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Railway Earthworks: Integrating Ground Investigation Data into Ground Models

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Abstract

This paper discusses the development of fit-for-purpose property distributions or ground models for rail network planning and system modelling. Poor ground conditions can be identified during route planning using network scale ground models based on former geological mapping and site investigation. Rapid geophysical and geotechnical surveys can be combined to identify material changes causing heterogeneity and larger scale structural features within natural or made ground, and provide inputs for process monitoring and modelling. Case studies include the effect of engineering interfaces on the propagation velocity of surface waves and the movement of moisture fronts through an aged, Victorian end-tipped embankment.

Keywords: geophysical, geotechnical, ground model, embankment, earthworks, surface waves, cone penetration test, property distribution, stiffness, resistivity, moisture movement.

1 Introduction

1.1 Geoscience Information in Planning and Development

UK Planning Policy [1, 2] defines the underlying principle of ‘sustainability’, which requires development based upon sound scientific information and analysis of risk. This principle now drives increasing application of geoscientific information in planning and development of major transportation and utility infrastructure [3, 4]. However, planners and engineers have little use for the chronological distribution over the land surface presented by traditional geological maps because this is not compatible with their requirement for information relating to the engineering performance of the ground. Thematic or applied geological maps provide geological information interpreted into classes that are directly applicable to planning and engineering decisions, such as depth of cover and engineering property characteristics [5].

Advances in computing and Geographic Information Systems (GIS) now enable the construction of 3D conceptual models of the subsurface that can provide the property distributions at various scales that are fit-for-purpose for route planning or even numerical process modelling [6]. Depending upon the scale of application, these distributions or ground models can be applied at many levels of network planning and rail system modelling associated with the development of major transportation networks. For example, using former geological mapping and site investigation data, the representative heterogeneity associated with lithostratigraphic distribution can be constructed into regional scale ground models for use in the identification of poor ground conditions and follow-up investigations during route corridor assessment. Also, by integrating geotechnical and geophysical ground investigation data, a physical property distribution matrix can capture site scale heterogeneity. This could provide the input to model near-operational processes and ground responses required to aid site specific impact assessment and design of infrastructure.

1.2 Development of Ground Models

Information on the engineering property distribution within natural and engineered ground can be gathered at different scales, such as from geological, engineering geological and thematic maps, site investigation reports, geotechnical or geophysical surveys and borehole logs. By combining these data within a GIS, engineers now have the opportunity to develop and visualise a 3D model on a standard desktop PC of a highly heterogeneous environment. There are two key objectives behind ground model development; firstly, the development of a physical property distribution that represents true heterogeneity with a resolution that is fit for the scale of application, and secondly, the use of the model to study process-property interactions.

The construction of a ground model requires three fundamental tasks including:

I. identification / classification of the materials present in the model,
II. identification of the spatial distribution of those materials, and
III. attribution of the properties (geotechnical, geophysical) of those materials.

The ground model provides the spatial delineation of the finite media within a framework or matrix, to which physical and mechanical properties of engineering relevance are attributed [6]. It also delineates and attributes properties to the boundaries and discontinuities between the finite media. The ground model can then provide the input to investigate or predict the affect of processes upon the magnitude and spatial rates of change of model properties, i.e. property evolution. Furthermore, if the modelling process is adaptive, feedback effects of property evolution upon processes can also be modelled such that long term deterioration can be investigated.

1.2.1 Network Planning and Route Corridor Assessment

The objectives of a route corridor assessment include understanding the engineering challenges posed by the geology and topography, such that follow-up ground investigations and infrastructure plans can be developed [3, 4, 5, 7]. The engineering geological appraisal of the encountered rocks and soils is required within a framework model that can capture lithostratigraphical and topographical variability but still be readily visualised across a regional scale, such as spanning 10s of kilometres. GIS-modelling environments, such as GeoVisionary and Geological Surveying and Investigation in 3 Dimensions (GSI3D) [8, 9, 10] can now hold multiple, large geoscience and terrain databases, enabling high resolution visualisation, for example of the geology and topography along a route corridor.

1.2.2 Investigation, Modelling and Monitoring Site Processes

Transport infrastructure models were primarily required to determine the effect of traffic loads upon stresses and strains within the track or pavement, ballast and subgrade components [11]. Modelling approaches range from analytical methods [12, 13] to numerical methods incorporating finite element meshes [14, 15]. Models are useful when assessing performance under new load regimes due to structural changes and new traffic conditions. In most models, the subgrade elements are represented by uniformly layered media attributed with bulk properties. While appropriate for new construction, this uniform layered model does not represent the heterogeneity that has developed in superficial geology or aged infrastructure. New approaches are required that can bring the heterogeneity discovered during site investigation into the modelling regime, if for example, we are to understand the condition and long term deterioration of aged infrastructure. A number of well understood relationships exist between geophysical properties such as resistivity [16, 17] and dielectric constant (a key parameter in radar surveys) [18, 19] and geotechnical properties such as lithology and moisture content. By combining geotechnical and geophysical data, it is possible to relate mechanical or engineering properties to lithological and moisture variation, providing a basis for attribution of properties and classification of condition within a heterogeneous ground model [20]. More importantly, the change of key properties can be monitored via investigation of the time lapse differences between repeat measurements, enabling assessment of spatial rate of change and thus, potential prediction of long term deterioration. For example, time lapse, volumetric resistivity images can be interpreted into moisture content to visualise groundwater movement and make some assessment of the plasticity changes and potential stability risks in natural and engineered slopes [16, 17, 21, 22].

2 Ground Models for Route Corridor Assessments

2.1 Materials and Spatial Distribution

A base ground model is constructed that captures the engineering geological characteristics within a composite digital terrain model (DTM). DTM data sources include geomorphological surface observations, ground surveys, NEXTMap® and Lidar datasets. Information on the engineering geological characteristics is primarily gained from the traditional ‘desk study’ review of geological structure, lithology, mineralogy, ground water and geotechnical properties [8, 10], but should be underpinned by an understanding of the formation processes of the rocks / soils along the route. Lithostratigraphic outcrop is primarily determined from traditional geological maps, but more representative ground models can be constructed with additional incorporation of sub-crop information, e.g. from borehole logs. Large borehole databases are advantageous not only for coverage, but also because the log descriptive entries may have been unified, such that consistent classification criteria are used, which aids borehole-borehole correlation and delineation of subsurface boundaries. Accurate borehole correlation is critical to the final model, and care must be taken to ensure that each lithostratigraphical sub-unit is correctly attributed [8]. This invariably involves some degree of subjective analysis to discriminate between deposits that are lithologically similar but may have been deposited in very different environmental settings (e.g. fluviatile, glacigenic, anthropogenic).

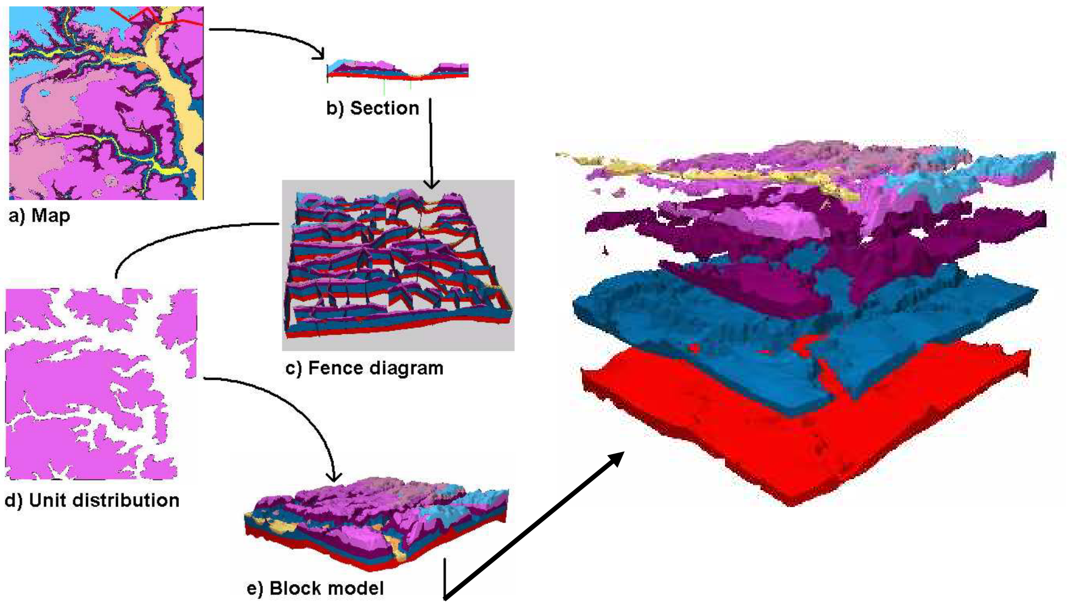

Figure. 1. Construction of a ground model incorporating a 3D interpretation of geology within GSI3D.

a. Traditional geological maps provides surface outcrop.
b. 2D sections consistent with outcrop and including available subcrop data (e.g. borehole logs).
c. Fence diagram, network of 2D sections with layers interpreted within the geology lexicon.
d. Spatial triangulation of 3D distribution of each geological unit.
e. Block ground model incorporating all units for visualisation / manipulation.

The model building process begins with the construction of a network of 2D sections based upon all available outcrop and subcrop information, producing a fence diagram (as shown in Figure 1). The geological layers within these sections are interpreted within a harmonised scheme, such as the Geological Lexicon scheme (www.bgs.ac.uk/lexicon), to identify layers in different sections that belong to the same three-dimensionally distributed geological units. Interpretation is within an appropriate GIS modelling environment, such as GSI3D, which spatially interpolates (for example using Delaunay triangulation) and correlates layers within the network of sections to provide a model of the 3D geology beneath the DTM. This initial base model can be constructed to specified depths appropriate for engineering purposes, e.g. 30 to 50 m will enable characterisation well into the rockhead required for engineering design. It can be visually manipulated to identify zones requiring further data gathering and re-interpretation.

2.2 Attribution of Properties

Tables of attributed properties are developed from all the data used to construct the 3D ground models, including geotechnical, hydrogeological and geophysical data that are required to model the outcome of mechanical and engineering stresses, hydrological and wave propagation (vibration) processes. The property tables are usually linked to a properties database that stores property and location information, which enables the spatial attribution of properties into the model. Property database examples include the BGS National Geotechnical Properties Database that stores spatially attributed standard borehole, core and laboratory test data in AGS format [23].

Synthetic 1D profiles and 2D sections of the geological variability can be created along any route corridor digitised across the land surface via spatial interpolation of the underlying 3D volumetric model of geology and attributed engineering characteristics. During route corridor assessment, synthetic sections can be examined to identify poor ground conditions and plan further phases of ground investigations. These new data are used to iteratively re-interpret and update the ground model to improve its representation of the actual ground conditions, for example by increasing resolution and scale of geological heterogeneity, gathering and attributing further geotechnical, geophysical and hydrogeological property data to the model. The 3D volumetric model, derivative synthetic profiles and sections provide input property distributions for process modelling, where the scale of application will depend upon the level of uncertainty arising from the resolution of the underlying datasets used in construction. Generally, these ground models have primary applications at regional scale planning, but where there are high densities of ground investigation data, such as in urban, city areas, high levels of certainty in the ground model will enable site specific modelling.

2.3 Case Study: Manchester-Liverpool Railway

2.3.1 Geological Context

Geologically, the Manchester region straddles the southern part of the Carboniferous South Lancashire Coalfield and the northern part of the Permo-Triassic Cheshire

Basin (Figure 2). To the south and west, the Carboniferous Coal Measures are overlain by Permo-Triassic rocks of the Sherwood Sandstone Group, which is the second most important aquifer in the UK. Quaternary superficial deposits laid down during the Devensian glaciation cover most of the area, reaching thicknesses in excess of 40 m. The deposits include glacial till (gravelly and sandy clay), glaciolacustrine deposits (laminated clays and sands) and glaciofluvial outwash (sands and gravels). Post-glacial deposits, associated with the proto-Irwell include alluvium, river terrace gravels, and peat (Figure 2). Extensive areas of made ground are present, and include colliery spoil tips, material dug during the construction of the Manchester Ship Canal and general inert and biodegradable fill.

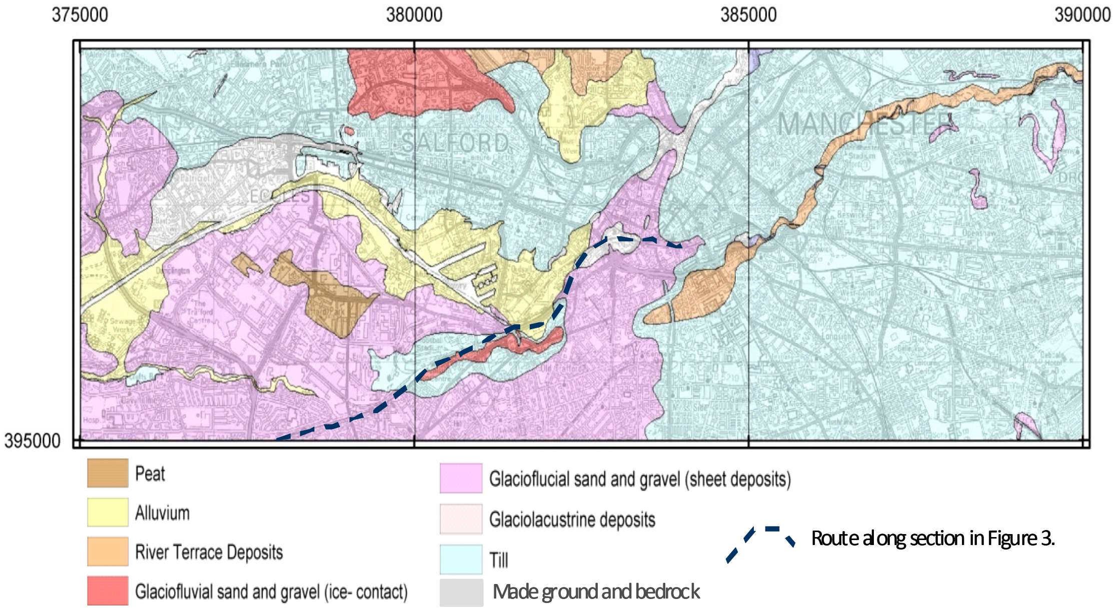

Figure 2. Solid and drift outcrop in the Manchester urban area.
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2.3.2 Synthetic Section for Route Assessment

The volumetric ground model is interrogated to produce synthetic sections along any digitised surface route, such as along a proposed transportation corridor. Figure 3 shows an example of a section generated along part of the Manchester – Liverpool railway (on the Network Rail mainline network) using the Manchester ground model, which included 6500 borehole records as part of its construction [8]. These boreholes would have been a part of the many ground investigations undertaken during the historical development of the Manchester urban area. The data gathered from many of these investigations such as field tests, field samples and laboratory test results were collated and stored in a database that includes geological, geotechnical, geophysical, hydrogeological properties and associated location information. These data are spatially located or attributed into the geological units within the ground model, which are used to develop an engineering geological interpretation of the synthetic 2D section.

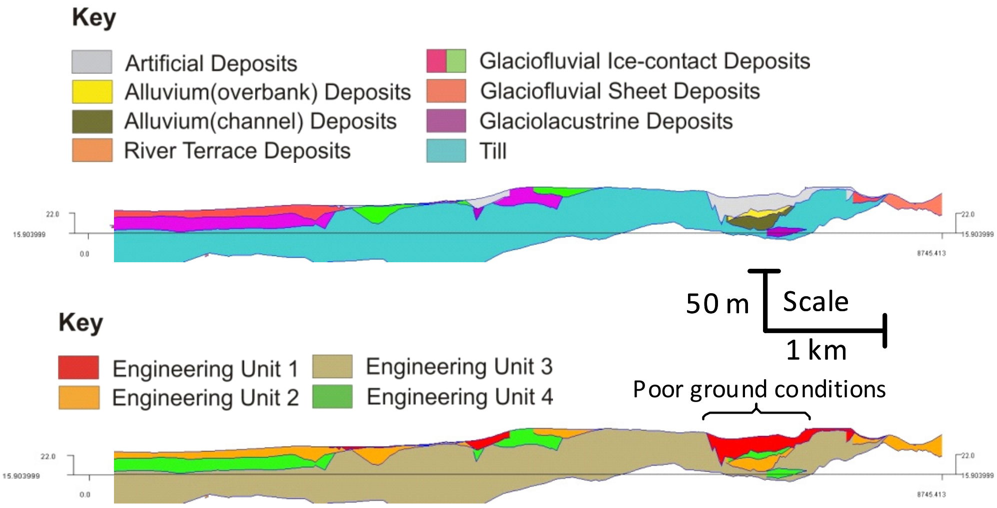

Figure 3. Upper: Synthetic geological cross-section along rail route.
Lower: Synthetic engineering geological cross-section along route.

Practical difficulties in constructing the ground model occur when the DTM does not correlate with the detailed borehole levels observed during site investigation. This is a particular problem with thin, near-surface deposits such as made ground, where discrepancies between the DTM height and that of the levelled borehole (e.g. 2 to 3 m) may be of the same order of magnitude as the deposit being modelled. Where possible these anomalies have been dealt with by re-hanging the boreholes to the modelled surface. A further limitation of the model relates to its effective resolution. At a borehole density of between 1 and 257 data points per square kilometer, coverage in some parts of the study area is quite poor. This has a bearing on the applicability of the model at different scales of usage. It is important that data are processed in a way that ensures important relationships are not obscured at site or regional scale, and also that data are not over-interpreted beyond their intended useful range.

Four engineering geological units were identified (Table 1) [8] within the synthetic cross-section based, in this case, on particle size distribution and standard penetration test data, derived from the properties database (that have also contributed to the National Geotechnical Properties Database for the UK). The lower section in Figure 3 now provides a means of assessing the engineering characteristics along the route because these geotechnical properties are spatially linked via the databases to the units in the section. For example, poor ground conditions can be identified via associated low penetration resistances where Engineering Unit 1, Infilled Ground outcrops and overlies Engineering Units 2a, Alluvium:- River Channel Deposits and Units 4a, Alluvium:- Overbank Deposits). This area could have problems with variable ground conditions or contamination due to the Artificial ground at the surface and possible differential settlement because there is a mixture of soft clayey and dense gravelly Alluvial deposits. In cases of new route plans, such areas would be selected for further site investigation to identify the extent and distribution of properties at a resolution specific to the required infrastructure about this location.

Engineering Geological Unit	Geological Units	Characteristics
UNIT 1: Highly Variable Artificial Deposits	Disturbed Ground; Landscaped Ground; Made Ground; Worked Ground; Infilled Ground	Highly variable composition, thickness and geotechnical properties
UNIT 2a: Coarse Soils	Alluvium:- River Channel Deposits; River Terrace Deposits; Glaciofluvial Sheet Deposits	Medium dense – dense SAND & GRAVEL with some buried channels-lenses of clay, silt & peat.
UNIT 2b: Coarse Soils	Glaciofluvial Ice-contact Deposits	Loose – medium dense, fine – medium SAND.
UNIT 3: Fine Soils:- Firm	Glacial Till	Firm – very stiff, sandy, gravelly CLAY with some channels-lenses of medium dense – dense sand and gravel.
UNIT 4a: Fine Soils:- Soft	Alluvium:- Overbank Deposits	Soft – firm CLAY, occasional sand, gravel & peat lenses.
UNIT 4b: Fine Soils:- Soft	Glaciolacustrine Deposits	Soft – stiff laminated CLAY, occasional sand lenses.

Table 1. Overview of the engineering geological characteristics along the rail route.

2.4 Synthetic Shear Wave Sections: Modelling Applications

The engineering geological synthetic sections provide the framework and properties to construct specific input property distribution matrices required to model key processes, such as surface wave propagation associated with the vehicular dynamic loading. A particular concern relates to the amplification of ground surface displacements generated by heavy, high speed vehicles, for example where train speeds approach the Rayleigh wave velocity [24, 25]. Generally, direct surveys for Rayleigh wave velocity are not routinely undertaken during ground investigations. However, in the absence of direct measurement, density-effective stress controlled algorithms, specific to each of the engineering geological units, can be applied to model body shear wave and Rayleigh wave velocity-depth profiles [26, 27, 28].

The most significant proportion of disturbance generated by vehicle loading propagates in the form of a Rayleigh wave [24, 25]. Also, the disturbance is mostly confined to the near-surface within one wavelength of the Rayleigh wave and is in the form of ground roll affecting the engineered track, pavement, subgrade and shallow geology. While the Rayleigh wave velocity is required to model transportinduced ground displacements, it can be derived as a fraction of the shear wave velocity for rocks and soils, using [24, 25]:

$$V_R = \frac{(0.87 + 1.12\nu)}{(1+\nu)} V_S \qquad 1$$

where ν is Poisson's Ratio. The bulk density, ρ_b, is the volumetric sum of the densities of the solid rock/soil particles, ρ_s, pore water, ρ_w and the unsaturated air voids, ρ_a. The contribution of the air component is negligible because of its very low density, so the bulk density of a soil approximates to:

$$\rho_b \cong (1-n)\rho_s + n\, S_w\, \rho_w \qquad 2$$

where S_w, the proportion of water saturation varies from zero to one, and n is the soil porosity. Having established a density - depth relationship, effective stress, σ' (Pa) can be derived by considering the total submerged weight acting per unit area:

$$\sigma' = g\, d\, (\rho_b - \rho_f) \qquad 3$$

where: $g = 9.81ms^{-2}$, d = burial depth (m), ρ = density (kgm^{-3}) and the subscripts 'b' and 'f' imply bulk and fluid densities respectively. The shear wave velocity, Vs is related to the strength of the soil solid framework matrix, which increases with burial depth and increasing effective stress. Lithology controls the grain friction and interactions within the framework matrix, and thus, controls the propagation velocity of a shear wave through a rock or soil [28]. Like density, lithology determines a specific effective stress dependent relationship applied to derive the velocity at a specific depth. These can take the form of Vs changing on the basis of a power law of effective stress [26, 27, 29, 30, 31] such as:

$$Vs = A.\sigma'^{B} + C \qquad 4$$

where A, B and C are constants (and B is an exponent of effective stress).

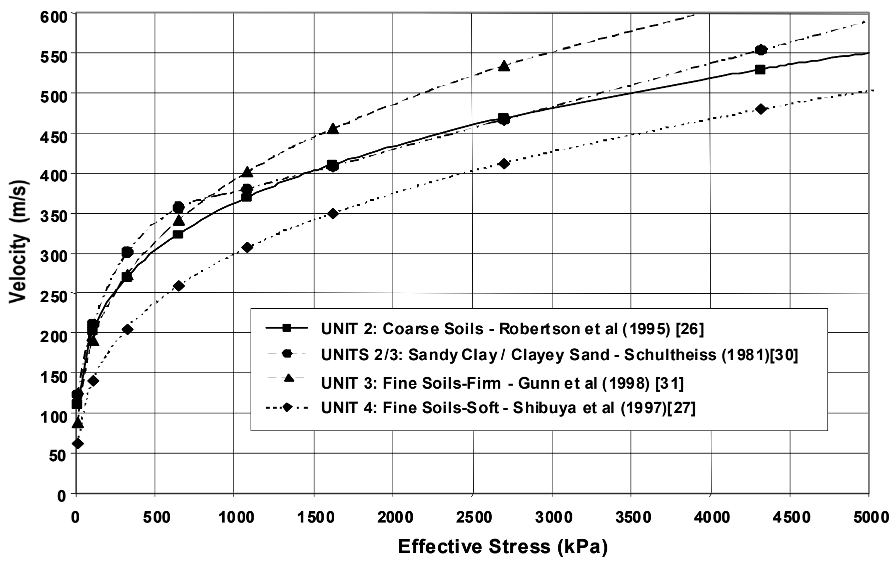

Figure 4. Example effective stress, lithology-specific shear wave velocity profiles for application to the Engineering Unit classes of the engineering characterisation.

Figure 4 provides some examples that could be applied to the Engineering Units of Figure 3 and Table 1 to derive shear and Rayleigh wave velocities, and small strain stiffness-depth profiles [26, 27, 28, 29, 30, 31]. These algorithms can be applied to construct representative velocity-depth sections at engineering interfaces, where Figure 5 shows the example of a thickening wedge of either UNIT 2 (Fig. 5b) or UNIT 4 (Fig. 5c) within the glacial till of UNIT 3 underlying the rail route. There would be an increase in the velocity of short wavelength (< 5 m) Rayleigh waves as they propagated from UNIT 3 (glacial till) into a wedge of UNIT 2 (coarse soils), whereas there would be a decrease in velocity as they propagated into a wedge of UNIT 4 (soft soils:-fine). The dynamic strains within the soils either side of the interface will differ, broadly related to their different small strain stiffnesses [29], contributing to amplification of ground displacement where the Rayleigh wave propagates from firm to soft soils [24, 25]. Thus, these interfaces are likely to be associated with risk of ground deformation, pumping of fines and differential compaction along the rail route. Hence, the synthetic sections can be used in the route assessment to identify locations requiring follow-up investigations to more fully characterise the site materials, their distribution and properties.

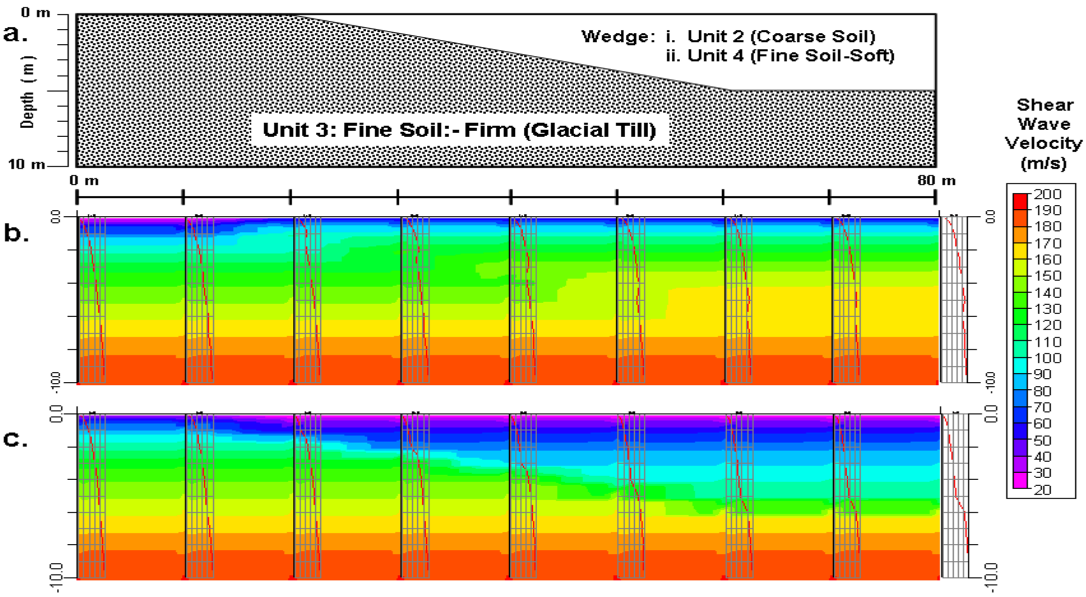

Figure 5. Shear wave velocity-depth sections across thickening wedge interface.
a. Engineering interface: wedge thickening to 5 m over 40 m.
b. Wedge comprising Unit 2 overlying Unit 3.
c. Wedge comprising Unit 4 overlying Unit 3.
(Density, stiffness and Rayleigh wave velocity can similarly be modelled).

3 Ground Models with Site Scale Heterogeneity

3.1 Site Case Study: Victorian Earthworks

An investigation methodology is demonstrated on a section of earthworks SW of East Leake, Nottinghamshire (Figure 6), which were constructed as part of the former Great Central Railway using local materials excavated from adjacent cuttings to the SW at the East Leake Tunnel (bridge 314) and to the NE (bridge 313). Construction at East Leake fell within contract No. 1 Annesley to Leake by Logan and Hemmingway and contract No. 2 Leake to Aylestone by Henry Lovatt [32]. The material was tipped and then compacted by subsequent movement of shunting locomotives and tipping wagons across the tipped material. The tipping method used along this section of the line was not stated explicitly by the chief engineer, Frederick Bidder in 1900 [32], but has been deduced to have been end tipped from current observations and the information recorded by the engineers practising at the time. This includes photos by S.W.A. Newton of end tipping wagons with the initial H.L. on their side panels. This study focuses upon a 100 m long section, roughly mid-way along the embankment, which totals approximately 800 m long between bridges 313 – 314, Figure 6.

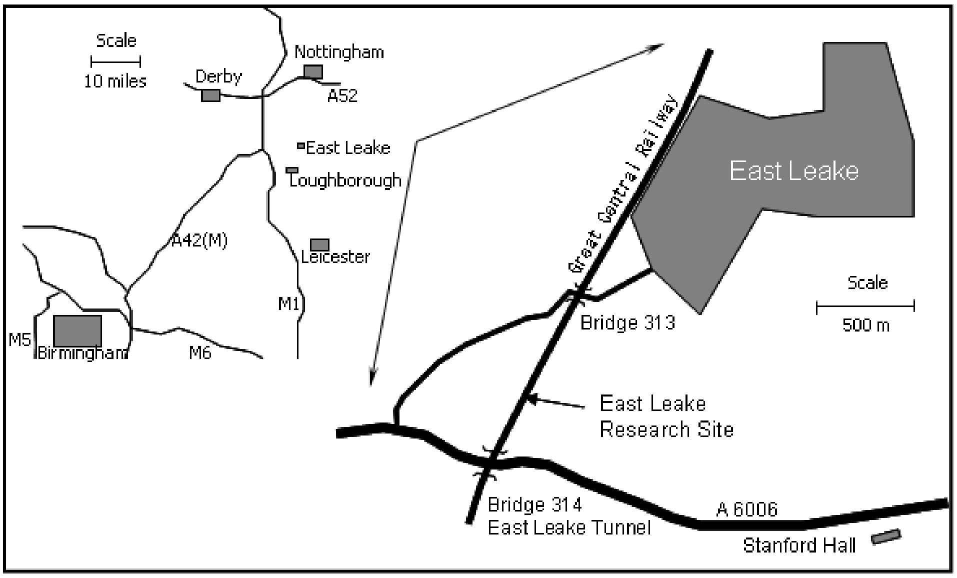

Figure 6. Location of the site on the former Great Central Railway near East Leake, South Nottinghamshire.

3.1.1 Materials and Spatial Distribution

It is normal practice to approach site investigations in a phased manner, undertaking desk study reviews and initial site reconnaissance prior to ground investigation activities [33]. Having established a historical and engineering background, identification of materials at a site scale (Task I) is mostly reliant upon invasive methods such as pitting, drilling and coring in order to access site materials and provide ground truth. Whereas, mapping material distribution (Task II) and assessing properties and change in properties (Task III) can be achieved with increasing use of non-invasive geophysical methods, especially if sound geophysical-geotechnical property relationships exist, enabling imaged geophysical properties to be used as proxies for geotechnical properties [33]. Routine use of differential global positioning systems (DGPS) for accurate location of field surveys has driven the increasing integration of multiple field datasets into a unified ground model. DGPS use a stationary reference station to calculate differential corrections for its own location over time that are caused by the satellite-based positioning errors. Post-processed measurements allow more precise positioning, because most GPS errors affect the reference and roaming or surveying receiver nearly equally, and therefore can be cancelled out. DGPS are an enhancement to GPS that provide improved location accuracy, from the 10-metre nominal GPS accuracy to about 10 centimetres in case of the best implementations [34].

3.1.2 Properties for Attribution: Surveys and Layouts

The investigation at East Leake represents a culmination of several survey phases from September 2005 to September 2010. Intrusive survey activities include: dynamic cone penetration resistance tests (dCPT) [35] to 3 m on the crest and flanks, shallow pitting to 1 m, drilling and core sampling to 8 m and static cone penetration resistance tests (sCPT) [36] to 10 m depths on the crest. Non-intrusive survey activities include: ground penetrating radar surveys (GPR) [18, 19] to assess the ballast-fill interface, 2D resistivity profiles along the axis and transects across embankment [16, 17, 21], continuous surface wave (CSW) and multichannel analysis of surface wave surveys to ascertain shear wave velocity and small strain stiffness logs to 8 m depth across the embankment [37]. While the total length of embankment surveyed covers up to 300 m, more intense activity was focused over a 140 m length (0 m to 140 m in Figure 7) where closer spaced sampling of intrusive methods of between 5 m to 10 m enabled the development of 3D distributions of some properties.

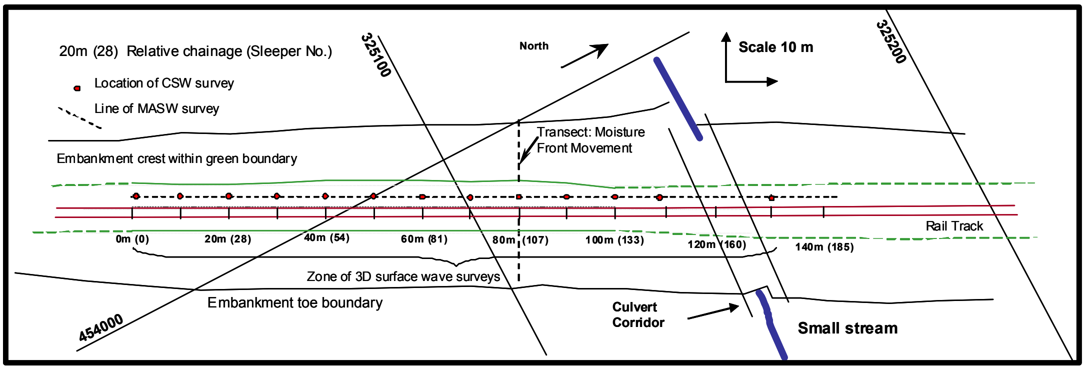

Figure 7. Location and orientation of surveys in relation to the embankment and local features. (140 m long section shown in Figure 9).

3.2 Materials within the Earthworks

In total seven shallow pits (to 1 m) and seven boreholes were completed on the crest within the section between chainages 20 m and 130 m. From the materials recovered it was deduced that the embankment was built up on the Branscombe Mudstone

Formation (formerly Cropwell Bishop Formation) of the Mercia Mudstone Group. Table 2 summarises some of the embankment fill materials discovered from borings along the section investigated.

General Depth Interval	Unit Description	Engineering Geological Description	Potential Borrow Locality / Geology
Surface to between 0.5-0.75 m	Soiled modern BALLAST	Dark grey, coarse angular GRAVEL (ballast 50-75mm) incl. granodiorite and clinker in a matrix of black silty sand / fine ash gravel matrix. Sulphide smell to soil.	?
0.6–0.95 m	Early phases Or Original BALLAST	Coarse, flat angular GRAVEL up to 50mm overlying rotted, angular – sub-rounded granodiorite cobles to 250 mm across. Coated in a buff yellow-brown clay matrix,	Charnwood Forest Switherland Wood rock crusher / Possibly granodiorite of the Mountsorrel Complex
0.2-2.4 m	Glaciofluvial Sand / Gravel	Yellow to red-brown medium – coarse sand with well rounded quartz and sandstone gravel (20-60 mm dia.) with occasional cobbles.	Local Glacial Deposits / Surrounding fields or Local Quarries in Leake or Gotham
Generally, 0.8–1.25m but occas. lens to 2 m	Degraded Siltstones	Green-grey siltstones appearing to weather green grey silts and silty clays. Where degradation is incomplete, the siltstone shatters to blue-green silty, sandy gravel.	East Leake Tunnel cutting to SW / Likely: Blue Anchor Formation (Mercia Mudstone Group) Or possibly Cotham Member (Penarth Group)
0.95–5.5 m	Dark Grey- Black Degraded Mudstones	Very weak, black, thinly laminated Mudstone weathers to firm dark grey mottled strong orange and occasionally yellow to white gravelly CLAY. Gravel is fine to coarse, angular to subangular, flat lithorelicts of very weak thinly laminated (0.5-1.0 mm) mudstone.	East Leake Tunnel cutting to SW / Westbury Formation (Penarth Group)
1.75–5.5 m	Red-Brown Degraded Mudstones	Firm, red-brown, fragmentary clay/weak mudstone admixed with green clay/mudstone enclosing quartzose pebbles, angular fragments of green dolomitic siltstone and yellow, fine-grained sandstone and occasional coal but could also be debris of Thrussington Till.	East Leake Bridge Cutting to NE / Branscombe Mudstone Formation formerly Cropwell Bishop Formation (Mercia Mudstone Group)
5.5 m plus	Stiff Mudstone Bedrock	Stiff red-brown MUDSTONE	*In situ* / Branscombe Mudstone Formation (Mercia Mudstone Group)

Table 2. Summary of the materials recovered from pits and boreholes at the site.

Across the site, soiled modern ballast generally occurs from the surface to around 0.5 m. Materials underlying the modern ballast to the SE of the section (approximately chainages 0 m to 75 m) comprise the original engineered ballast pavement as described by Bidder [32] and Fox [38] in 1900, of angular granodiorite gravel over granodiorite cobbles. Glaciofluvial sand and gravel occurs beneath the modern ballast across the NE of the section. The sand is generally uncemented but occasionally the sand was bound within layers around 100 mm thick by fine, white, powdery non-carbonate cement believed to be gypsum leached from other fill materials. Siltstone appears to have been used as an original final dressing to the earthworks fill prior to the laying of the original ballast, but has degraded in situ in the embankment. It occurs across much of the section but appears to pinch out into the glaciofluvial sand and gravel towards the NE. All of these materials overlie degraded mudstones that make up the bulk of the earthworks fill either comprising dark grey-black Westbury Mudstone and Clay or red-brown Branscombe Mudstone and Clay.

3.3 3D for Embankment Condition Assessment

The lack of common construction practices and the development of solutions on the job contribute to aged infrastructure being unique and highly heterogeneous. The heterogeneity can be investigated using ground models developed via the integration of the geophysical and geotechnical property data gathered as part of the site investigation. The fill in this section of embankment was removed from the East Leake Tunnel cutting, approximately 300 m to the SW to maintain a level grade across the low stand until the East Leake bridge to the NE. Figure 8 presents a 3D model of small strain stiffness based upon extensive coverage of surface wave surveys over a 300 m section of the embankment [37]. GPS and DGPS surveys were also undertaken along this section, enabling the small strain stiffness distribution model to be located in the British National Grid (BNG).

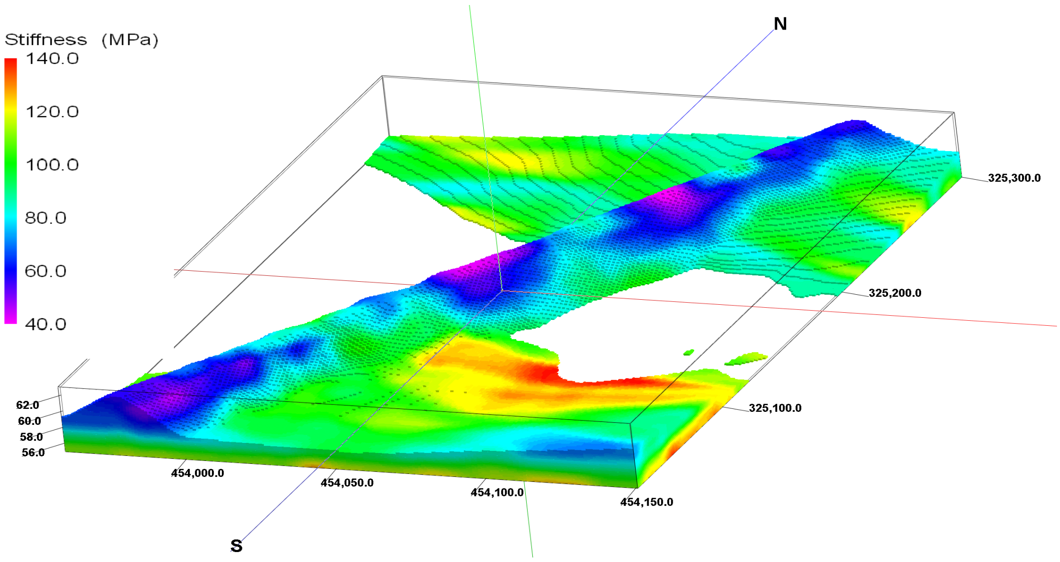

Figure 8. 3D embankment stiffness model based on surface wave surveys.

The materials would have been transported from the tunnel cutting to this point and end tipped over a concaved surface dipping away from the cutting at around 30 degrees (similar to the current angle of the embankment shoulders). The distribution of materials within the embankment as it was progressed away from the cutting may then reflect the materials as they were encountered in the cutting unless local stocks were employed. The distribution of materials will also control the associated distribution of embankment geotechnical and geophysical properties, and thus overall heterogeneity.

Synthetic 2D sections can be constructed from 3D ground models to support an interpretation of the materials, variability and overall condition along the embankment, such as in Figure 9. Cone penetration resistance (9a) and the small strain stiffness (9b) properties were combined to develop the site interpretation (9c), which is presented with a section of the railway geometry along the embankment (9d). Table 3 summarises the properties of the materials identified in the interpreted section in Figure 9c.

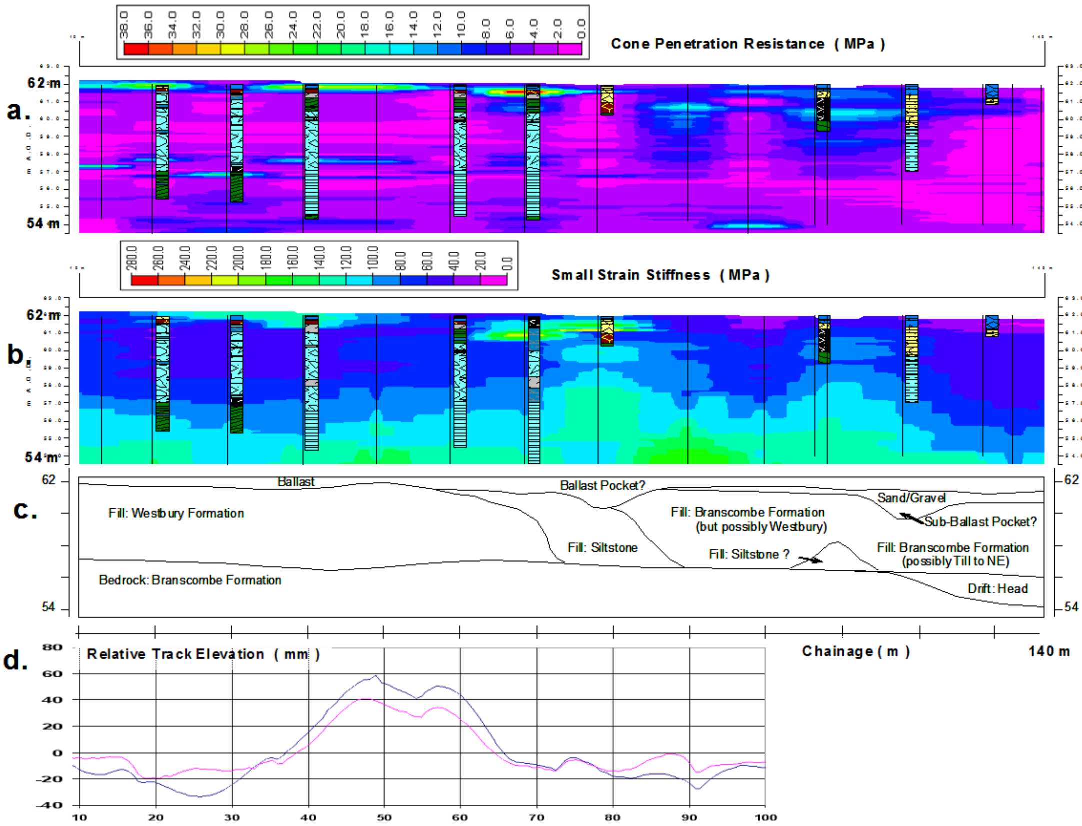

Figure 9. Material and property variability in Victorian end-tipped embankment.
a. CPT Resistance section; b. Small strain stiffness section;
c. Engineering geological interpretation; d. Railtrack geometry

It is believed that the tunnel cutting would have begun in the Branscombe Mudstone and progressed SW into Siltstones of the Blue Anchor Formation before encountering the shaley Westbury Mudstone. Both log observations and mineralogical evidence confirms the weak Mudstone and gravelly Clay between 0.6 m to 5.3 m to be degraded products of the Westbury Mudstone Formation, whereas the Siltstone, gravelly Silt and silty Clay are degraded products of the Blue Anchor Formation. Because the embankment was advanced away from the cutting towards the NW, the presence of the Siltstone of the Blue Anchor overlying gravelly Clay of the Westbury Formation in the borehole at 70 m could indicate that local stocks of siltstone were kept, for example to provide the top dressing in the first instance. Bidder (1900) [32] and Fox (1900) [38] observed practices in ‘soft clay embankments' whereby blankets of 'burnt clay, clinker ballast or coarse gravel' were used to dry the clay, improve drainage and prevent the clay fill from pumping up into the ballast under dynamic loading. At this point, it is possible that Siltstone from stocks may have been used to stabilize the embankment during rainy weather and allow works to progress.

Engineering Geology		**Occurrence**	**Range of Properties**	
Unit	**Characteristics**		**Stiffness (MPa)**	**Penetration Resistance (MPa)**
Bedrock	stiff MUDSTONE; diggable	Below 5 m depth; zone of high stiffness, extending laterally across the most of the section up to around 125 m in NE;	80 – 160	MUDST 2 – 4; SILTST (skerry) up to 10 - 14
Drift	Firm CLAY; easily diggable	Below 5 m depth from 125 m – 140 m; zone of low stiffness; Head deposits comprising slumped Till and Branscombe Mudstone	60 - 80	Mostly < 2; occasionally 2 - 4
Ballast	stiff coarse GRAVEL and COBBLES; difficult to dig, especially cobble layer.	Shallow interval to 0.5 m occasionally 0.75 m; high stiffness; extending across SW half of the section, possibly related to the presence or competency of the cobble layer associated with the original ballast	Mostly 100 – 120; Occasionally to 160 where COBBLES encountered	Mostly 8 -10; Increasing were COBBLES encountered > 20
Fill	GRAVEL comprising weak MUDSTONE (Westbury Formation) degraded to CLAY; easily diggable	1 m – 5 m interval; low stiffness; extending across SW half of section	40 – 60	MUDST 2 – 4; Occasional SILTST to 10 – 14
Fill	SILTSTONE degrading to sandy GRAVEL and glaciafluvial SAND and GRAVEL; difficult to dig.	sporadic in fill, often occurring as lenses, e.g. 75 m – 100 m and 110 m – 115 m; high stiffness;	>100 up to 160	Mostly 6 – 10; Occasionally 10 – 14; Very low when degraded 2 – 4.
Fill	weak MUDST (Branscombe Formation, Thrussinton Till or Head) degraded to CLAY; easily diggable	1 m – 5 m interval; low stiffness, extending from 120 m or even from 90 m to 140 m	40 – 60	Mostly 2 – 4 (suspect MUDST); Occasionally 10 – 14 (where SILTST suspected)

Table 3. Victorian, end-tipped embankment: Engineering geology and properties.

3.4 Heterogeneity: Effect on Deterioration of Condition

Very poor track geometry was observed over a 20 m interface zone between the fill comprising clay and gravel sized lithorelicts of Westbury Mudstone and fill comprising sand, gravel and siltstone. The development of poor geometry on the

NE side is coincident with a thinning of this lens of coarser materials with greater small strain stiffness (Figure 9b). Resistivity measurements respond well to the lithological and associated moisture content variability across this interface. The lens of fill comprising sand, gravel and siltstone produced a wedge shaped zone with resistivities above 150 Ohm.m, whereas the fill comprising Westbury Mudstone had resistivities in the range of 40 – 75 Ohm.m [17, 20]. Furthermore, specific relationships between moisture content, saturation and resistivity can be developed that enables the moisture content changes that drive the differences between repeat resistivity measurements be interpreted [16, 17, 21, 22]. By installing permanent, in situ electrode arrays, as in the case of the ALERT systems, groundwater movement within the subsurface can be holistically visualised using a series of 3D time lapse, interpreted resistivity-difference images [39, 40] (often termed 4D), Figure 10. These remote systems can monitor the impact of ground water movement on soil moisture, related geotechnical properties (consistency) and surface movement. Recent innovations in time lapse, differential resistivity image processing also support movement tracking of the individual sensors within the monitoring network. We can now establish cause and effect between coupled sub-surface and surface processes in ground failure events. Wilkinson et al. (2010, 2011) [16, 41] monitored up to 1.6 m of down slope movement on sensor groups at the top of the earth flow lobe with sixteen measurements over one year.

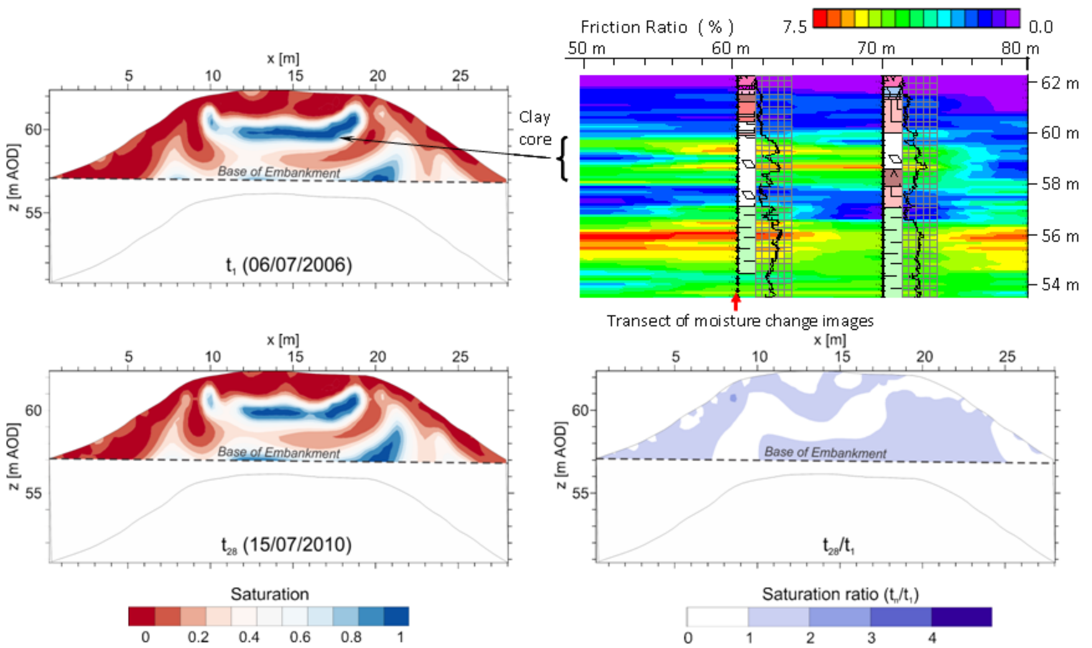

Figure 10. Clay-rich core identified in CPT friction ratio section (top right); migration of ground water about clay-rich core interpreted from saturation change ratio (bottom right).

Measurements at the East Leake embankment have provided new insight into the moisture movement through this heterogeneous engineering interface. Wetting and drying fronts have been observed to migrate through the earthworks, responding rapidly to rainfall patterns. The friction ratios in the fill comprising Westbury

Mudstone on the SW side of the interface are very high (Figure 10), possibly indicative of breakdown of the mudstone to clay. This clay-rich zone is located within the core of the embankment approximately between 2 – 3 m depths. Groundwater movement, such as caused by perching and lateral migration about this clay-rich core can be interpreted from the images of moisture content changes throughout the embankment. Heave in zones of clay-rich, degraded mudstone could be the reason for the elevated track geometry at this interface. Regimes of different dynamic moisture ranges within the embankment can also be identified, for example with three-fold moisture changes within the upper 1 m on the flanks.

4 Discussion: Modelling Ground Heterogeneity

This paper demonstrates that the engineering geological characteristics of artificial, engineered and natural ground are controlled by the subsurface distribution of materials and can be highly heterogeneous. That heterogeneity can be captured by 3D ground models, whose spatial resolution can be made fit-for-purpose at several scales of network planning. Core components for model construction include a DTM and a spatial-properties database, which underpins the attribution of geological and engineering properties to the ground model. The spatial coverage or resolution of the properties database is key to the scale of application of the ground model. But, even in the absence of geophysical properties required for modelling specific processes such as Rayleigh wave propagation, these can be interpreted if robust geotechnical-geophysical property relationships exist and can be attached to each of the engineering geological classes within the model framework.

Both case histories demonstrated the importance of the interfaces between contrasting engineering geological materials in controlling significant variability in geophysical properties, such as small strain stiffness and seismic velocity. Generally, modern GIS and model framework platforms are available to support the construction of property distribution models with sufficient resolution to enable poor ground conditions and problematic interfaces to be identified at different scales of network planning. Interfaces between denser, stiffer materials and poorly consolidated, weak materials are liable to be potential sites for problems associated with traffic loading requiring specific mitigation measures. Synthetic geological and engineering geological sections cut from a 3D ground model can be applied to locate potential problem sites. Associated geophysical property sections modelled via effective stress controlled algorithms can provide a property matrix for input into Rayleigh wave propagation modelling using finite element schemes.

Use of consistent co-ordinates for spatial attribution of property data enables iterative update and improvement of the ground model with subsequent ground investigation data. Also, standard protocols for model updates are becoming more commonplace due to routine use of GPS and DGPS during site investigation. These provide an enabling platform that supports further integration of data gathered during different investigations. For example, geophysical property data gathered during site surveys can augment the characteristics of specific engineering geological units and improve model resolution. Surface wave surveys can be deployed for gathering additional shear and Rayleigh wave velocity and small strain stiffness data where problem sites are identified during route assessment. Property distribution models that capture the site scale heterogeneity are of paramount importance for modelling site specific problems and designing appropriate infrastructure to overcome them. The assignation of a uniform ground stiffness of 80 MPa alone, such as by Woodward *et al.* (2011) [24] and El-Kacimi *et al.* (2011) [25] will not aid any understanding of ground displacement amplification phenomena due to lateral and vertical heterogeneity found in most ground conditions. Greater insight will be gained in relation to the Rayleigh wave-induced ground displacement assessments, for example along the UK's newly proposed HS2 route, if underpinned by small strain stiffness models capturing the ground heterogeneity in high resolution.

Repeated cycles of wetting and drying within the core of many transportation earthworks are driving long term processes leading to the progressive deterioration of material integrity, collectively referred to as "ageing". Gradual loss of strength in clay due to irreversible plastic strains related to repeated shrinkage and swelling is probably most well known [42]. Other moisture-driven processes are equally important to ageing but can be specific to the litho-stratigraphy of the source material. For example, fabric micro-voiding and rupture is associated with fill sourced from mudrocks including significant evaporite deposits, such as the rocks from the Permo-Trias and Lias covering much of central England [20, 43]. Aged infrastructure comprises unique heterogeneity that cannot be easily modelled and therefore deterioration must be monitored in situ. A full climate vulnerability assessment requires knowledge of the condition the embankment is in, where this condition fits within the progressive deterioration life-cycle and how close this point is to any threshold condition that would trigger rapid instability.

Simple, half-space or even layered models do not readily accommodate the heterogeneity of superficial geology, artificial and engineered ground. Ground models that capture the heterogeneity with a resolution that is fit-for purpose are required, especially to improve the rigour of process modelling. Process modelling and monitoring would benefit from a ground model that best captures the true heterogeneity of the ground. This can be achieved by using property distributions based upon integrated geotechnical and geophysical ground investigation data as input matrices.

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