Geotechnical characterisation of mine waste for modelling potential climate change impacts on mine waste mobility.

Vanessa J Banks,[1] Edward Bruce,[1] Ben Dashwood,[1] Catherine Gandy[2]
Matthew R. Kirkham,[1] Nikhil Nedumpallile-Vasu,[1] Tim Longstaff,[3]
Abby Moorhouse-Parry,[4] Barbara Palumbo-Roe [1] and Hugh Potter[5]

[1]*British Geological Survey, Nicker Hill, Keyworth NG12 5GZ, vbanks@bgs.ac.uk;*

[2]*School of Engineering, 3rd Floor Devonshire Building, Newcastle University Newcastle upon Tyne NE1 7RU;*

[3]*orkshire Dales Rivers Trust, 8 Kings Ct, Pateley Bridge, Harrogate HG3 5JW;*

[4]*Coal Authority 200 Lichfield Lane, Mansfield NG18 4RG;*

[5]*Environment Agency, Horizon House, Bristol BS1 5AH*

Abstract

Driving spoil, mine waste and tailings are common in stream valleys that have been subject to lead-zinc mining, where they comprise potential diffuse contaminant sources. Climate change is predicted to increase rainfall intensity and peak stream flows in some periods but also lead to decreased rainfall and lower stream flows in other periods, both of which may affect their environmental impacts from abandoned metal mines. Here we report on the challenges of investigating geotechnical processes and material characterisation at abandoned metal mines as part of the DIFFUSE (Newcastle University, Centre for Ecology and Hydrogeology and British Geological Survey) project.

Introduction

Water, as a source of power, was fundamental to the siting and layout of many of the now abandoned, lead-zinc metal mines in the UK. Many were engineered to optimise the use of gravity in processing. Consequently, driving spoil, mine waste and tailings are common in stream valleys that have been subject to mining, where they comprise diffuse contaminant sources. There is an associated potential for the diffuse contamination to manifest by rainfall infiltration, groundwater leaching, or by sediment mobilisation. Although apparently largely stable, mine waste instability in the context of future climate change has implications for long-term river quality. Here we report on techniques and the challenges for geotechnical characterisation as a component of the DIFFUSE project (CA18/2/1/4) undertaken at Great Eggleshope in the North Pennines, UK, in the context of the broader project aims to assess the impacts of diffuse mine waste on surface water quality using rapid and transferable technologies. The DIFFUSE project is funded by the Water and Abandoned Metal Mines (WAMM) Programme, a partnership between the Environment Agency, Coal Authority and Defra (the UK Dept for Environment, Food and Rural Affairs).

Mine waste in the Great Eggleshope valley originates from a number of mines, including the Wiregill (California) Mines (operated intermittently from the mid-1700s to 1930s; spoil heaps reworked in the 1970 (Fairburn 2009)) and East and West Hush, first recorded in the mid-1500s with East Hush on the valley side and West Hush in the valley floor with abandoned valley side leats that suppled the water for hushing. The host (Mississippian to Pennsylvanian) geology comprises fine-to very coarse- grained feldspathic sandstones, siltstones, mudstones with marine shaley mudstones, claystone, coal and seatearths of the Stainmore Formation, overlying the limestones, sandstones, mudstones, with rare coals of the Alston Formation, which crops out in the valley floor. Vein hosted mineralisation is classified as a fluoritic sub-type of the Mississippi-Valley type. The veins strike on various bearings and there is a mapped fault that crosses Great Eggleshope Valley ENE to WSW, with a downthrow to the south.

Although variable in their grading and geotechnical properties mine wastes can be subdivided into zones that reflect the source of the mine waste in the context of the historic site operation. Research at Great Eggleshope focused on (i) a "bund" adjacent to the west side of the Great Eggleshope Beck, comprising mine waste that ranged from boulder to silt grade, interpreted as driving spoil and (ii) an historic dressing floor (shown on historic maps) that comprised slightly gravelly, sandy silt and sand with some clay (Figure 1a). Mine waste from the dressing floor was identified as a contaminant source with respect to concentrations of lead, zinc and cadmium, which exceed environmental standards (Higgins and Lovett 2017) and was confirmed in analyses undertaken within the Tees-Swale naturally connected project) and field leaching tests undertaken by Newcastle University.

Great Eggleshope Beck, an upland stream with a catchment area of 11.68 km2, is classified as an alluvial stream (Carling 1988). The stream is flashy with a relatively low base-flow index (0.33). Data from comparative studies by Carling and Reader (1982) indicate that 75% of the suspended sediment load of the beck is derived from mine waste delivered via a tributary stream. This is reflected in the finer bedload component being more uniformly graded than other upland streams. Fine sediment can be stored temporarily as lenses of fine material in zones of flow separation; alternatively, it may be transported through the system as bedload. The contribution of bedload from strata rendered unstable by stream undercutting is evident (Carling and Reader, 1982). Additionally, we have noted that mine waste sediment is also mobilised by suffosion processes within the driving spoil heap and evidenced by substantial depressions in the upper surface of the bund, as well as by surface erosion and channelling of the materials on the dressing floor.

Geotechnical (pertaining to the geological, geophysical and hydrological) characterisation of the mine waste is fundamental for generating model input parameters as required for assessment of firstly the mine waste slope stability assessment and secondly the fines or tailings erodibility. Typical of abandoned mine sites, Great Eggleshope is remote with difficult access for sampling and in-situ testing demanding portable and rapid techniques. A further challenge is that mine waste properties stretch conventional geotechnical testing techniques. Firstly, because of the extreme range in grain size, particularly the distribution of cobble and boulder grade material, which undermines the value of in-situ probing techniques. Secondly the volume and heterogeneity of the waste, from which it can be difficult to obtain truly representative samples. Mine waste differs to naturally occurring soils (engineering definition) in that it is commonly angular and platy, which affects the geotechnical properties, requiring consideration in laboratory-scale testing. We

***Figure 1** a Left: areas of investigation, looking north with drainage crossing the dressing floor in foreground and vegetation free driving spoil bund mid-distance. b Right: field sampling of the stream side of the driving spoil bund. Note range in grain size and seepage.*

***Table 1** Hydrological data: Great Eggleshope Beck (Carling 1988; Carling and Reader 1982).*

Mean Annual discharge	Mean Annual Flood	Bank full discharge	Bank full return period	Storm event suspended sediment	Suspended sediment transport	Bedload transport
m3s^{-1}	m^{3}s^{-1}	m^3/s^{-1}	Years	mg/L	t km^{-2} year^{-1}	t km^{-2} year^{-1}
0.1923	6.38	5.60	0.9	30	12.07	0.55

phased geophysical techniques (to explore representation) with targeted sampling of the driving spoil (hand excavated pits) and testing (cohesive strength meter) of the finer sediments associated with the dressing floor. The investigation approach and methods were guided by BSI (2020). Monitoring techniques were established with baseline ground-based LiDAR and unmanned aerial vehicles (Centre for Ecology and hydrology drone surveys). These techniques were combined to optimise 3D monitoring of mine waste erosion. Here we present an overview of the field and laboratory techniques, the generated data its application, and the remnant knowledge gaps.

Methods

Conceptual understanding with respect to the historic operation of the abandoned mine site, in conjunction with reconnaissance visits, which benefitted from the sparsely vegetated nature of the mine waste, provided the context of the broad classification of mine waste and selection of investigatory techniques (Figure 1b and Table 2). Subsequent stages of investigation were designed to address uncertainty in geotechnical representation of the mine wastes. Two areas were targeted for reconnaissance investigation with geophysics: the former dressing floor (fine-grained, high metal concentration) and driving wastes (coarser, lower metal concentration). In the area of the former dressing floor there was uncertainty regarding sediment thickness, sediment stratigraphy and distribution of stream channels evident from channels in the dressing floor. For the driving spoil, the investigation aimed to address uniformity of the bund and groundwater conditions with two key questions posed: *what are the in-situ geotechnical properties of the mine waste? and were there any changes in material type or placement techniques during the "construction" of the bund?*

Sampling for geotechnical characterisation (Figure 1b, Table 2) was scheduled to achieve the parameters required for slope stability analyses (driving spoil bund) and erodibility analysis (dressing floor). A reliable digital terrain model was a prerequisite for the slope stability modelling, and this was achieved using ground-based LiDAR scanning techniques.

Electro-magnetic (EM) conductivity was carried out using a *CMD Explorer* (GF Instruments, sro) instrument. Deployed in walking, continuous measurement, mode with an integrated GPS sensor for positioning, the three transmitter-receiver dipoles at differing separations undertake simultaneous determinations of electrical

***Table 2** Great Eggleshope Beck geotechnical mine waste characterisation.*

Test Area	Analysis	Analytical technique requirements	Sampling method	Laboratory methods	Standards
Driving spoil bund	Slope stability	Slope angles, density, shear strength, water content	3 No. hand excavated pits and surface sampling	Grading, water content, small shear box [parallel graded]	BS 5930 BS 1377 (BSI 2020 and 1990)
Dressing floor	Erodibility	Grading	Surface and density ring samples	Grading	BS 1377

conductivity and magnetic susceptibility at depths of approximately 2.2m, 4.2m and 6.7m. The EM conductivity readings were inverted to represent material resistivity.

Ground penetrating radar (GPR) imaging was deployed on the western side of the dressing floor to assess the potential of the technique for mapping the thickness of tailing deposits. A *Sensors & Software Noggin Smart Cart* system was used, incorporating a 250 MHz GPR antenna, an odometer wheel, battery and a digital video logger providing the operator with an instant display of the GPR signal. This instrument transmits high frequency electromagnetic waves downwards and measures the reflected EM radiation resulting from contrasts in the electrical properties of the subsurface materials that influence reflection, dispersion, and attenuation of the transmitted pulse as it propagates through the sub-surface.

A Riegl VZ-1000 LiDAR (Light Detection and Ranging) scanner was used to generate a high-resolution baseline survey (accuracy of ± 8 mm). It was deployed in conjunction with GPS to facilitate subsequent nesting of UAV monitoring and to fix the repeat LiDAR scanning to monitor the stability of the driving spoil bund beside the beck. Repeat scanning was carried out with a Pegasus backpack LiDAR set-up, facilitating more rapid slightly lower resolution data collection.

Field testing of the erodibility of the mine waste on the dressing floor was conducted with a cohesive strength meter, which uses a vertical water jet fired at the sediment surface in short pulses (0.5s) of increasing force with data logged every 0.1 s for 3 s. Testing was carried out in accordance with a standardised procedure (Sediment Services 2004 Operating Manual). The jetting programme is adjusted (in a series of pre-set routines) to reflect the anticipated grading of the soil. Changes in the volume of sediment suspended in response to jetting are determined from the reduction of (infra-red) light transmission across the test chamber and logged to an onboard computer. Small, disturbed samples were taken from each of the test locations for moisture content and grading analyses.

Although the majority of the field and laboratory testing procedures were guided by British Standard approaches, some mine-waste specific adjustments were required. The mine waste in the driving spoil bund necessitated modification to the material preparation procedure for the shear box testing, as discussed below. The direct shear box technique, using a 100 mm shear box (imposing an upper grain size of 3.3 mm), was used to determine the shear strength parameters along a shear surface within representative samples of the granular material from the driving bund. Drained testing was carried out with normal stresses of 6, 12 and 24 kPa (calibrated 504.8 N/mm proving ring). Each stage of the test commenced with consolidation of the sample. The rate of shear was 0.15 mm/min.

Method evaluation, results and application

Internal erosion or subrosion (suffosion) processes, as suspected in the driving spoil bund, can occur where particle size, density and packing conditions allow particle movement through the matrix. One of the simplest index parameters for assessing suffosion potential is the uniformity coefficient, defined from the particle size distribution curves as U= D60/D10 where D60 is the grain size below which 60% of the sample falls and D10 the grain size below which 10% of the sample falls. U values for both the driving spoil and the dressing floor were variable but high (6.44 to 343 in 20 dressing floor samples and even higher in the driving spoil) confirming the potential susceptibility of these materials to suffosion. The grading analyses were also used to provide a preliminary assessment of the hydraulic conductivity of the dressing floor waste (0.81 to 1 x 10-4 cm/sec) and of the driving spoil (0.3969 to 1 x 10-4 cm/sec).

There were no obvious consistent changes in the conductivity properties of the driving spoil bund, as interpreted from the EM survey, supporting the hypothesis that geotechnical properties determined from hand-excavated pits in the near-surface of the bund could be assumed to be representative of the bund mass. Magnetic susceptibility data indicated a small, but consistent, increase in magnetic susceptibility with depth, perhaps due to the presence of more mineral-rich fine material towards the base of the bund. U values described above show that this could be a secondary suffosion feature. The EM survey of the dressing floor identified a continuous, low resistivity feature, running along the south-east length of the site (Figure 2), which joins the Great Eggleshope Beck. This may be a manifestation of the former course of the Great Eggleshope Beck (as suspected from a comparison of satellite images of the area) and potentially indicating a fluid/ contaminant pathway through the mine tailings to the Beck. Results from the GPR indicated a material change at 2 to 3 m. Further interpretation is required.

The erosion meter, designed to measure the critical erosion shear stress of fine sediments, returned the results as a transmission percentage against eroding pressure for each 0.1s period of the incrementally increased (0.5 Psi) jetting pressure increments. These were converted from Psi to kPa for analysis. The equivalent horizontal stress was approximated from the vertical pressure using the conversion curve established by Tolhurst et al. (1999). This is valuable in modelling the depth and velocity of flowing water that might lead to sediment mobilisation in the event of flooding. The results indicate that there is spatial variability in the erodibility of the dressing floor tailings with a critical shear stress of 5–10 N m^2.

Overcoming the material challenges in the laboratory context required consideration of scaling issues. Near surface disturbed, bulk samples of the driving spoil were taken for direct shear box testing, but in the absence of access to a very large shear box to accommodate the coarse grain size of the driving spoil, techniques for assessing the representation of the mass by the finer-grained material were required. Optical analysis of the shape and material composition of the finer grained component of the samples formed a gateway for the application of parallel grading techniques (Lowe 1964). Further, the low percentage of fines, necessitated combining the bund samples to achieve the required volume. Resulting shear strength parameters comprised a friction angle of 68 degrees and a residual cohesion of 1.54 kPa. Using these data, slope stability modelling was undertaken using firstly a limit equilibrium based USGS code Scoops3D, implementing the 3D Simplified Bishops method which calculates a factor of safety (FoS) across the bund as the factor by which the shear strength could be reduced to bring it in equilibrium with the shear stress. Secondly, a 2D finite element-based shear strength reduction slope

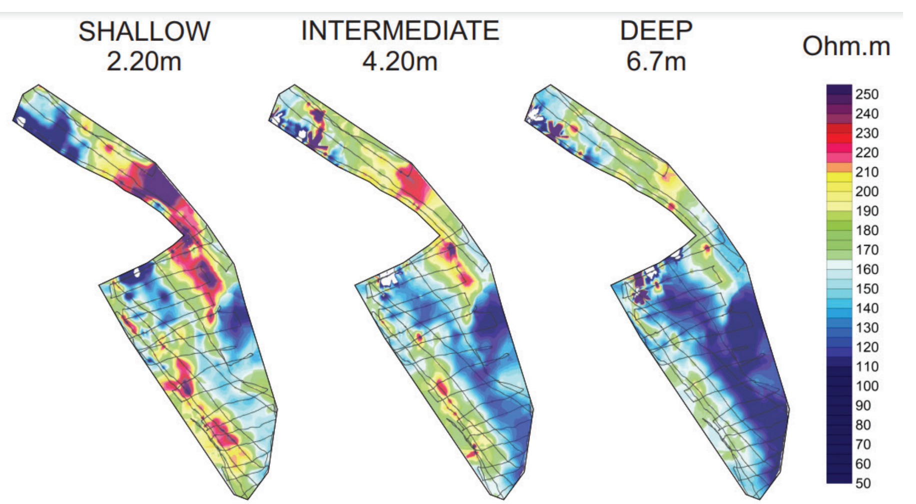

Figure 2 EM returns as electrical resistivity of the dressing floor at Great Eggleshope; low resistivity areas link to stream to east with increasing depth. Looking north to the top of the page.

stability with RS2 software (Rocscience) was run. Using this code, the impact of stream undercutting on bund stability calculated as a strength reduction factor (assessed using an elastoplastic Mohr-Coulomb model with input parameters taken from the shear box test results with literature-based estimates of Young's modulus and Poisson's ratio under drained and saturated conditions along a cross section of the bund) was examined.

Conclusions and future research directions

Data from a 6-year hydrological monitoring project reported by Carling and Reader (1982) and Carling (1988) provided evidence of ongoing mine waste erosion. The results of the geotechnical testing undertaken on samples from Great Eggleshope have been used to characterise the mine, for example in terms of its propensity to suffosion and to provide input parameters for slope stability and erodibility modelling. The geophysical surveys, together with more traditional geotechnical testing provide the basis for assessing the potential impacts of diffuse sediment on the Great Eggleshope Beck and farther downstream.

A distinct advantage of the continuous measurement mode of the EM and GPR geophysics is the profile-based returns that facilitates greater volumetric coverage of the ground than is the case with conventional intrusive investigation techniques (Figure 2). This provided reassurance with respect to representation of the surface materials for the full thickness of the driving spoil bund. Another advantage, which is also an interpretative challenge necessitating calibration and validation, is that the geophysical returns directly reflect the physical condition of the ground (composition, density and water content). Electrical techniques are particularly responsive to changes in soil moisture, which is likely the reason for the low conductivity zone in the EM returns in the area of the dressing floor from which the channel is suspected (from satellite images) to have migrated.

This investigation has highlighted the additional challenge associated with calibrating the geophysics with coarser mine waste density. The deployment of in-situ techniques requires an appropriate scale and capacity for application with the risk of measurements being representative of individual boulders rather than the mass. This situation is exacerbated where the mine waste has been placed or regraded at steep angles that require engineered access for investigation. Therefore, a key knowledge gap remains with respect to the in-situ density of the dressing spoil, necessitating parameter estimation for slope stability modelling. Pragmatic approaches such as this introduce modelling uncertainty that requires accommodation in the design factors of safety.

Repeat LiDAR scanning did not identify any significant change in the bund profile between between November 2021 and November 2022, a period of relatively benign meteorological conditions. Baseline data are available for comparison with any future surveys. The slope stability and erodibility modelling approaches can be parameterised to further explore the impact of anticipated extremes.

More leaching analyses of the driving spoil and other mine heaps, as well as of the stream bedload, together with statistical analyses of the data, would be required to quantify the potential load from these sources. Whilst hydrological parameters such as permeability can be estimated from grading curves, given the different shape and packing properties of the mine waste when compared with natural soils from which these empirical methods have been derived, it is considered that in-situ hydraulic testing would be beneficial for refining the permeability data and any estimates of groundwater flow in the mine waste.

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