* geotechnical techniques, such as penetration testing, for determining collapsibility of loess has been tried but with limited success (Milevski, 1988).

Non-invasive geophysical ground investigation techniques are often not fully integrated, or accepted, in geotechnical engineering projects. An improved *in-situ* methodology would provide huge benefits to the civil engineering industry, in terms of improved knowledge of soil conditions and reduction of risk, and provide an important new tool with which to mitigate the effects of geological hazards from problematic soils, such as collapse. Telford *et al* (1990) give a background to the main established geophysical methods available, and CIRIA (2002) give a good overview of the application of geophysical methods for engineering site investigation purposes. Although many can provide a variety of information relating to the *in-situ* properties of soils, the general trend within civil engineering is to favour conventional geotechnical ground investigation techniques, and there can sometimes be a lack of appreciation of geophysics and in what situations it can be applied. The consideration of appropriate geophysical methods, and their integration into site investigation works has been encouraged recently (e.g. BS5930:1999, CIRIA 2002) but despite the potential benefits offered, they still remain relatively under-utilised.

In-situ geotechnical soil assessment methods require disturbance of the ground and are point specific, so effective whole site assessment is not practically possible. The use of geophysics offers a non-invasive, rapid and cost effective assessment of large areas of the ground, providing information on greater volumes of soil than can be obtained by conventional methods. An appropriate methodology is to integrate information from geophysical, geotechnical and geological investigations to create a conceptual ground model, significantly reducing the risk of mis-interpretation and mis-interpolation which can result in a poor understanding of the true nature of the ground (CIRIA, 2002). By taking this approach to site characterisation, the problems of 'unforeseen ground conditions' producing delays and extra costs to engineering projects can be minimised.

A range of soil properties such as depth and lateral extent of soil deposits, depth to water table, moisture content and movement and stiffness of soil can all be assessed using various geophysical methods. There is also much potential for the use of geophysics to assess ground improvement work on weak and collapsible soils. However such methods are mainly at the developmental stage, but several useful studies have been conducted showing the ability of geophysical methods to provide information on properties of soils that are important when considering the potential for ground failure, such as moisture content and moisture movement. In some cases, established uses of geophysical methods can be applied in a novel way to provide additional information when considering the specific soil properties. For example, electrical resistivity methods can be used to monitor changes in moisture content and moisture movement in soils. Jackson *et al* (2002) describe work using electrical resistivity to monitor changing moisture content distribution within tropical red clay soil. In principle this specific case, performed on an embankment of engineered fill before, during and after failure, holds true for monitoring of moisture content and movement in any area of soil (see also 'Case Studies' section), particularly the presence of water in collapsible soil, as it is the most important factors in weakening mechanisms that result in collapse.

Considering collapsible soils, quantification of collapse-potential s currently only achievable to an acceptable degree of accuracy by laboratory or large-scale field tests. Determination of the depth and lateral extent of a collapsible soil deposit is generally achieved through 'traditional' ground investigation methods, sampling only a minute fraction of the total soil volume. Once combined with the geophysical approach, data from collapse-potential tests may be applied to whole volumes of ground. Also geophysics offers a potential solution to assessing the extent to which dynamic compaction has improved the strength of collapsible soils, and reduced the collapse potential. Several investigations of the *in-situ* properties of natural collapsible soils have been conducted recently. In the UK, The British Geological Survey conducted shear wave and resistivity measurements on collapsible soils. Birmingham University have also conducted fieldwork on the collapse mechanism of soils and Nottingham Trent University have conducted several studies into the properties of collapsible soils and have performed a preliminary geophysical assessment of collapsible soils properties and effects of dynamic compaction ground improvement work (see 'Case studies' section'). Such studies have allowed an insight into the applicability of certain geophysical techniques for determination of useful information regarding collapsible soil properties to be obtained. Work and development is on-going, but such studies offer preliminary indications that there is promise for the success of the application of geophysics. Some initial conclusions can be drawn, and details are given in the 'Case Studies' section.

Case studies

Seismic survey to assess dynamic compaction on loess

An investigative field study was conducted on an area of loess soil in Kent, south-east England, to investigate whether a seismic body-wave survey could be used to assess the change in ground conditions as a result of small scale dynamic compaction ground improvement. Seismic body-waves consist of P (compressional) waves and S (shear) waves. It can be difficult to obtain good near-surface P wave data (Baker *et al* 1999), but in theory the densification of soil resulting from ground compaction should be detectable by a recorded increase in the velocity of seismic waves passing through the improved layer. The amount of increase in velocity indicates the degree of increase in density of the material. Also, by examining breaks in the seismic data recorded, it may be possible to determine the depth to which the densification has been performed.

P-wave velocity is governed by the undrained bulk modulus of a material, while S-wave velocity will vary as a function of shear modulus and density, and so can still yield useful results even in saturated conditions. For example, there is evidence of geotechnical value in shear stiffness measurements surface seismic wave measurements (Matthews *et al* 1996, Matthews *et al* 1997).

Traditional shallow seismic body-wave surveys were conducted using a sledgehammer and shot plate seismic source, geophones being fixed on the ground surface at 1m intervals along a 25m long survey line. Data was recorded before and after ground compaction over the test area. Also, dynamic cone penetrometer (DCP) tests provided data that could be compared to the seismic survey results. The DCP is a simple, portable means of measuring the resistance of ground material to the penetration of a cone, in terms of mm/blow, as it is vertically driven into the ground by a series of blows. Ground compaction was achieved by the use of a non-standard small scale dynamic compaction rig, consisting of a 700kg weight dropped from a height of approximately 1.5 - 2m, compacting the ground over an area approximately 2m either side of the survey line. The DCP results before ground compaction showed that the stiffness of the loess in the upper 700mm of ground was variable (approximately 44–75 mm/blow cone penetration), but after ground compaction across the test area there was a distinct increase in cone penetration resistance (approximately 16–40 mm/blow cone penetration), particularly in the upper 300-400mm of ground but also to a lesser degree down to at least 700mm depth.

Figure 1. Seismic survey being conducted at loess test site, before ground compaction. Geophones can be seen next to the tape measure in a line running towards the camera).

After compaction the P wave velocity was recorded at approximately 800ms^{-1} in the upper layer The results from this preliminary field study show increases in seismic velocity when soil is densified by ground compaction can be detected by a simple seismic P-wave survey. Findings from the work show there is potential for assessing ground compaction work, over large areas, on problematic soils such as loess.

Electrical resistivity imaging of moisture variations in a tropical soil road embankment.

As described above, tropical red clay soils are a complex assemblage of peds and bonds composed primarily of clay minerals, iron and aluminium oxides, their geotechnical behaviour being highly sensitive to their moisture content. Red soil road embankments often suffer severe vertical and lateral deformations, most notably evidenced by severe longitudinal cracking in the road pavements which develops close to the embankment shoulders as the soil materials respond to moisture variations over successive wet and dry seasons. In tropical and subtropical regions a wide spectrum of residual red clay soils are extensively developed and used, of necessity, in many engineering works. The engineering behaviour of these materials is significantly influenced by soil fabric and mineral composition, which can vary markedly with climate (rainfall and temperature). In their natural state the soils are relatively free draining and even in areas of high rainfall tend to be only partly saturated. They also tend to posses relatively high field strengths resulting from bonding of aggregated soil particles and the effect of soil suctions arising from their partially saturated condition. However, problems are often encountered when these red clays are used in earthworks such as road embankments, which can suffer severe vertical and lateral deformations (‘hydro-deformation’) as the soils respond to moisture variations over successive wet and dry periods. Typical deformations often result in severe longitudinal cracking of the road pavement close to the embankment shoulders, the most serious tending to form at locations where ‘moisture sensitive’ clay minerals occur in the embankment fills.

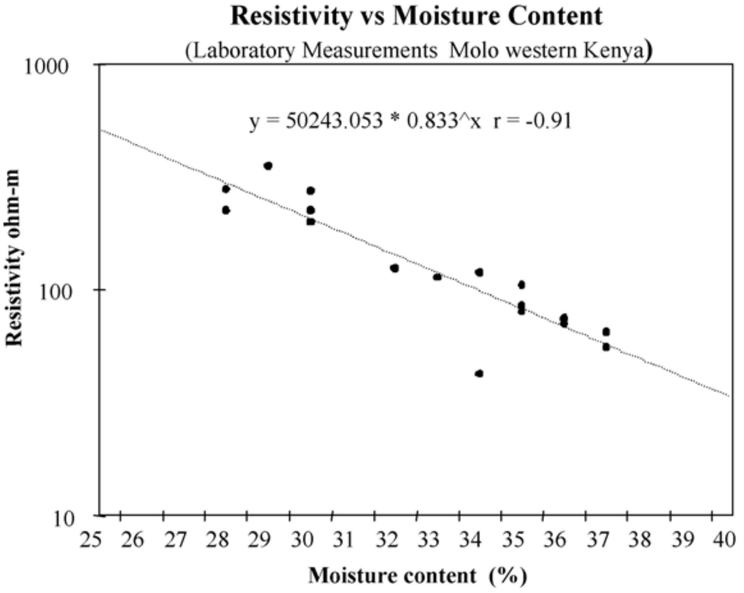
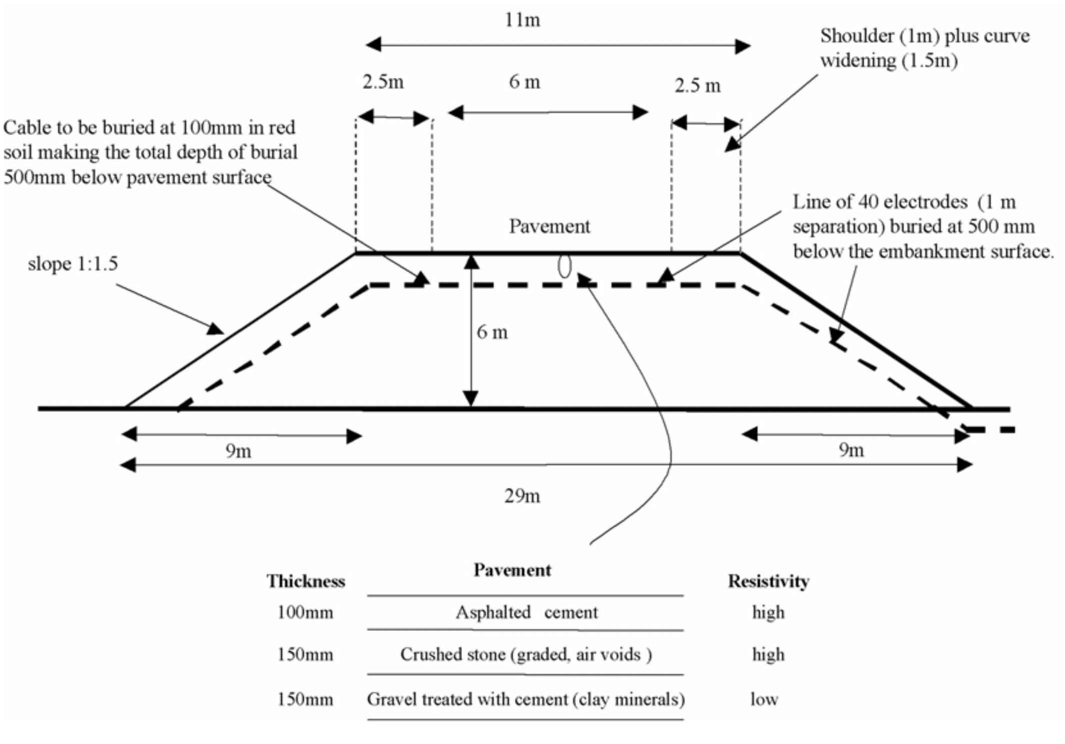


Figure 2. Empirical relationship between resistivity and moisture content derived from laboratory measurements (Jackson *et. al*., 2002)

Over an eighteen-month period between 1993-1994 the British Geological Survey (BGS), in collaboration with the Materials Testing & Research Department, Nairobi, carried out a study to monitor seasonal moisture movements in a red soil embankment during construction of the Molo-Olengurone road in Rift Valley Province, Kenya (Jackson *et al,* 2002). The road embankment was located in an area of undulating uplands and volcanic foot-ridges where annual rainfalls exceeded 2000mm with a short dry season between February and March. The residual soils mainly comprised dark reddish brown andosols characterised by the presence of amorphous allophane, halloysite and kaolinite clay minerals derived from Tertiary volcanic tuffs; existing embankments in the area had a history of post-construction deformation. Monitoring of seasonal water movements within the embankment was undertaken using a non-invasive electrical resistivity imaging system designed at the BGS. As electrical resistivity is sensitive to moisture content within a soil, the basis of the operation was to ‘image’ moisture variations by means of measured variations of resistivity over the monitoring period. In order to use electrical resistivity as a proxy for moisture content it was necessary to establish a relationship that applied to the embankment materials concerned. Being predominantly clays, the compacted embankment soils allowed matrix conduction of electrical current. Consequently, carefully taken and preserved representative ‘undisturbed’ core samples of the red clay embankment materials were obtained so that controlled experiments could be carried out in the laboratory to determine the variation in resistivity with changing moisture content. A consistent relationship between resistivity and moisture content was established and subsequently used to relate non-invasive assessments of embankment resistivity to moisture content, enabling moisture variations within the embankment to be monitored (Figure 2).

Resistivity data was acquired by means of a line of 40 electrodes, with a spacing of 1 m, deployed across the embankment, with electrode contacts located at 500mm depth below the road pavement (Figure 3). A major advantage of this technique was that subsurface measurements could be made without the need for numerous access holes bored through the embankment fill, which itself can lead to modification of the natural pattern of moisture movement within the embankment materials. Each line of electrodes recorded data over a ‘volume slice’ approximately equivalent to a 2m wide section across the whole embankment width to its full depth. The resistivity data could thus be presented as a cross-sectional resistivity ‘map’. Successive measurements at selected intervals enabled a sequence of resistivity images to be obtained which could be interpreted in terms of moisture movement patterns over time.



Thickness	Pavement	Resistivity
100mm	Asphalted cement	high
150mm	Crushed stone (graded, air voids)	high
150mm	Gravel treated with cement (clay minerals)	low

Figure 3. Red Soil Embankment Design (e.g. Molo-Olenguruone road K19 + 300) (Jackson *et al*., 2002)

The corrected moisture content sections are shown in Figure 4 where the values of moisture contents near the surface of the embankment can be seen to have varied substantially over the 18-month monitoring period. The dataset for April 1993 has lower moisture contents (higher resistivities) in some of the central regions that have been attributed to electrode contacts being initially poor. This is partly due to the ground around each electrode being disturbed during installation and not having sufficient time to recover. An increase in moisture content can be seen in the topmost 2.5m from April 1993 to Dec 1993a. Significant rainfall occurred during this period and the asphalt top layer was added in November. Subsequently, after the pavement had been laid, the moisture content of this topmost soil-layer reduced gradually. Substantial changes in moisture content were also observed on the right hand side (RHS) of the embankment over the depth interval 4 – 8 metres. Field observations identified a seepage horizon that had developed close to this level. Its drainage over the embankment's right shoulder is the likely cause of the high moisture contents in the 4 – 8 m depth interval, (as seen on the Dec 93b section in Figure 3).

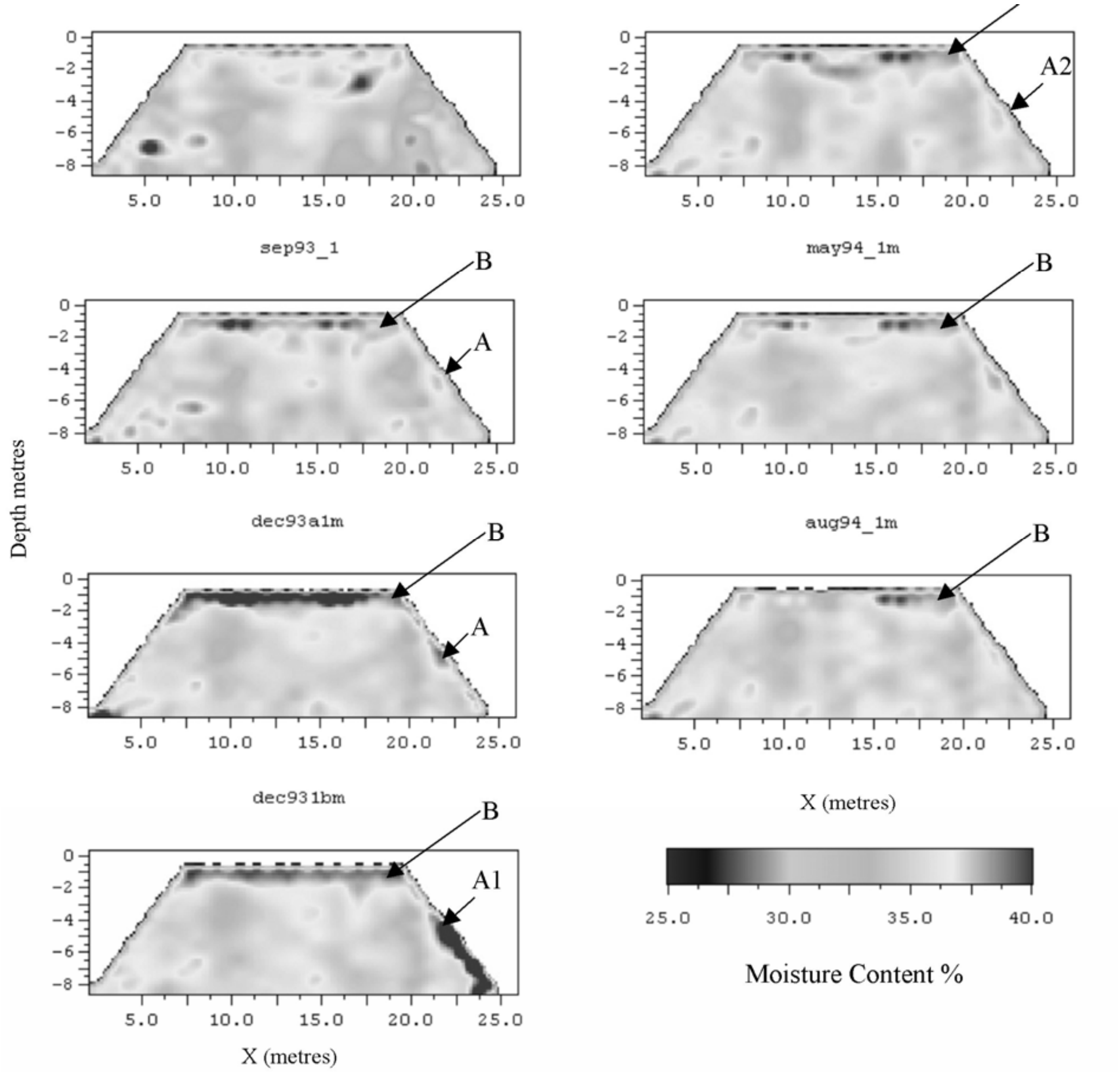


Figure 4. 2-D sections of moisture content, derived from the field resistivity measurements. **A** - seepage horizon in embankment side slope 6 months after construction. **A1** - 3 months later at time of landslip. **A2** - gravel drains installed to intercept seepage water and stabilise slope. **B** - zone of persistently high moisture content in right shoulder (Jackson *et al.*, 2002)

The high apparent moisture contents delineated on the RHS of the embankment were consistent, both temporally and spatially, with a slope failure on Dec 15th 1993 (Figure 5). It would appear that water exited from a seepage horizon at 2-3m that saturated the side of the embankment and caused a corresponding reduction in shear strength, eventually resulting in a landslip. After the landslip, gravel drains were installed to combat the build up of moisture in this area.

The sections in Figure 4 post dating the slip (Dec 93b) indicate that the embankment responded favourably with reduced moisture contents in the affected depth interval, returning to their September 1993 values. The zone of higher moisture content (B in Figure 4) persisted in the right shoulder after the asphalt pavement was laid in November 1993, while the central portion beneath the pavement dried back.

Figure 5. Slope failure in RHS of embankment following high December rainfalls resulting in seepage and saturation of embankment sideslope (see A1 in Figure 4) (Jackson *et al*., 2002).

Being non-invasive, automatic and using simple metal electrodes, resistivity surveying is ideal for embankment and other monitoring applications. Moisture content being the only seasonal control of resistivity, monitoring changes in electrical resistivity with time enables subtle changes in moisture to be extracted from complex background values.

The resistivity/moisture content imaging techniques used in the embankment study have recently been applied to monitoring moisture movements during a field ‘hydro-collapse’ trial of loessic deposits in Kent. Here, resistivity monitoring of moisture variations have been supplemented by shear-wave transducers installed at depth intervals below a loading plate in order to monitor stiffness changes in the loess as it is gradually flooded under an applied load. Resistivity and shear-wave probes have also been used to acquire rapid field profiles of geophysical data to supplement penetrometer, lithological and sampled geotechnical profiles at the Kent test site. Preliminary results from the acquired geophysical measurements have indicated their potential for establishing a characteristic ‘footprint’ of the loess sequences likely to undergo hydro-collapse when flooded under load. The results of this study are due to be published in Autumn 2003.

Results in Figure 6 compare moisture content resistivity relationships for both tropical red clay soils and loess from Ospringe, Kent. The trend line from Figure 2 is displayed along side a one developed in a similar way using samples of brickearth from the Ospringe site in Kent. The brickearth can be seen to be far more conductive than the tropical red clay soil, although it has far grater quartz content, illustrating the complex control of clay mineralogy.

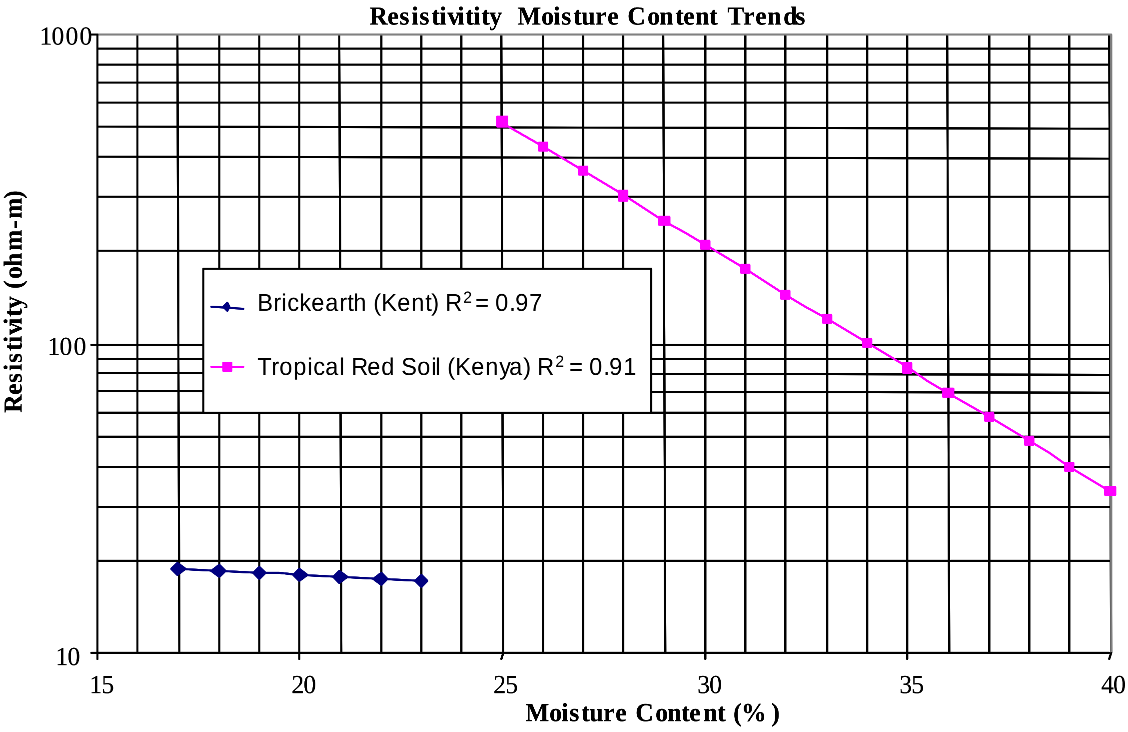


Figure 6. Resistivity, moisture-content relationships for two problematical soils. The individual laboratory measurements for the tropical red soil are shown in Figure 2.

Summary

Problematic soils occur worldwide, and deformation or movement during or after engineering works is a truly global problem. *In-situ* properties of natural collapsible soils such as loess are often variable and difficult to predict, so an effective site investigation program, including *in-situ* ground investigation, is essential for the optimum characterisation and prediction of soil behaviour. The greatest problems arise when the existence and extent of the potential for soil collapse are not fully appreciated prior to the commencement of construction work. Consequently, identifying and characterising collapsible soils and estimating the collapse potential are extremely important factors. A requirement exists for *in-situ* characterisation of the extent to which soil collapse might effect a site. Also, *in-situ* investigations can be used to assess the effectiveness and degree of any soil improvement work that is undertaken. Often, geophysical methods for ground investigation can be over-looked or under appreciated. There are several soil properties that can be determined by geophysics, which are of interest when specifically considering useful characterisation of collapsible soils. The case studies presented in this paper show examples of recent work where geophysical methods have been used to obtain information about the properties of collapsible loess soil. There is much potential for useful information to be provided to the geotechnical engineer through the appropriate use of geophysical methods. Geophysics can be used to rapidly, effectively and non-destructively assess *in-situ* collapsible soil properties over wide areas. Integration of such surveys into site investigations will improve the engineers knowledge of *in-situ* site conditions and enhance the efficiency of ground engineering work undertaken on collapsible soil sites.

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