In-situ characterization of strength and stiffness in a weathered mudstone profile

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ABSTRACT

The weathering profile in mudstone outcrops can range from weathered clay to unweathered mudstone. The strength and small-strain stiffness of these materials, and of stiff clays and weak rocks in general, is critical to the design of geotechnical structures. Monitoring data and ground investigation data were gathered during the construction of a trial embankment founded on weathered, Jurassic-aged mudstone, for the HS2 high-speed railway project (UK). These data included outputs from in-situ downhole geophysical tests and extensometers at the embankment location. These were compared to ground investigation data from the wider mudstone outcrop over an 18.2 km stretch of the route. The installation of extensometers prior to loading by the embankment construction enabled the measurement of in-situ strains for a range of small and medium strains. It was therefore possible to characterise the stress-strain behaviour of the individual layers within the ground profile.

The results showed that stiff clays derived from weathered mudstone at shallow depth (<10 mbgl) are characterised by low undrained shear strength (<300 kPa) and by maximum stiffness values that are comparable to laboratory measurements from fine-grained soils. However, the unweathered mudstone at greater depth (>15 mbgl) showed higher strength (>300 kPa) and higher maximum stiffness than the overlying clay. Both the strength and stiffness profiles showed a transition zone between the weathered clay and the unweathered mudstone. This zone included a partially weathered mudstone that had the visual appearance and index properties of a mudstone, but the strength of a stiff clay (i.e. $\tau_u < 300$ kPa).

Keywords: weathering; mudstone; geophysics; extensometers.

1. Introduction

It can be difficult to obtain undisturbed samples for the laboratory testing of stiff soils and weak rocks, such as those in weathered mudstone outcrops. It is therefore difficult to characterize the engineering properties of the ground profile. This is particularly critical for many geotechnical structures such as foundations, retaining walls and cut slopes that are constructed in the most weathered materials, located at or close to the ground surface.

In-situ testing and the back-analyses of structural behavior from full-scale trials can be used to obtain engineering properties in-situ. However, such trials can be more time consuming or expensive than routine soil sampling and laboratory testing (O'Brien, 2023). Their use is therefore often limited to large projects where they can more significantly reduce construction risks, programme (i.e. schedule) or cost.

The construction of the HS2 high-speed railway between London and Birmingham is one of the UK's largest construction projects and includes the construction of many geotechnical structures across mudstone strata ranging in age from the Paleogene to the Triassic periods. It therefore includes a large, continuous ground investigation along the route (>160 km) and a number of instrumented full-scale structures.

This paper describes the use of in-situ geophysical tests, the back-analyses of a trial embankment and data from the HS2 ground investigation to characterize the engineering properties of the weathering profile in a Jurassic-aged mudstone.

2. Materials

An 8.2 m high trial embankment was constructed between November and December 2020 at a site north of Banbury, England (Figure 1). The embankment was located on an outcrop of weathered mudstone from the Charmouth Mudstone Formation. It is part of the Lias Group, which outcrops continuously across central England from Dorset in the southwest to Yorkshire in the northeast. The Lias Group of clay-rich sediments was formed in shallow seas (180-205 Myr ago), subjected to overconsolidation and then exposed to glacial and periglacial weathering (Hobbs et al. 2012).

The trial embankment was 150 m long and 95 m wide at the base, with a slope angle of approximately 23° (Figure 2). An RST instruments EXINLIN-1100 vibrating wire inline extensometer was installed beneath the centre of the embankment with anchors at 0, 5 10, 20, 30, 40 and 60 mbgl. It was installed among other instrumentation (not shown) as part of a monitoring programme to measure long-term ground settlement. During construction, a series of drone surveys were used to measure the increasing embankment height. Displacements of the extensometer anchors were clearly observed in response to each of eight stages of embankment construction.

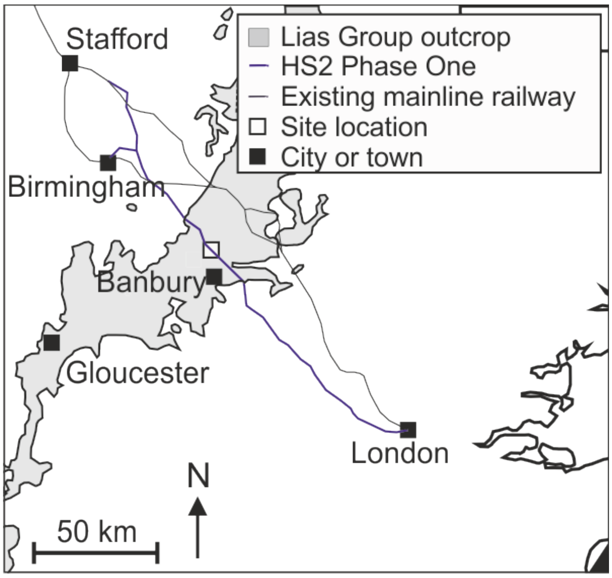

Figure 1. The trial embankment is located north of Banbury, England in an outcrop of the Lias Group. The alignment of the HS2 high-speed railway and connecting mainline railway is also shown. Adapted from Briggs et al. 2022.

Figure 2. Aerial photo of the 8.2 m high trial embankment (Image courtesy of getmapping plc, Infoterra Ltd & Bluesky, Maxar Technologies, Mapdata @2024)

Downhole geophysical measurements (seismic tests) were undertaken in four boreholes close to the embankment trial by a specialist contractor as part of the HS2 ground investigation. The P-wave and S-wave seismic velocities were measured at 1 m intervals within the boreholes to 63 mbgl. They were detected by a BGK-7 multi element geophone that was pneumatically clamped within the borehole for each test interval.

The embankment trial was located close to the midpoint of an 18.2 km long ground investigation area in the Charmouth Mudstone Formation (Lias Group). The ground investigation was delivered as part of the HS2 project by commercial contractors. It included 373 individual exploratory holes, with associated sampling and testing in commercial laboratories. Table 1 shows a summary of the soil laboratory testing data reported by Briggs et al. (2022).

Table 1. A summary of soil laboratory testing data from the Charmouth Mudstone Formation (Briggs et al. 2022)

Material property	Median	Mean	COV (%)
Moisture content (%) (N=1256)	20	21	32
Liquid limit (%) (N=1256)	54	54	21
Plastic limit (%) (N=1256)	24	24	14
Undrained shear strength (kPa) (N=223)	180	302	116

3. Method

3.1. Weathering classification for the ground investigation data

Briggs et al. (2022) reported test data from the ground investigation located either side of the trial embankment site. This included 1256 soil classification tests and 223 undrained unconsolidated (UU) triaxial shear strength tests on samples obtained from clay and mudstone layers of the Charmouth Mudstone Formation (up to 80 mbgl). The samples were compared to weathering classifications recorded in the strata description of the associated borehole logs, to interpret the weathering profile of the mudstone outcrop (Table 2).

Table 2. The weathering classification for Lias Clay in accordance with (a) BS 5930:2015+A1:2020 Approach 4, (b) Spink and Norbury (1993) and (c) a shortened version of the description in Norbury (2020)

Weathering class for weak rocks (a)	Weathering class for Lias Clay (b)	Shortened description (c)
Reworked (E)	Reworked (E)	Stiff light grey CLAY
Destructured (D)	Destructured (D)	Not observed
Distinctly weathered (C)	Distinctly weathered (C)	Very stiff to stiff fissured light brown CLAY
Partially weathered (B)	Partially weathered (Bb)	Very stiff fissured and sheared bluish grey CLAY
Partially weathered (B)	Partially weathered (Ba)	Extremely weak to very stiff fissured bluish grey MUDSTONE
Unweathered (A)	Unweathered (A)	Extremely weak to very weak fissured bluish grey MUDSTONE

The weathering profile was recorded in the ground investigation using 'Approach 4' for weak rocks (BS 5930:2015+A1:2020) and converted to the Spink & Norbury (1993) weathering classification for Lias Clay (Table 2). This conversion separated the partially weathered (Class B) category into partially weathered mudstone (Class Ba) and partially weathered clay (Class Bb).

Briggs et al. (2022) described a gradational weathering profile in the Charmouth Mudstone Formation near Banbury. Figure 3 shows a transition from unweathered (Class A) mudstone at depth (>15 mbgl) to clay (Class Bb-E) at shallower depth. These are separated by a layer of partially weathered mudstone (Class Ba).

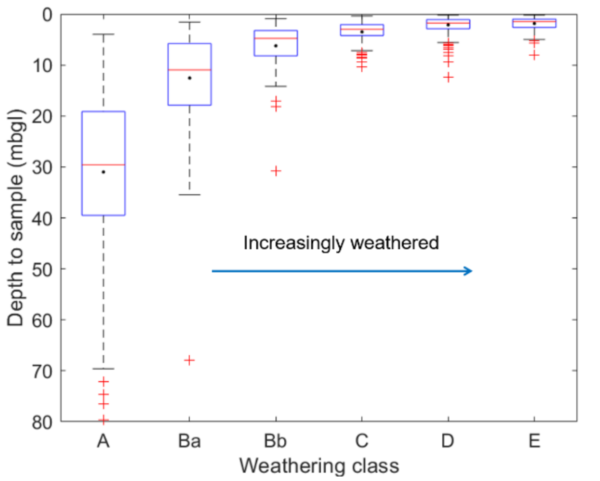

Figure 3. A boxplot showing the sample depth (mbgl) of 1256 soil classification samples in the Charmouth Mudstone Formation near Banbury (from Briggs et al. 2022). The data are categorized by weathering class (A-E)

3.2. Shear modulus profile from geophysical measurements

The downhole geophysical measurements were used to calculate the maximum shear modulus (G_{max}) of the ground profile (Pa) using the relationship:

$$G_{max} = \rho V_s^2 \tag{1}$$

where ρ is the bulk density (kg/m^3) and V_s is the shear wave velocity (m/s). For comparison, a shear modulus (G_{max}) profile was also calculated using the Vardanega & Bolton (2013) equation for fine-grained soils:

$$\frac{G_{max}}{p'_r} = \frac{B}{(1+e)^{2.4}} \left(\frac{p'}{p'_r}\right)^{0.5} \tag{2}$$

Where p' is the mean effective stress, p'_r is a reference stress (taken as 1 kPa), e is the void ratio and B is the typical soil structure coefficient (B = 20,000). The equations used input values (e.g. bulk density and e) obtained from soil samples excavated close to the trial embankment.

3.3. Stress and strain beneath the trial embankment

The extensometer measurements were used to calculate the vertical strains for two layers beneath the embankment centre (5-10 mbgl and 10-20 mbgl). These corresponded to the spacing between pairs of extensometer anchors. The strains ($\varepsilon_{zLayer,Stage}$) were calculated from the deformation of each layer at each stage of embankment construction ($\delta_{zLayer,Stage}$), relative to the initial layer thickness (Z_{0Layer}):

$$\varepsilon_{zLayer,Stage} = \frac{\delta_{zLayer,Stage}}{Z_{0Layer}} \tag{3}$$

The changes in vertical stress beneath the trial embankment were calculated using the analytical equations for vertical loading and plane strain conditions described in Poulos and Davis (1974). The vertical stress was calculated at the midpoint of the layers defined by the extensometer magnet spacing (calculation not shown). The vertical loading was obtained from the known embankment geometry at each of the eight construction stages and the unit weight of the embankment fill (back-calculated as ~22 kN/m^3).

4. Results

The undrained shear strength measurements from UU triaxial tests in the Charmouth Mudstone Formation near Banbury are shown in Figure 4. These show that the weathered clays (Class Bb-E) were characterized by an undrained shear strength of less than 210 kPa (75th percentile) and located at less than 11 mbgl (75th percentile). The weathered mudstone (Class Ba) was characterized by an undrained shear strength of 140-310 kPa (interquartile range) and was located between 10 and 20 mbgl (interquartile range). This corresponds to the shear strength of a clay (i.e. τ_u < 300 kPa). The unweathered (Class A) mudstone was located at depths greater than 15 mbgl (25th percentile).

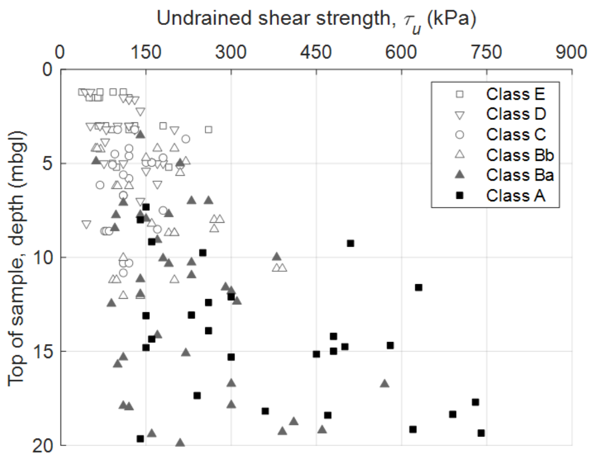

Figure 4. The undrained shear strength of the samples (Class-A-E), up to 20 mbgl. Adapted from Briggs et al. 2022.

Figure 5 shows the in-situ shear modulus (G_{max}) profile derived from downhole geophysical testing. This shows that the G_{max} profile increased linearly with depth through the weathered clay at the near surface (to 8 mbgl). This aligns with the shear modulus profile determined using the Vardanega & Bolton (2013) equation for fine-grained soils. Below 8 mbgl the gradient of the shear modulus with depth increases relative to the Vardanega & Bolton (2013) equation. It also shows greater scatter. This shows the transition to the less-weathered clay (8-13 mbgl) and mudstone (>13 mbgl) at greater depth. Comparison with Figure 3 shows that this aligns with the transition from partially weathered clay (Class Bb) to partially weathered mudstone (Class Ba).

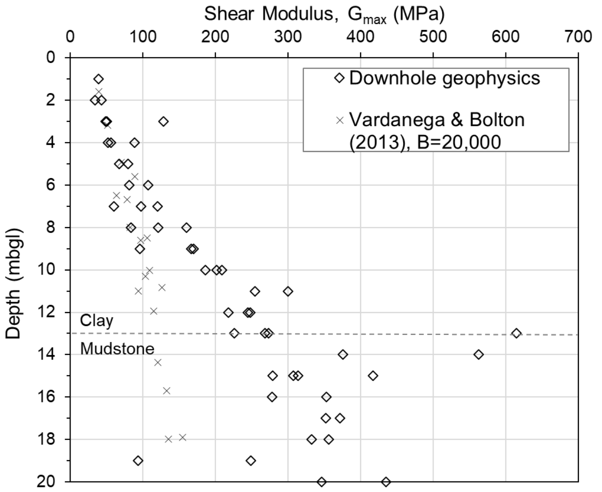

Figure 5. The Shear Modulus (MPa) profile measured in four boreholes close to the trial embankment compared to results from the Vardanega & Bolton (2013) equation.

Figure 6 shows the vertical stress and vertical strain within soil layers beneath the centre of the embankment, in response to seven stages of embankment construction (the first of the eight stages produced negligible displacements and is not shown). This shows that the secant stiffness of the layers reduces with increasing strain, in agreement with the non-linear stress-strain behavior shown by other stiff clays and weak rocks (Atkinson 2000; Clayton 2011; O'Brien 2023). The layer at greater depth (10-20 mbgl) was in the less-weathered clay and mudstone. It is stiffer than the overlying, more-weathered clay (5-10 mbgl).

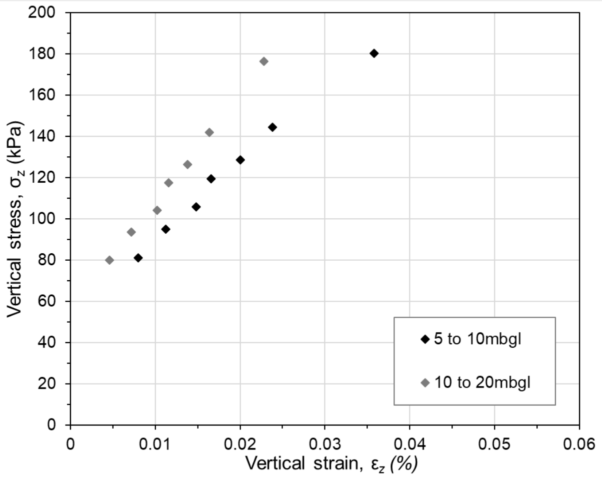

Figure 6. Vertical stress (σ_z) vs strain (εz) within the soil layers beneath the centre of the trial embankment during construction.

5. Conclusions

Measurements from an instrumented embankment and an 18 km length of ground investigation were used to characterize the engineering properties of weathered Charmouth Mudstone (Lias Group). These showed a gradational weathering profile from weathered (Class C – E) clay at the near surface, to unweathered (Class A) mudstone at greater depth (>15 mbgl). These were separated by an intermediate zone of Class Ba Mudstone that had the visual appearance of a mudstone but the undrained shear strength of a clay (τ_u < 300 kPa). The visual misclassification of this zone as an unweathered mudstone (Class A) could lead to unsafe material strength assumptions for geotechnical design.

Downhole geophysical shear wave velocity measurements confirmed the presence of a gradational weathering profile. The near surface clays (to 8 mbgl) had a maximum shear stiffness that compared to the Vardanega & Bolton (2013) equation derived from the laboratory testing of fine-grained soils. However, at greater depth the maximum stiffness was greater than the Vardanega & Bolton, (2013) prediction. This shows a change in stratigraphy from weathered clay to less-weathered (i.e. partially weathered) clays and mudstones.

Extensometer measurements taken during the construction of an instrumented embankment confirmed that the clay and mudstone at greater depth (10-20 mbgl) was similar to the weathered clay materials (i.e. not rock-like), but still stiffer than the overlying clay. This is consistent with the gradational weathering profile shown in the ground investigation and the maximum shear stiffness profile.

6. Acknowledgements

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