Introduction

Towed-array Capacitive Resistivity Imaging (CRI; Kuras et al., 2007) has proved to be a viable, convenient and effective technique for acquiring multi-channel high-resolution Electrical Resistivity Tomography (ERT) data with dense lateral coverage on engineered and/or highly resistive surfaces. As resistance data measured with capacitive coupling under quasi-static conditions are equivalent to conventional galvanic data, popular ERT interpretation schemes such as least-squares smoothness-constrained (i.e. minimum-structure) 2D or 3D resistivity inversion are fully applicable to CRI data and have been used successfully. However, this approach can be computationally expensive, and for certain specialised applications, much simpler earth models (e.g. 1D with moderate lateral variations) may be sufficient to adequately reflect the subsurface structure under investigation and a significant amount of a-priori information (e.g. structural design specifications) may exist that can be used to constrain the inverse models. One way to exploit these simplifications is to employ piecewise 1D Laterally Constrained Inversion (1D-LCI; Auken et al., 2005), which divides the subsurface into a series of 1D earth models connected laterally by model constraints that control the similarity between adjacent models and the propagation of subsurface information along a given interpretational profile. In this study we demonstrate the feasibility of applying 1D-LCI to towed-array CRI data and show the utility of this approach for the analysis of datasets acquired to assess road subgrade condition.

Methodology

1D-LCI has been developed to aid interpretation of electrical sounding datasets with dense profile-oriented coverage and large sensitivity overlaps between individual soundings, such as those produced by the CVES and PACES methods (Auken et al., 2005). Conceptually, the 1D-LCI approach tends to work best in sedimentary environments where layered models are often capable of representing the actual geology more accurately than smooth minimum-structure models. The primary parameters of the earth model adopted for 1D-LCI are layer resistivities and layer thicknesses. Lateral connections between models are achieved by requiring approximate identity between neighbouring parameters within a specified variance. The nature and size of the lateral constraints can be considered as a-priori information on subsurface variability that is imposed on the inverted model. A series of soundings is then inverted as one system, providing layered and laterally smooth model sections with sharp layer interfaces. Ground truth can be incorporated as a-priori information at any point in the profile, from where the information propagates to the adjacent models by means of the lateral constraints.

The benefits of 1D-LCI are not limited to DC resistivity and the methodology has been successfully applied to profile-oriented data acquired with a range of techniques, including ground-based transient EM (Christiansen et al., 2007), airborne transient EM (Viezzoli et al., 2008) and airborne frequency-domain EM (Siemon et al., 2009). Most of the existing work has concentrated on regional scales and depth ranges of tens of metres. The present study aims to test the applicability of 1D-LCI at the site scale and within the top 2-3 m of ground.

Road subgrade assessment with CRI

Towed-array CRI extends the scope of ERT to roads and pavements with asphalt or concrete surfaces. An ideal application for this methodology is the non-destructive testing (NDT) of road foundations, particularly the subgrade layer and the underlying geology, with the aim of assessing bearing strength or characterising subsurface drainage beneath roads (Kuras et al., 2004). In this context, ERT is regarded as a valuable complement to the few available in-situ NDT techniques that can provide quantitative data in the road environment (e.g. Ground Penetrating Radar, Falling Weight Deflectometry, Neutron Moisture Probe/Nuclear Density Gauge, Plate Load Test). Bulk resistivity can provide information on moisture content and/or lithology variations that may otherwise be difficult to resolve with conventional techniques.

The engineering design and structural makeup of roads is tightly controlled by specifications set by national transportation authorities (e.g. UK Highways Agency, 2009). These specifications can be exploited as a-priori constraints within the 1D-LCI methodology; for example, variations can be assumed to occur primarily within the electrical properties rather than the layer geometry.

The TRL test site

We have considered the subgrade trial road at the Transport Research Laboratory (TRL) in Berkshire, UK, as a template for this study. This experimental facility has a length of 36 m and comprises a range of different subgrade materials representing varying strength of support. The trial road design is based upon the UK specifications for a heavily trafficked motorway and uses a flexible pavement and compacted granular sub-base overlying the subgrade layer. Three commonly used subgrade material types (sand, chalk and clay) are placed in three adjacent sections (Figure 1), each being 12 m long. The pavement layer is 390 mm thick and consists of Hot Rolled Asphalt (HRA). The thickness of the sub-base layer is 150-225 mm; the subgrade layer is 600 mm thick. The site is underlain by the Bracklesham Beds, a series of clays and marls with sandy beds, deposited in the Middle Eocene.
Predictive numerical modelling was undertaken, simulating the collection of five-channel towed-array CRI data over the trial road. The limited road width, combined with the equatorial dipole-dipole geometry of the BGS prototype CRI system (dipole length 1.5 m, separations from ~1 m to ~5 m, Figure 2), demanded a 3D DC forward calculation. The model resistivities reflect the likely contrasts between the relevant materials (Figure 1). The resulting apparent resistivities, contaminated with 5% Gaussian noise, are shown in Figure (3a). The corresponding experimental data, as acquired by Kuras et al. (2004), are shown in Figure (3b) for comparison.

1D-LCI of synthetic data

The synthetic CRI data were re-arranged into five-point soundings around a common centre location. The lateral distance between these soundings was 0.25 m. A total of 197 soundings were used, covering an overall distance of 49 m. 1D-LCI was then applied to this dataset. A typical result is shown in Figure 4. Due to the small number of available sounding points (here: five), the expected vertical resolution of the CRI data was limited, hence our most basic inverse model consisted of three distinct layers (topmost layer = pavement plus sub-base, middle layer = subgrade, bottom layer = underlying geology). The road design thicknesses listed above were used as starting values for the layer thicknesses of the individual 1D models; these were not allowed to vary as part of the inversion process. Instead, the layer resistivities were allowed to vary freely, with lateral constraints applied across a coupling width of two models, which means that only immediate neighbours are mutually constrained. No vertical constraints were imposed on the three model layers, indicating that resistivity variations in one layer need not necessarily have a corresponding effect in the layer above or below. Horizontal constraints of 0.2 were used, indicating that neighbouring model resistivities are tied together with an uncertainty of approximately 20%. The inversion result (Figure 4) demonstrates the ability of 1D-LCI to discriminate the subgrade layer from the overlying pavement and the underlying geology. After 10 iterations, the total model norm (Auken et al., 2005) had reduced to 0.458. The a-priori information (layer thicknesses) together with the lateral constraints appear sufficient to deal effectively with the noise contamination of the synthetic data. As expected, the more conductive clay subgrade is resolved particularly well, while the more resistive materials (sand, chalk) remain less well characterised, as their resistivities are underestimated, along with the resistivity of the underlying geology. However, this is still a very useful result as problem zones within road foundations tend to be mainly associated with conductive targets (e.g. clay lenses, moisture ingress).

1D-LCI of real data

The experimental CRI data were pre-processed in similar fashion, except that the lateral resolution (distance between soundings) was ~0.06 m. A total of 398 soundings were used, covering a distance of nearly 24 m. The 1D-LCI result is shown in Figure 5. While the basic model still comprises three layers, each design layer was now divided into two sub-layers, which were tied together by vertical constraints of 0.2 to allow greater variability within the design layers. The design thicknesses were again used as starting values, but were now allowed to vary by a factor of 1.1, thus accounting for potential deviations from the desired value. While the inversion result suggests a greater similarity between the subgrade layer and the underlying geology, the clay subgrade section at $x \geq 24$ m is still recognisable and reasonably well resolved. The total model norm was 0.95 after 21 iterations.

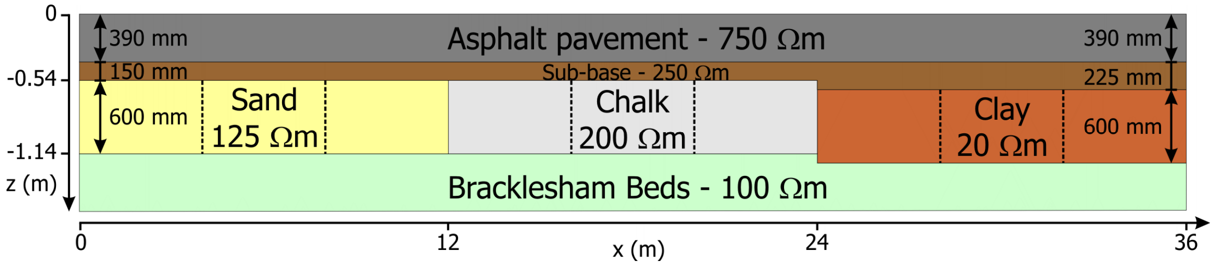

Figure 1: Design layout of the subgrade trial road at TRL with synthetic model resistivities.

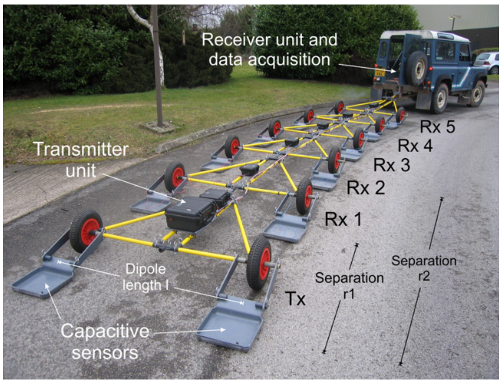

Figure 2: Five-channel towed-array CRI system.

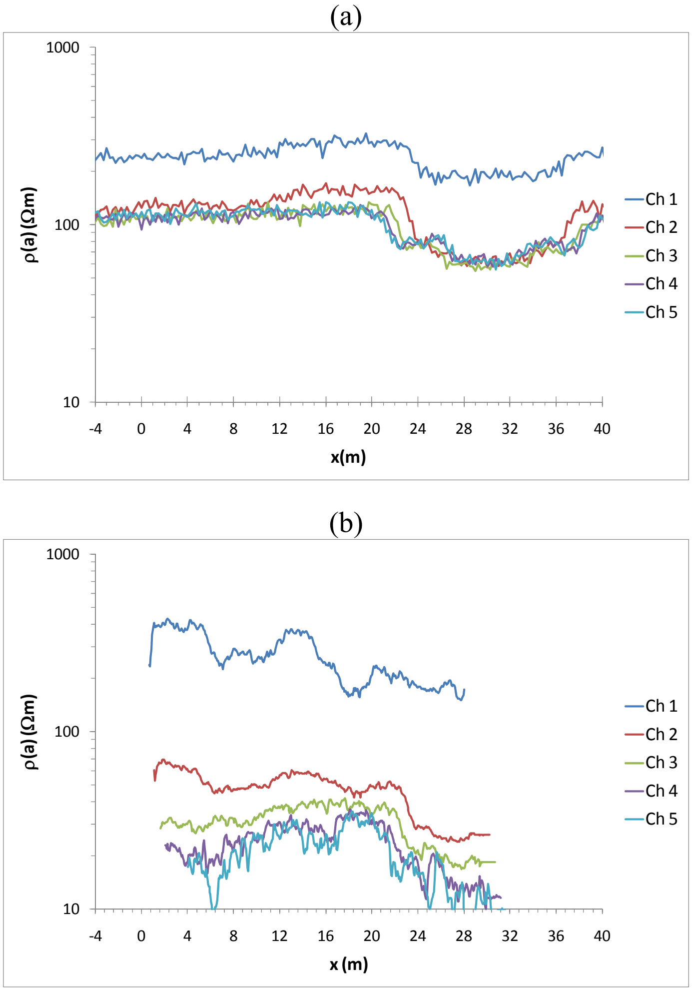

Figure 3: Synthetic (a) and real (b) apparent resistivity data collected with a five-channel towed-array CRI system over the trial road.

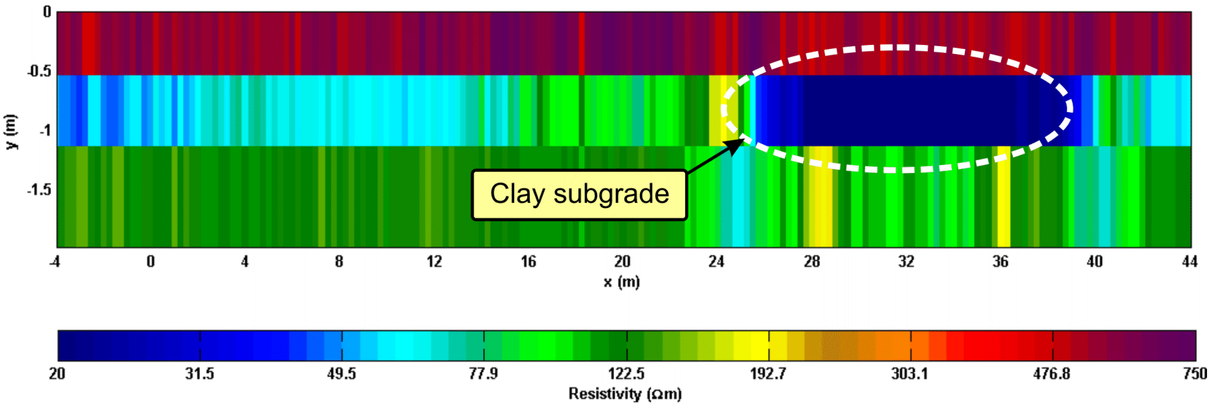

Figure 4: 1D-LCI inverted model section for synthetic data simulating the five-channel CRI response over the trial road.

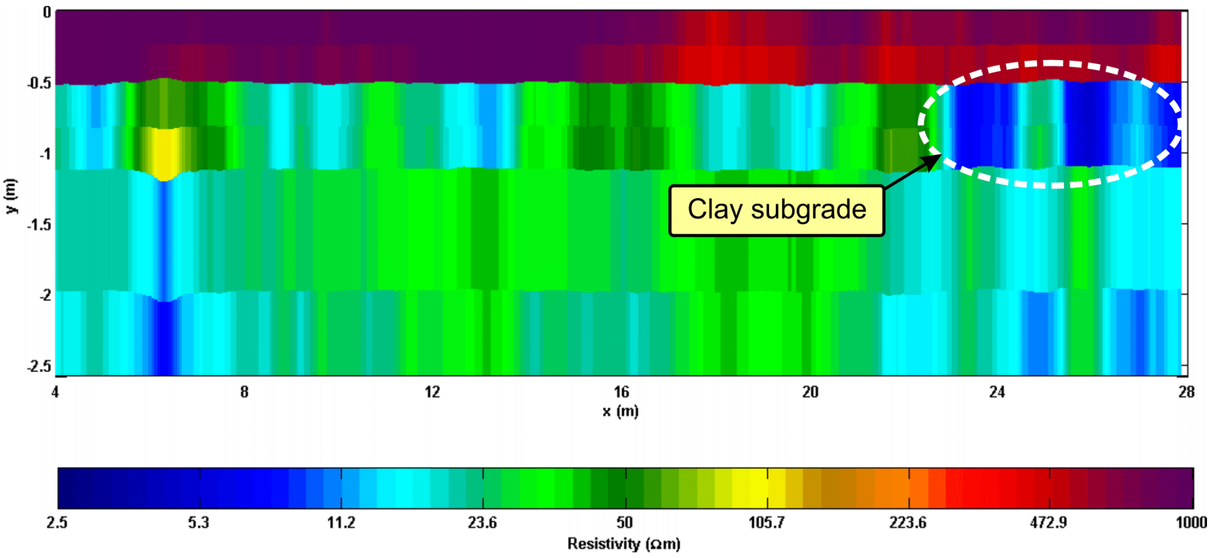

Figure 5: *1D-LCI inverted model section for experimental data obtained on the subgrade trial road.*

Conclusions

Our results demonstrate the feasibility of applying 1D-LCI to towed-array CRI data. The methodology holds promise as an interpretational tool that is well adapted to design constraints that can simplify the geophysical assessment of road foundations. In that context, 1D-LCI may be preferable over least-squares smoothness-constrained (i.e. minimum-structure) resistivity inversion.

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