Identification and implications of the London Clay Formation divisions from an engineering perspective

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**ABSTRACT**

Historically, engineers frequently viewed the London Clay Formation (LC) as uniform, homogeneous and rather uninteresting, Chris King’s seminal work provided a much deeper insight into the characteristics of the LC and how it can be split into divisions, based on the depositional history of the formation and the microfauna present. LC water content profiles were compiled from continuous cores as part of an investigation into variations in tunnelling-induced settlements across St James’s Park, allowing distinct zones to be identified. These were found to coincide exactly with the divisions identified by Chris King almost twenty years earlier. Water content profiles can be developed as part of a ground investigation and used to help establish the boundaries between King’s divisions. Based on two further water content profiles from Hyde Park and St John’s Wood a new methodology for locating the boundaries of the divisions, involving a trend-line for sub-Division A3, is proposed and tested, relevant to conditions in central London. In developing the method, significant differences in the elevation of the divisions between the three sites is observed, suggesting geological processes such as folding or faulting have influenced the LC along the ~5-km length of the section.

Once the boundaries of the LC divisions are known, geotechnical engineers have a greatly improved overall understanding of the ground conditions and how the ground will respond to engineering works such as tunnelling and deep excavations. Broad engineering implications of the divisions are described and discussed, citing case histories where possible.

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1. Background

Civil engineers have been working on and within the London Clay Formation (LC) for at least two centuries. Generally, it is regarded as a good medium for deep excavations and is the preferred medium for tunnelling in London, being able to stand unsupported for periods in which temporary or permanent structures can be built. It is also a reasonable foundation material. Intact, unweathered London Clay is often described as stiff becoming very stiff with depth fissured blue clay, while the weathered material is usually firm and brown as a consequence of the oxidation process (Chandler and Apted, 1988). For decades it has mostly been regarded as a uniform and homogeneous material.

Tunnellers and miners working in London Clay perhaps have the greatest knowledge of the material from a practical working experience. Mackenzie (2014) relates how discontinuities in the clay often intersect each other and that their surfaces are often “coated with a plasticised clay paste resembling heavy engine oil”. He goes on to report that when “an advancing tunnel face encounters intersecting discontinuities in the clay it can give rise to the development of a wedge . . . which may slide out into the advancing tunnel . . . the upper surface of the wedge of clay, lying in the invert of the tunnel, often exhibits slight regular corrugations which give it the appearance of the back of a large animal, with its ribs showing through the skin, covered in clay grease – hence the origin of the term ‘greasyback’”. Mackenzie also notes that these wedges often move out of the tunnel face silently and suddenly and can weigh anything from 500 kg to more than 5000 kg and hence pose significant risks to safety and initiate progressive destabilisation of the tunnel face. Such features were also identified by others investigating the LC (e.g. Skempton et al., 1969) but without the unifying realisation, provided by King (1981), that these features are found within specific horizons within divisions and that these are reasonably consistent in thickness across the LC in London. Knowledge of where such discontinuities might occur, as well as other features such as silt and sand partings and claystone horizons would benefit greatly the understanding of engineers planning to excavate in or construct above the LC.

The seminal work of King (1981) opened a completely new dimension into the composition and sub-stratigraphy of the LC.

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split the LC into five divisions from A to E (from the base upwards), delineating them using micropalaeontological identification and depositional sequencing. In very simple terms, each division is associated with a major transgressive-regressive cycle during which the seas in which the LC were laid down, first spread (transgressive) and deepened, with primarily fine grained materials being deposited, and then receded (regressive) with water depths reducing and consequently progressively coarser materials being deposited. Each division (cycle) therefore has a ‘coarsening upwards’ grain size distribution (although the grain size increases are often quite minor because of the considerable distances from the shoreline). The different depths and environments led to specific microfauna evolving at different times, some existing for only limited periods, thus allowing the micropalaeontological identification of the divisions. A summary of the divisions is shown in Figure 1 (after King, 1981, Figs. 7 and 8). Each of the divisions has its own geological and geotechnical characteristics. The LC spans both the Hampshire and London basins and extends out into the North Sea and into northern Europe. Within central London primarily only the lower Divisions A and B are found, with sometimes Division C in higher ground, the divisions above having been removed by erosion. In London the LC is generally underlain by the Lambeth Group (LMBE) and in some locations (usually towards the east) the Harwich Formation (formerly Division A1), details of which are given by Skipper and Edgar (2019).

During construction of the Jubilee Line Extension (JLE) tunnels, significant variations in settlements were observed between the vicinity of Westminster, including the south of St James’s Park.

**Fig. 1.** Stratigraphy of the London Clay Formation (after King, 1981, Figs. 7 and 8). n.b. the terms for the strata above and below the LC have now changed: ‘Virginia Water Formation’ is now referred to as the Bagshot Formation and ‘Woolwich and Reading Beds’ as the Lambeth Group (LMBE).
(SJP), and the north of SJP. The reasons for the larger-than-expected settlements were investigated because of their potential effect on future tunnelling projects. Although it was known that the method of tunnelling was partly responsible for the variations in settlement, an important aspect of the study was to establish whether the ground conditions could have also contributed significantly. Five pairs of 40-m deep boreholes (BH1 to BH5) were sunk, using cable-percussion techniques, across St James’s Park along the rough alignment of the tunnels (see Fig. 2), with one borehole being used to profile the strength with depth and the other to take continuous driven U100 samples (100 mm in diameter and 450 mm long). The latter were to be split for detailed geotechnical and geological logging. It was also decided to take frequent water content samples (typically at 150 to 200-mm intervals). The water content profiles compiled from these measurements were used to identify zones within the LC (over the depth investigated – containing Divisions A and B) which were found to be reasonably consistent across the park. Dr Chris King inspected the cores and the zones identified from the water content profiles coincided exactly with his divisions, based on depositional cycles and microfauna (confirmed by de Freitas and Mannion, 2007). The study concluded that the geology across the park and the divisions also certainly did contribute to the large settlements monitored, as described by Standing and Burland (2006).

Other methods of identifying zones (and hence the divisions) within the London Clay Formation were investigated at the time of the original study (Standing and Burland, 1999) and subsequently by Hight et al. (2003, 2007) and Pantelidou and Simpson (2007). The potential for using other methods of identifying the divisions is discussed in this paper. A new methodology for determining the boundaries between them using water content profiles is then developed, based on two further detailed water content profiles compiled from boreholes at Hyde Park (HP) and St John’s Wood (SJW). Finally, reasons for identifying the divisions and their implications are discussed from an engineering perspective. It should be noted that the LC divisions and sub-divisions are referred to using the terminology in King (1981) rather than those given in the more recent British Geological Society regional guide covering London (Ellison, 2004). Also the term ‘division’ or ‘sub-division’ is used here as by King (1981) rather than ‘unit’ or ‘sub-unit’. Where sub-divisions are further divided, these are referred to as ‘sub-layers’.

2. Identifying the divisions using engineering characterisation techniques

The definitive approach to establishing the boundaries of the LC divisions is through identification of various microfaunal assemblages that existed during different depositional cycles, primarily marine flood events (King, 1981; Ellison, 2004). The former must be done by a suitably qualified micropalaeontologist with relevant knowledge and experience. In this section other alternative geotechnical engineering characterisation methods are considered.

The intention is to observe how such characteristics vary with depth, seeking to identify those that show most clearly changes between the sub-divisions. Important factors to consider regarding the associated measurements of a particular characteristic are: their frequency and accuracy; their variability and reliability; the ease of determining them; the time and cost involved; and whether any degree of subjectivity is involved. Clearly, the greater the frequency and accuracy of measurement, the better defined should be the resulting profile. However, this needs to be balanced in conjunction with the time, effort and cost involved.

The following methods are given roughly in order of increasing complexity, with laboratory tests covered first followed by field measurements. Specifications for the geotechnical laboratory tests and field measurements mentioned below are given by BS1377-1 (BSI, 1990), which has been replaced by BS EN ISO 17892 (BSI, 2014a,b)) and BS5930 (BSI (1999), now replaced by BSI (2015)) respectively.

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Fig. 2. Location of boreholes at St James’s Park.

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2.1. Water content, w (BS 1377-2 (BSI, 1990) now replaced by BS EN 17892-1 (BSI, 2014a,b))

This is a quick, cheap and reliable measurement and has been used, with success, for identifying the LC sub-divisions as described above. It simply involves weighing the soil at its natural water content and then again after oven drying (w = mass of water present / mass of dry solids). Therefore, only mass measurements are required. Ideally, measurements should be made on intact samples but it may also be possible to achieve a reasonable water content profile (henceforth referred to as w-profile) from disturbed samples (refer to BS5930 (2015) for suitable methods of sampling). Essentially the greater the clay content within a soil and the greater its activity, the higher the value of w. Practical considerations are covered later in the paper along with recommended frequency of measurements.

2.2. Bulk unit weight, γ (BS 1377-2 (BSI, 1990) now replaced by BS EN 17892-2 (BSI, 2014a,b))

This is also a very simple measurement but involves trimming a sample such that its volume can be measured accurately. Measurement of volume is less accurate compared with that of mass and the time and cost involved are greater. As variations in bulk unit weight fall within quite a narrow range for many soils, the likelihood of seeing marked changes within the LC is unlikely. This was found to be the case by Standing and Burland (1999, 2006) where γ values were noted to lie between 19–20 kN/m³ for the SJP profiles; Hight et al. (2003) findings were similar.

2.3. Atterberg limits, wL and wF (BSI 1377-2 (BSI, 1990)) now replaced by BS EN 17892-12 (BSI, 2018))

Soils are frequently assessed in terms of their Atterberg limits; the liquid and plastic limits (expressed as water content, wL and wF respectively) essentially relate to two states when (i) the soil is able to flow and (ii) it starts cracking. The plasticity index, PI, is calculated from (wL – wF). The liquid limit and plasticity index are plotted on a Casagrande chart as wL versus PI from which it is possible to assess the degree of plasticity (which ranges from low to extremely high). The plasticity characteristics are mainly dependent upon the percentage and type of clay minerals present. The test procedure, although standardized, can be prone to some subjectivity, especially for the plastic limit test (although, if carried out correctly, the values are repeatable), and takes considerably more time than a simple water content measurement (it involves several of these at different soil states) and is typically four to five times more expensive. Both disturbed and intact samples can be used but the tests require larger samples than either those for water content or bulk density.

Standing and Burland (1999, 2006), Hight et al. (2003) and Pantelidou and Simpson (2007) plotted profiles of wL, wF and PI with depth. Generally wL provides the best correlation with the LC divisions, although in the first two sources there were insufficient data points for clear trends to be identified. Pantelidou and Simpson consider a very large database of results which are plotted in terms of height above the base of the LC. They argue that the Atterberg limits are material properties and so are a more appropriate measure compared with natural water content which is state dependent. The relevance of this is discussed later in the paper. Although broad trends are evident in their wL profile there is very considerable scatter in the data. The use of Liquidity Index, (wL – wF)/PI, is also investigated by them but as this is related to both the Atterberg limits and the natural water content it does not hold any additional benefit.

2.4. Clay content and activity

The clay size content (<0.002 mm) is obtained from particle size distribution (PSD) curves generally from pipette analysis, the preferred method, but hydrometer analysis can be used. The test is about 10 times more expensive than that of water content and requires more material. Activity is the clay content divided by PI. This measure provides good correlations with clay mineralogy but because two tests are involved (Atterberg limits and hydrometer analysis), with much greater cost and effort implications, practically it is unlikely that a detailed profile of activity with frequent depth intervals would be compiled for identifying the boundaries between the divisions.

2.5. Mineralogy

Mineralogy is not often identified in ground investigations but might provide a useful correlation with the LC divisions, in the same way as clay content and activity. A more sophisticated technique involving X-ray diffraction (XRD) is required, which is relatively expensive. Huggett and Knox (2006) provide useful information on the mineralogy of the LC but do not specifically discuss variations between its divisions and focus mainly on the upper Divisions D and E at Hampstead Heath for which there seems to be little variation in the percentages of smectite, illite, chlorite and kaolinite present.

2.6. Standard Penetration Test (SPT) and U100 driving blow counts

During the investigation at SJP, alternating SPTs and U100 samples (BS EN 1997-2: BSI, 2007) were taken in the five strength profiling boreholes. Although, driven U100 samples are now not considered suitable for strength testing (BS EN 1997-2: BSI, 2007), the idea was to check for differences in strength along the tunnel alignment using the methods available at the time of the original ground investigations for the JLE project. The numbers of blows applied when driving the U100 sampler were also recorded (although the primary purpose of taking the samples was to test them in the laboratory to obtain values of undrained shear strength). These can sometimes supplement the number of blows recorded as the SPT N-value (Vaughn, 1994). Generally, the primary trend is an increasing N-value or number of blows with depth with no marked changes at the sub-division boundaries. For the SJP case, small but noticeable increases in strength were observed along the northern part of the section as discussed by Standing and Burland (2006). Hight et al. (2003) also investigated several SPT N-value profiles and also concluded that they are not useful in identifying trends.

2.7. Cone penetration testing (CPT)

Two CPTs, where cone end resistance, sleeve friction and excess pore water pressure behind the cone were recorded, were also undertaken during the SJP investigation in the vicinity of the Imperial College instrumented section (see Fig. 2 and Nyren et al., 2001). A major limitation of the CPT is that its penetration into the LC is limited (typically to about 10 to 15 m) because of its strength and so to advance deeper it is necessary to retract the cone rods, pull off the position, drill the hole out using a drilling rig, case the hole and then reposition the CPT truck to continue the test. This is very time consuming and expensive, especially if the sequence has to be repeated several times. The results from the CPTs performed at SJP did not show clear differences between the LC divisions. However, Hight et al. (2003) report greater success when changes in pore water pressure were monitored using a face-mounted piezometer element.

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2.8. Other methods

A number of other more specialist methods have been mentioned by Hight et al. (2003) such as: natural gamma radiation, resistivity, and shear wave velocity; and by Pante-lidou and Simpson (2007): conductivity. Gamma logging has been successfully used within the London Clay Formation as shown by Ellison (2004). The advantage of the method is that the depth of the data is known and this tool can be used in cased boreholes.

During the logging of the cores from HP, colour was carefully logged using Munsell colour charts as part of the detailed descriptions in which three categories relating to hue (the sheet number), value (y-axis) and chroma (x-axis) are recorded. There was little variation in colour with the descriptors being 5Y/2.5/1 (described in the Munsell charts as black) at the very top (Division C), changing slightly to 5Y/3/2 (dark olive grey) which continued to roughly the base of A3 and then 5Y/3/1 (very dark grey) for A2.

3. Interpretation of water content profiles for St James's Park, Hyde Park and St John's Wood

The water content profiles from SJP are shown in Figure 3, which also includes the boundaries between the divisions encountered. It should be noted that sub-Division A3 was divided into two further sub-layers (A3i and A3ii) as the upper part of the sub-division contains numerous silt and sand partings which clearly could have important engineering implications. This was the only part of the zoning that differed from King's divisions and sub-divisions. The boundary between A3i and A3ii is somewhat subjective as it relates to where the partings are no longer observed and so this sub-layer boundary is not considered here. Also, the upper samples from Bh2 had dried out to some degree prior to water content determination and so the w measurements were judged to be unreliable and are not presented. As explained by Standing and Burland (2006) there is a 4.5-m step in the upper surface of the LC between BHs 1 and 2 and BHs 3 to 5 because the two groups of boreholes straddle a terrace marking a change in Pleistocene gravels, with older Kempton Park Member river terrace deposit lying to the north of the lake in SJP, which has been eroded south of it and replaced with more recent terrace deposits, the Shepperton Member (as can be roughly seen in the BGS, 1920 6-inch series map of the area). As a consequence of this, the water contents south of the lake were 1 to 2% higher in the upper depths of the w-profiles, the effect becoming negligible towards the base of sub-Division B2.

The general trends observed from the w-profiles at SJP are as follows. Starting from the base of the boreholes, water contents in the sub-Division A2 are generally lower than those above as it is the sandiest division. The A2 profiles are also more erratic as there are frequently closely spaced alternating layers of silty clay and very sandy clay, although sometimes these are bioturbated resulting in the mixing of layers. There is generally a step increase in water content at the junction between A2 and A3, the latter having a higher clay content at the base. Water contents generally decrease upwards in sub-Division A3, indicating an increasing coarse content, evident near the top by the presence of silt and sand partings as shown by the grain size distributions in Figure 1. Another clear step increase occurs at the interface with B1, reflecting the more clayey nature of Division B. Sub-Division B1 is typically 1 to 2 m thick and is very silty. The silt content in B2 is lower, reflected by a further step increase in the w-profile at the base of B2. Within B2 there is much less scatter and only small variations in mean values. Hight et al. (2003) further divided sub-Division B2 encountered at Heathrow into sub-layers representing depositional cycles.

![Fig. 3. w-profiles and sub-divisions for St James's Park boreholes (after Standing and Burland, 2006).](https://doi.org/10.1016/j.pgeola.2018.08.007)
As part of a research project investigating the effect of tunnelling on existing tunnels, run in conjunction with the Crossrail tunnelling project, numerous boreholes were drilled to install a variety of instrumentation at a location in Hyde Park (HP) adjacent to Bayswater Road, just east of Lancaster Gate underground station. Some of the boreholes were drilled using triple-tube rotary coring techniques, providing high quality samples for soil laboratory testing (n.b. it is essential that any drilling fluid is wiped from the soil core immediately after its retrieval to prevent any imbibing of water). The core from the deepest hole, extending to 68 m below ground level, was used for detailed soil description and for compiling a w-profile. This is shown in Figure 4, along with the LC divisions which were defined based on the w-profile and the experience gained from SJP. Chris King also logged the core and confirmed the division boundaries, the only major difference being between the A3i and A3ii sub-layers. At this location a small thickness of Division C was encountered at the very top of the LC in this area (confirmed with a micropalaeontology analysis performed by Chris King). This is allows the full thickness of sub-Division B2 to be established. Additionally, this borehole extended beyond the base of the LC, which was defined at the top of a sand channel, which had eroded away the upper part of the Lambeth Group just after or in the later stages of its deposition. A full borehole description is given by Wan and Standing (2014).

Another detailed w-profile was compiled from a deep rotary triple tube core borehole sunk at St John’s Wood (SJW), with the cooperation of Concept Engineering, as shown in Figure 5. At this location, the ground surface level is considerably higher than the other two sites and a much greater thickness of Division C is present. Again the core was inspected by Chris King and the boundaries he identified and those estimated from the w-profile were essentially the same. At this site the base of the LC was not

![Fig. 4. w-profile and sub-divisions for Hyde Park borehole.](image-url)

![Fig. 5. w-profile and sub-divisions for St John’s Wood borehole.](image-url)

![Fig. 6. Relative locations of boreholes referred to in study.](image-url)

reached despite the borehole extending to 70 m below ground level.

The relative positions of the seven w-profile boreholes are shown in Figure 6, along with two additional borehole locations in Westminster (also shown in Fig. 2) where soil descriptions were used to identify the upper and lower levels of the LC as well as the boundary between Divisions A and B (sourced from Burland and Hancock, 1977 and Burland and Kalra, 1986). The lithostratigraphical correlation is more than 6 km long.

The respective reduced levels and thicknesses of the LC sub-divisions encountered at the three sites are given in Table 1. Note that the reduced levels are expressed as 'm aPD' where aPD relates
to ‘above project datum’ (PD) which was set to be 100 m above Ordnance Datum (OD). The thickness of A2 from the Hyde Park borehole is 11.3 m, which combined with that of A3 (13.0 m), gives a total thickness of Division A of 24.3 m. The mean of the A3 thickness is 12.4 m with a maximum deviation of 0.6 m. The thickness of the more silty sub-Division B1 is fairly consistent with a mean of 1.6 m with a maximum deviation of 0.3 m. Sub-Division B2 has a mean thickness of 28.4 m with maximum deviation of 0.1 m at Hyde Park and St John’s Wood where measurements are available. The total thickness of Division B at both sites is 29.8 m (this division is associated with the greatest transgressive incursion of the sea).

Overall the thickness of the divisions and sub-divisions is quite consistent. However, this is largely masked when combining the w-profiles from the three sites, plotting the data against reduced level as shown in Figure 7. In view of the consistency in thicknesses

| Table 1 | Base levels and thicknesses of LC sub-divisions at study sites. |
|---------|-----------------------------------------------------------------|
| Bh      | A2  | Thickness (m) | A3  | Thickness (m) | B1  | Thickness (m) | B2  | Thickness (m) | C  | Thickness (m) |
| SJP Bh1 | –   | 69.9         | 11.9| –              | 81.8| 1.6          | 83.4| –              | –  | –              |
| SJP Bh2 | –   | 69.3         | 12.5| –              | 81.8| 1.6          | 83.4| –              | –  | –              |
| SJP Bh3 | –   | 68.3         | 12.3| –              | 80.6| 1.6          | 82.2| –              | –  | –              |
| SJP Bh4 | –   | 68.4         | 12.3| –              | 80.7| 1.6          | 82.3| –              | –  | –              |
| SJP Bh5 | –   | 67.3         | 12.6| –              | 79.9| 1.9          | 81.8| –              | –  | –              |
| Hyde Park | 62.9 | 11.3       | 74.2| 13.0          | 87.2| 1.5          | 88.7| 28.3          | 17.0| –              |
| SJW     | –   | 84.6         | 12.1| 96.7          | 1.3 | 98.0         | 28.5| 126.5         | –  | –              |

**Fig. 7.** w-profiles from SJP, HP and SJW plotted together using reduced levels.
of the sub-divisions, the w-profiles can be correlated by the sub-divisions. A similar exercise was performed by Hight et al. (2003) for a number of sites across London where w-profiles were available, using the SJP data as a template. Given the detailed nature of the w-profiles from the three sites discussed here, the w-profiles have been aligned to a fixed point that then constitutes a datum (or reference level). Two logical positions that might be considered are the base of either sub-Division B1 or A3 as these points are well defined in all the w-profiles. There is not a great difference between the resulting combining profiles, but the former was selected as this constitutes a boundary between Divisions A and B. The reduced level of the base of Division B for BH1 at SJP was chosen as the datum or reference point (81.8 m aPD) as there was greatest confidence in the five boreholes from this location. The w-profiles with the reduced levels adjusted according to the base of Division B, setting them all to 81.8 m aPD, are presented in Figure 8. The boundaries between the sub-divisions are also marked on the figure along with the adjusted values for HP and SJW. The combined w-profiles can now be seen to lie within clearly defined zones, even for the lower part of B2, B1 and A3 where there are the greatest number of data points as these sub-divisions are common to all the boreholes.

The consistency in thickness between the sub-divisions of the LC is evident when the boundaries are plotted with distance along the length of the section connecting the boreholes as shown in Figure 9a. The fact that the boundaries are not horizontal suggests that a geological process has occurred, such as folding or faulting causing the LC to dip or be stepped (the regional dip in this area is about 2° to the SE). There are insufficient boreholes in the section to identify whether the profile is dipping or stepped (or both): either (or both) might be possible as the strata dip at less than 0.2° over the length of the section and the adjustments needed to line up the base of Division B are 5.4 m and 14.9 m for the HP and SJW w-profiles respectively. In view of this, the boundary lines between the divisions may not be as linear as shown in Fig. 9a. A clearer impression of the consistency in thickness of the sub-divisions is evident when plotting the boundaries using the adjusted levels as shown in Fig. 9b. Estimates can be made of the depth of the base of the LC and, for those boreholes that did not intersect this level, how much further they needed to be extended to sample it.

Fig. 8. w-profiles from SJP, HP and SJW plotted together using adjusted reduced levels so that the base of Division B is set to 81.8 m aPD.

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4. Establishing the boundaries of the LC sub-divisions using w-profiles

In order to have a whole number for the datum (or reference) level, it was decided to set it from 81.8 m aPD to 30 m for the boundary between Divisions A and B with all other depths adjusted accordingly as shown in Figure 10. The w-profiles plotted in Fig. 10 are identical to those in Fig. 8 except all depths are shifted by 51.8 m and referred to as 'adjusted level' and expressed in metres (in this form the base of the LC is just above zero and the full height of the LC column extends to about 80 m). Enlarged plots of the 30 m below and above the new datum level.
(reference level) are presented in Fig. 11a and b, thus covering all of Divisions A and B respectively.

A clear trend is evident in the data within sub-Division A3 with limited scatter as shown in Figure 11. Patterns are less clear in sub-Division B2 although there are still strong trends. It, therefore, seems that a trend-line drawn through the sub-Division A3 w-profile could be used as a means of identifying and locating this sub-division within a w-profile from a borehole where the LC divisions are to be identified. The reasons for choosing the A3 w-profile specifically are given below.

- It has the clearest trend with depth with limited scatter and the w values steadily increasing with depth, relating to a coarsening upwards sequence (King, 1981) shown in Figure 1, suggesting a linear best-fit might be appropriate.
- The full thickness of this sub-division was encountered in all seven boreholes.
- Its thickness along the section is consistent, being 12.4 m with a maximum deviation of 0.6 m.
- As it lies towards the base of the LC it is likely to be encountered in suitably deep boreholes where the LC is present. If it is not, only sub-Division A2 should be present and, therefore, the base of the LC readily reached with a borehole more than about 12 m deep during a ground investigation.
- Variations in water content from swelling subsequent to removal of overburden above will be less than those for the overlying sub-divisions at this greater depth (the effect diminishing with depth). At SJP the water contents in sub-Division B2 south of the park were slightly higher due to the erosion of the 4.5 m of London Clay and Kempton Park Member (compared with values at corresponding depths north of the park) but effect on sub-Division A3 below it was negligible.
- Sub-Division A3 is recognisable in all sections in the London and Hampshire Basins (King, 1981, p.96).

There are 494 data points within the sub-Division A3 w-profile. Initially, a best-fit line was obtained using a least squares analysis. However, this resulted in a poor correlation and so a best-fit line was drawn by eye (using a thick pencil, as was often recommended by Professor Skempton!) and then adjusted slightly by optimising how much of the data fell outside set limits (e.g. ±1%). The line adopted after this exercise is shown in Figure 12 a: it has a slope of
−2.35 m%/w (w increasing with depth by 0.43%/m) and an intercept of 81.5 m (relative to the new reference level at 30 m). The water contents associated with the best-fit line are about 22% and 27% at the top and base of A3. Also marked are the boundaries of ±1% and ±2%, within which there were more than 95% and 88% of the data points respectively (ignoring a handful of obvious outliers which are still included in the plot). Differences between the measured and calculated w values are presented in Figure 12(b). Assuming that water content increases with increasing clay content, positive values imply that the soil has a greater clay content than the calculated line suggests and negative values that it is less clayey or more sandy. There are consistently more positive values, even towards the top of the sub-division where it contains the silt and sand partings, suggesting that the best-fit line slightly underpredicts in this upper region. However, overall the fitted line and deviations from it are adequate for the purpose of establishing a trend line for identifying sub-Division A3 (and hence, given the consistency of thicknesses, the sub-divisions above and below it). In fact all that is required is a trend line inclined at a slope of −2.35 m%/w, extending over a depth of say 12 m.

The methodology is tested using a data set compiled from a set of boreholes sunk for the Royal Opera House presented by Hight et al. (2003). This site is roughly 1 km to the east of SJP. The w-profile is presented in Figure 13a, along with the A3 trend-line to the side of the plot. The data points are intentionally shown without connecting lines as these help the eye identify trends. Even in this form it is clear that there is only one part of the w-profile that the A3 trend-line fits best and where there is little scatter. The trend line is overlain onto this part of the data in Figure 13b, where the data points are joined and the interpreted LC division boundaries drawn. At this location the base of the LC was established from boreholes extended well into the Lambeth Group LMB (where there is another rapid reduction in w values). The magnitude of w values at the top and base of A3 are consistent with those of the data presented in Figure 12a, suggesting that the intercept value is similar. The frequency of w measurements at this site was about every 0.6 m, compared with the accumulated number of measurements from the seven boreholes used to create the A3 trend-line where the frequency is every 0.175 m. This suggests that a lower frequency of w measurements, at say 0.5 m might be adequate.

Another w-profile compiled from measurements at the Terminal 5 site at Heathrow is presented by Hight et al. (2007, Fig. 4). This figure indicates that the A3 trend-line developed here fits the associated w ranges reasonably well, in both terms of slope and intercept. However, it should be noted that at this site, which is about 24 km west of central London, the thickness of the divisions is not the same as in Central London (e.g., Division B is about 24 m thick compared with the 30-m thickness observed at the HP and SJP sites described here).

The fact that the mean values of w at the top and base of A3 are similar at all of the sites discussed here (being about 22% and 27%), extending over several kilometres, suggests that although w is a state dependent variable, this does not have a major influence on the values encountered in the sub-Division A3. Even if it were to vary, the effect on the distribution and hence slope of the A3 trend-line should not be significant. As the difference in thicknesses of the upper part of the LC eroded between the three sites varies by up to about 40 m (minimum erosion at SJW and maximum at SJP), the lack of variation in water content also suggests that the swelling index in sub-Division A3 is very small (<0.1 say).
5. Some practical considerations regarding w measurements

As the sample size required for water content determination is small, the tests can be carried out at higher frequency than other laboratory tests. The data relating to the Royal Opera House represented on average a measurement every 0.6 m, which was sufficient for matching the A3 trend-line. In practice a greater frequency might be prudent. At SJP, HP and SJW the frequency was typically about every 0.2 m.

For the purpose of water content profiling (and detailed soil description) a cable percussion borehole where U100 samples are taken continuously, or almost so (say with a small spacing between

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them, e.g. 0.3 m) is sufficient (Baldwin and Gosling, 2009). The depth to which the sampler is driven is 0.45 m which includes a 0.1-m long shoe sample. Usually the upper and lower part of the main sample (within a liner) are removed to allow effective waxing of the sample ends on site. Taking w samples from both ends of the main length therefore provides two samples over 0.45 m, although the upper part of the main length might be disturbed from cleaning out the borehole following the previous sample. In this way an initial w-profile can be compiled from site sampling without extruding the U100 samples. However, the results from these measurements should be interpreted with some caution (as should samples taken from piling operations if this is attempted). If rotary coring is used it is important to remove thoroughly all traces of drilling mud before sealing the cores or taking w samples and to minimise time of exposure to the drilling mud. Again small w samples can be taken from the ends of the cores and any sub-divided lengths prior to sealing.

In all cases where detailed logging is to be made, the samples need to be split. When dealing with the U100 samples and cores from SJP and HP, these were split using a pair of 0.45-m long blades mounted on a mechanical press so that the sample could be set up between them to split it diametrically. This produces, with a minimal effort, good quality split samples. One half was photographed and sample w samples (typically 30 to 50 g) dug out of the other half prior to logging. The w samples should be weighed immediately and then again after placing in an oven for a day to obtain the wet and dry masses. In the case of the samples from SJW the samples were split by hand and it was not always possible to take the w sample at that moment. This is evident from the w-profile (Fig. 5) where the scatter in data points is greater than those for SJP and HP.

It might also be possible to take w samples during the course of an excavation. However, this is often not practicable for reasons of safety and also from the perspective of knowing exactly the sample depth and location. Also, at this stage, the design would be essentially complete and the measurements would primarily serve to confirm conclusions regarding the LC divisions made following the ground investigation.

In all cases measurements should be carried out in accordance to BS EN ISO 17892-1: 2014 (which replaces BS1377-2 (BSI, 1990), using a balance with a resolution of 0.01 g (it may be necessary to specify this as part of the w measurements if the work is being done as part of a site investigation contract). If possible such a balance should be set up where the w samples are taken (e.g. on site for the initial w-profiling when U100 samples are being taken).

Whenever possible boreholes should be extended sufficiently to identify the base of the LC. Frequently this is not achieved and yet it makes identifying the boundaries of the divisions so much more straightforward. When the boreholes were drilled at SJP the divisions assigned by Chris King were not appreciated as such and the boreholes were taken to 40 m, 10 m below the axis level of the deeper of the two JLE tunnels. In hindsight they should have been extended to the base of the LC and this would not have involved much more drilling as can be seen in Fig. 9b.

6. Engineering implications: some thoughts and examples

In this section the focus is on the broad characteristics of the divisions and sub-divisions and their potential influence on a variety of civil engineering works that might take place within or on the LC. No details are given concerning geotechnical parameters and their variation within the different divisions. Such information can be found in a number of publications, e.g. Hight et al. (2003) and others from the Géotechnique Symposium in Print held in 2007 (covered in issue 1). Often it is situations involving stress relief, especially with tunnelling and deep excavations, where insight into the nature of the divisions being encountered can be most useful (from a practical perspective).

6.1. Discontinuities

Greater concentrations of discontinuities tend to be found in the more clayey sub-divisions of the LC such as B2 and the lower part of A3 (A3ii as denoted by Standing and Burland, 2006). Skempton et al. (1969) differentiated between ‘joints’ and ‘fissures’, the former being more extensive and typically roughly vertical, occasionally polished with a thin layer of ‘gouge’ clay on their surfaces, similar to the features described by Mackenzie (2014). The term ‘fissure’ was reserved for the smaller scale, more randomly orientated discontinuities. When stress is relieved in the vicinity of stiff clay containing discontinuities, movements can take place along the more extensive joints and blocks of soil can be destabilised, as described earlier with reference to Mackenzie (2014) for the case of ‘greasybacks’ relating to safety and stability during tunnel construction works. They may have similar effects during larger deep excavations works, cuttings and vertical excavations for piles and caissons.

There is little information available concerning overall trends of fissure orientations (dip and strike) although Skempton et al. (1969) provide stereo-nets for the sites they investigated. Such information can realistically only be gathered by face mapping, e.g. of tunnel faces or within enclosed walled excavations, but usually this is precluded because of safety concerns.

6.2. Silt and sand partings

The primary concentration of these occurs towards the top of sub-Division A3 (A3ii as denoted by Standing and Burland, 2006) where they can be very frequent (every 0.1 m) and of thickness up to about 3 cm. Care needs to be taken when taking water content measurements in the close vicinity of these partings as clay adjacent to them will tend to draw in water when total stresses are relieved after sampling. Also, often the water within these partings seems to have connectivity and so, when intercepted, water ingress can occur. The tunnelling case study described by Standing and Burland (2006) illustrates how these features in conjunction with the discontinuities in sub-Division B2 above led to larger ground settlements.

These features were discovered during the ground investigation for the House of Commons car park (Burland and Hancock, 1976) prior to the designation of the London Clay Formation divisions documented by King (1981). There were concerns about water ingress into the base of the excavation from the sand and silt partings (and perhaps potential blow-out) and so to avoid these issues the diaphragm walls were constructed to a greater depth to cut off this horizon (i.e. below A3ii).

Another clear effect is their influence on permeability, resulting in much greater horizontal components than would usually be expected for the LC because of depositional anisotropy. In predicting long-term tunnelling-induced ground movements it has been shown that adopting a much higher factor (e.g. 25) leads to greatly improved predictions of movements (e.g. Avgerinos et al., 2016 when analysing conditions at SJP). Although the permeability of the A3ii sub-layer is higher than most, Hight et al. (2003) in presenting the results from numerous tests report that sub-Division A2 has the greatest permeability of all the LC divisions.

6.3. Claystones

Claystones can be very troublesome in all forms of underground work within the LC (claystones are sometimes referred to more generically as ‘cement-stones’ or from a geological perspective ‘concretions’; the commonly used term ‘claystone’ is used throughout this paper). They can be substantial in thickness (e.g. 0.1 to 0.4 m) and constitute major obstructions and encumbrances when drilling boreholes and bored piles, tunnelling and digging deep excavations.

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Generally, they are not continuous but exist at specific horizons. During the drilling of the 38 boreholes at HP, careful records were made of where claystones were encountered. **Wan and Standing** (2014) compiled these and identified three horizons where there is a much greater likelihood of hitting claystones. These are marked on Fig. 9b: of the 123 claystones encountered, 6.5%, 8.9% and 10.6% were found at about 114.3, 107.8 and 94.8 m aPD respectively (note that 5.39 m has been subtracted from these values to obtain adjusted values that are plotted in the figure). These particular concentrations were located within sub-Division B2 but claystones were found throughout the LC. More comprehensive studies are needed to investigate this further and establish the lateral extent of such specific horizons.

7. Conclusions

Identification of the LC divisions is very beneficial from practical civil engineering perspectives, especially for situations such as tunnelling, deep excavations and cuttings where the works involve ground stress relief. Broad knowledge of the location and characteristics of the divisions can also assist the analysis of works in the LC.

A variety of engineering characterisation techniques have been described and discussed. Compiling w-profiles seems the most effective and cheapest means of identifying the boundaries of the divisions.

A new methodology to this effect is proposed, involving a trend-line for sub-Division A3, using detailed w-profiles from three sites across a 5-km section across London. After setting the base of Division B as a reference level, the w distributions within each division and sub-division are well defined. This is especially the case for A3. Although water content is a state dependent variable rather than a material property, for sub-Division A3, within the LC there seems to be little variation in w values for the sites investigated. The A3 trend-line starts at the top of the sub-division with ~22%, increasing with depth at a rate of 0.43%/m to ~27% at its base, the A3 thickness being about 12 m.

The methodology has been tested against two case studies from **Hight et al. (2003)**, one in central London and the other at Heathrow. Practical suggestions are given to optimise the number of measurements required to compile a sufficiently detailed w-profile to allow identification of the division boundaries.

In compiling the w-profiles from the three sites in this paper, the lateral uniformity of the divisions has been highlighted. Also in setting the reference level, it was necessary to shift the reduced levels by up to 15 m, suggesting that geological processes such as folding and/or faulting have affected the LC.

Personal reflection

Dr Chris King’s work, in particular his seminal 1981 treatise, has made a significant impact in bringing together the disciplines of geology and engineering. Engineers now have a much greater appreciation of the LC and what it contains and what to expect when working in this material. Previously much had been learnt, from an engineering perspective, about geotechnical characteristics of the LC from specific locations and depths. What was not realised is that these can be connected together on a much wider global scale, Chris King’s geologically inferred divisions providing the key link.

It was a delight, privilege and honour to have worked and interacted with Chris. I miss him.

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