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River terrace sand and gravel deposit reserve estimation using three-dimensional electrical resistivity tomography for bedrock surface detection

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ABSTRACT

We describe the application of 3D electrical resistivity tomography (ERT) to the characterisation and reserve estimation of an economic fluvial sand and gravel deposit. Due to the smoothness constraints used to regularise the inversion, it can be difficult to accurately determine the geometry of sharp interfaces. We have therefore considered two approaches to interface detection that we have applied to the 3D ERT results in an attempt to provide an accurate and objective assessment of the bedrock surface elevation. The first is a gradient-based approach, in which the steepest gradient of the vertical resistivity profile is assumed to correspond to the elevation of the mineral/bedrock interface. The second method uses an intrusive sample point to identify the interface resistivity at a location within the model, from which an iso-resistivity surface is identified that is assumed to define the interface. Validation of these methods has been achieved through direct comparison with observed bedrock surface elevations that were measured using real-time-kinematic GPS subsequent to the 3D ERT survey when quarrying exposed the bedrock surface. The gradient-based edge detector severely underestimated the depth to bedrock in this case, whereas the interface resistivity method produced bedrock surface elevations that were in close agreement with the GPS-derived surface. The failure of the gradient-based method is attributed to insufficient model sensitivity in the region of the bedrock surface, whereas the success of the interface resistivity method is a consequence of the homogeneity of the mineral and bedrock, resulting in a consistent interface resistivity. These results highlight the need for some intrusive data for model validation and for edge detection approaches to be chosen on the basis of local geological conditions.

1. Introduction

Sand and gravel mineral resources are typically evaluated using desk studies, direct investigation using boreholes and trial pits, and material testing to establish particle size distribution and lithology (e.g. Smith and Collis, 2001; Wardrop, 1999). An accurate assessment of the volumes of overburden and mineral, and their distribution across the potential extraction area, is an essential pre-requisite for a mineral reserve assessment and therefore additional information to improve the accuracy and reliability of the geological model can be valuable. Geophysical approaches, including geoelectrical methods, have the potential to improve resource evaluation and reserve estimation by providing information in the gaps between intrusive sample points (Lucius et al., 2006), but have not yet been widely used by the mineral industry for sand and gravel reserve estimation.

Research into the use of 1D resistivity sounding for mineral deposit assessment has produced mixed results (Auton, 1992; Crimes et al., 1994), which led Crimes et al. (1994) to conclude that the accuracy of the technique was too poor to be of general use for sand and gravel exploration. One of the earliest references to the application of electrical resistivity tomography (ERT) is by Barker (1997), in which he describes a 2D survey from the Trent Valley, UK. Baines et al. (2002) applied 2D ERT with the aim of assessing its use for investigating aggregate resources, and in particular sand and gravel channel belts and valley fills. They considered sites in the Netherlands, United States and Canada. Beresnev et al. (2002) also sought to develop 2D ERT for sand and gravel prospecting, and used test sites in Iowa, United States to study glacio-fluvial deposits occurring as terraces and point bars. Lucius et al. (2006) considered a range of geophysical methods, including a brief assessment of 2D ERT for deposit evaluation. One of the only examples of the use of 3D ERT for sand and gravel mineral exploration and reserve calculation is given by Chambers et al. (2012), in complex river terrace deposits in the Great Ouse Valley, UK. In addition to work focussed specifically on sand and gravel resource assessment,

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a number of researchers have considered ERT for the more general, but nevertheless relevant, application of investigating coarse grained unconsolidated Quaternary deposits (e.g. Froese et al., 2005; Kilner et al., 2005; Revil et al., 2005; Turesson and Lind, 2005).

A significant limitation of ERT using smoothness constrained (Occam) least squares inversion approaches is that the resulting images exhibit smooth gradational variations rather than sharp boundaries, which can make quantification of subsurface structures difficult. Although this can be mitigated by using an L_1-norm (or blocky) inversion, sharp interfaces, such as those between different lithologies, remain indistinct. Consequently, geological boundaries are typically manually inferred from ERT models by visually identifying the steepest resistivity gradient in conjunction with any available ground-truth information (e.g. Sass, 2007). This approach is easily applicable to 2D sections where interfaces can be shown simply as lines, but are more difficult to achieve in 3D models where interfaces are defined by 2D surfaces. More recently, automated methods have been applied for both 2D and 3D datasets (Bouchedda et al., 2012; Chambers et al., 2012; Elwaseif and Slater, 2012; Hsu et al., 2010; Nguyen et al., 2005).

The aim of this work is to assess the potential of 3D ERT for characterising and quantifying mineral reserves. Here we consider economic river terrace sand and gravel mineral deposits overlying clay bedrock. Two methods are considered which automatically extract interface depths from 3D ERT models. The first assumes that the interface is located at the maximum slope of the resistivity-depth curve, and is therefore referred to as the 'steepest gradient method' (SGM). The second uses an intrusive sample point to calibrate the model by identifying the resistivity iso-surface associated with the interface, and is referred to here as the 'known interface method' (KIM). These approaches have been previously considered by Hsu et al. (2010) and Chambers et al. (2012) for similar applications, using 2D and 3D ERT respectively. In this case, we seek to validate our geophysical results using direct observations of the bedrock surface. This was achieved because, subsequent to the ERT survey, the study site was quarried exposing the bedrock surface. This provided a valuable opportunity for direct comparison of the observed and ERT-derived bedrock surfaces.

2. Study Site

2.1. Location and background

The site is located at a sand and gravel quarry near Norton Disney, Lincolnshire. The site lies approximately 10 km to the north-east of Newark and the River Trent, and 2 km to the west of the River Witham (Fig. 1). At the time of the 3D ERT survey the site was a grassed field bounded by woodland on three sides (north, east and west), with a road on the western edge. The land immediately surrounding the survey area has been worked for sand and gravel for many years. The most recently available borehole data was from 2005, and included holes drilled close to the ERT survey area as shown in Fig. 2. Two mineral assessment reports also cover the area immediately around the survey area (Gozzard, 1975, 1976). After the ERT survey had been completed the site was quarried, revealing much of the bedrock across the survey area.

2.2. Geology and hydrogeology

The general geology of the survey area (Berridge et al., 1999) consists of flat lying Lower Lias mudstone bedrock (Jurassic), which is overlain by river terrace deposits of the Balderton Sand and Gravel Member (Quaternary), and a thin layer of topsoil.

The Lias Group is composed predominantly of grey shaly mudstone, with minor limestone, sandstone and ironstone beds. The Norton Disney site is within the lower part of the Lias Group, the Scunthorpe Mudstone Formation. The Scunthorpe Mudstone Formation is characterised by grey, variably calcareous, silty mudstone with numerous thin limestones. The limestones are typically around 0.1–0.3 m thick, but can be strong, well cemented and laterally persistent.

The Balderton Sand and Gravel Member is a terrace deposit of the early River Trent, with a surface level at around 14 to 15 m above Ordnance Datum (AOD) at the Norton Disney site. Sand and gravel thickness in nearby boreholes is 7.8 to 9.8 m. The bulk of the deposit is described from the borehole logs as a brown and yellow-brown slightly silty fine to coarse grained gravelly to very gravelly sand, and very sandy gravel. A more general description for the Balderton Sand and Gravel (Berridge et al., 1999) describes it as gravel rich, consisting of rounded quartzitic "Bunter" pebbles with subordinate pebble-grade subangular flints and reddish brown Triassic sandstone and siltstone. An overall fining-upward trend is also described, from poorly bedded gravels at the base, to more distinctly bedded, sandier gravels at the top, with a brown to orange-brown sandy, gravelly soil at surface. Particle size analysis indicates 41 to 64% gravel (>4 mm), 30 to 55% sand and fine gravel (0.0625 mm–4 mm), and 4 to 6% fines (<0.0625 mm). Sections in the Balderton Sand and Gravel show cross-bedding and channel infill deposits, both of which were observed in section at the Norton Disney site. Although not observed directly during the site survey, cross bedding and pebble imbrication at other sites further south indicate deposition from river currents flowing towards the north-north-east.

Water levels recorded in lagoons within a few tens of metres of the site indicated that the water level during the survey was likely to have been approximately 4 m below ground level.

3. Methodology

3.1. Electrical resistivity tomography

Resistivity data were collected using an AGI SuperSting R8 eight channel resistivity instrument, multicore cables and stainless steel electrodes. Three-dimensional ERT data collection and modelling methodologies are widely described in the literature (e.g. Magnusson et al., 2010; Wilkinson et al., 2005) and so only a brief summary is presented here.

3.1.1. Survey design

The 3D ERT survey was carried out within an area of 120 m by 189 m (2.27 ha); we refer to the long axis of the survey area as *y*, and the short axis as *x*. A summary diagram of the survey grid is shown in Fig. 2, with the ERT lines shown in blue. The local origin ($x = 0$ m, $y = 0$ m) of the ERT survey area was positioned in the north-western corner of the field. The main survey lines were 189 m long, striking in a north-easterly direction, and were positioned at 6 m intervals to ensure adequate sensitivity to the regions between lines (Gharibi and Bentley, 2005), resulting in a total of twenty one lines. Sixteen additional survey lines, which were 120 m long, were positioned at 12 m intervals perpendicular to the strike of the main survey lines to reduce bias in the data associated with using a single line direction (Chambers et al., 2002). Two additional perpendicular lines were positioned at $y = 6$ m and $y = 186$ m to improve image resolution at the north-eastern and south-western margins of the survey. An along-line electrode separation of 3 m was used for all survey lines. The dipole–dipole array with dipole sizes (a) of 3, 6, 9, and 12 m, and dipole separations (na) of $1a$ to $8a$, were used; full sets of reciprocal measurements were collected for each line. The dipole–dipole array was used because it has favourable resolving capabilities relative to other common array types, it can efficiently exploit the multichannel capability of the ERT instrument, and it enables easy collection of reciprocal measurements (Dahlin and Zhou, 2004). The field survey time (i.e. total time on site) was 43 h; the measurement time (i.e. time taken for ERT instrument to collect the data) was 25 h.

3.1.2. Data editing

The combined dataset from the thirty-nine survey lines comprised a total of 46,196 reciprocal pairs. Reciprocal measurements provide the