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Geotechnical characterisation of alluvial soils used to contain industrial liquid wastes

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Abstract A wide range of geotechnical tests has been carried out to characterise an extensive alluvial deposit that is used as containment for a landfill in which liquid wastes are disposed. The landfill covers an area of 357 ha. Data obtained from the current and previous studies have been used to explore the variability of the properties of two alluvial layers. The upper layer is predominantly silty clay, while the lower layer contains a much wider range of particle sizes. Variations in hydraulic conductivity covering seven orders of magnitude have been measured in both layers. The selection of appropriate parameters for contamination migration studies is discussed.

Keywords Landfill · Clay · Alluvial soils · Index properties · Hydraulic conductivity

Résumé Une large gamme d'essais géotechniques ont été mis en œuvre pour caractériser une formation alluviale étendue destinée à servir comme barrière pour une décharge dans laquelle sont stockés des déchets liquides. La décharge couvre une surface de 357 ha. Des données fournies par les études passées et actuelles ont été utilisées pour étudier la variabilité des propriétés de deux couches d'alluvions. La couche supérieure est majoritairement une argile silteuse tandis que la couche inférieure présente une granulométrie plus étalée. Des variations de la perméabilité couvrant sept ordres de grandeur ont été déterminées dans les deux couches. On discute de la détermination des paramètres pertinents pour les études de migration des contaminants.

Mots clés Décharge · Argile · Sols alluviaux · Propriétés · Perméabilités

Introduction

Landfill facilities can provide economical waste management solutions. Design, construction and management of landfill facilities have been significantly improved to minimise their impact on groundwater quality over the last couple of decades. However, older landfill sites still remain as sources of groundwater contaminants. The site discussed in this paper is the Castlereagh Waste Management Centre, which is located 50 km to the west of Sydney, Australia. It was selected after intensive investigation of sites throughout the Sydney region and other areas up to 250 km from the centre of Sydney. It was opened as a secure landfill in 1974, primarily as a temporary repository site for the disposal of industrial liquid wastes. Before the opening of the site, these wastes were not disposed of in an environmentally sound manner (Waste Service NSW 1996). The site has accepted a wide range of industrial liquid and slurry wastes, but not those considered highly toxic and environmentally intractable. Table 1 shows a quantitative breakdown of wastes disposed of at the site in a typical year. Since the late 1980s, most of the liquid wastes have been pre-treated in a liquid waste treatment plant, removing most organic contaminants, before disposal as slurry. The site was closed in August 1998. In its 24-year operation over 1 million tonnes of liquid and slurry wastes have been deposited.

The site occupies an area of 357 ha on a low ridge and abuts forest to the northwest and southwest, a prison to the northeast and elsewhere semi-rural housing. A general site plan is schematically shown in Fig. 1. The site was expanded in stages in order to dispose of the waste and as a result 13 areas were filled. A simplified soil profile is shown schematically in Fig. 2. Waste cells were excavated in the clay layer and filled with domestic refuse, followed by the liquid waste that filled up to one third of the cell volume. The cells were then covered by the excavated soil.

The water table lies in the gravel layer and during the site operation water samples have been collected from numerous monitoring bores, some of which are indicated on Fig. 3, and analysed for contamination. A number of previous studies have reported that while many of these bores have shown little change in groundwater quality, contamination has been detected in some on-site locations. The concentrations of some of the contaminants detected in the bores are significant. For example, Woodward-Clyde (1994) reported that 47,000 µg/l of methyl ethyl ketone was detected in an on-site monitoring bore in Area 8 (Table 2). This indicates that the clay layer cannot be relied on to contain organic wastes securely. Contamination of the groundwater by heavy metal contaminants has not been detected even though significant quantities of these materials are also present in the waste. It is well known that heavy metal species are relatively immobile and their transport in soils is slow. Laboratory studies have shown that the transport of chromium and zinc in the Londonderry Clay is highly retarded due to the strong sorption of these species to the Clay (Airey and Carter 1995).

Table 1 Estimated quantities of liquid wastes disposed in a typical year before 1988 (courtesy of Waste Service NSW)

Waste	Estimated tonnes	Estimated percentage
Acids	2,968.5	7.07
Alkalis	6,267.7	14.94
Inert wastes	528	1.26
Inorganic chemicals	986.7	2.35
Organic chemicals	1,044.2	2.49
Organic solvents	4,889.2	11.64
Oil/water mixture	9,269.7	22.08
Pesticides	33.2	0.08
Paints, resins, inks	5,108.2	12.16
Plating and heat treatment	25.3	0.06
Putrescibles	5,400	12.86
Reactive chemicals	110.4	0.26
Textile and tannery	87.5	0.21
Washwaters	5,262.2	12.53

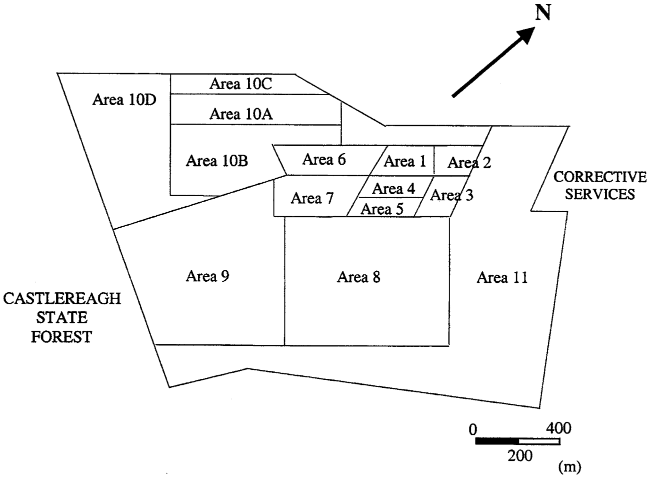


Fig. 1 A schematic site plan of the Castlereagh liquid waste depot

The Rickabys Creek Gravel outcrops in creeks to the northwest and southeast of the site, about 1,000 m from the site boundaries. Because of the low conductivity of the gravel layer and low hydraulic gradients, water movements have been difficult to detect; conservative estimates of contaminant transport suggest that it should take over 100 years for contaminants to reach the site boundaries (Woodward-Clyde 1994) and many hundreds of years to reach the creeks. The groundwater also tends to be highly saline and generally unsuitable for human use.

The data available suggest that the site was well chosen and is not responsible for any current environmental problems. Nevertheless, local concerns related to

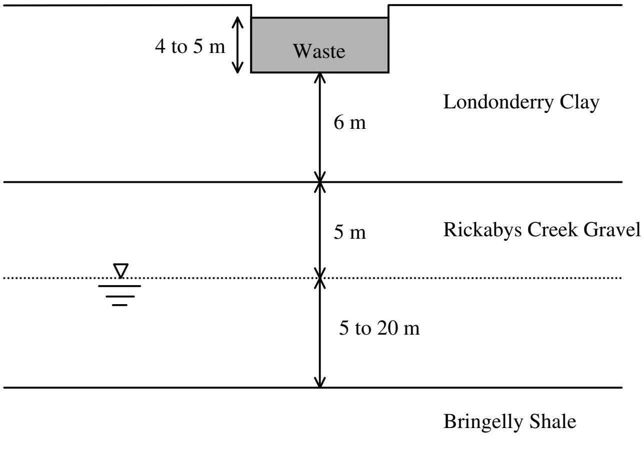


Fig. 2 A typical geological section through a waste cell

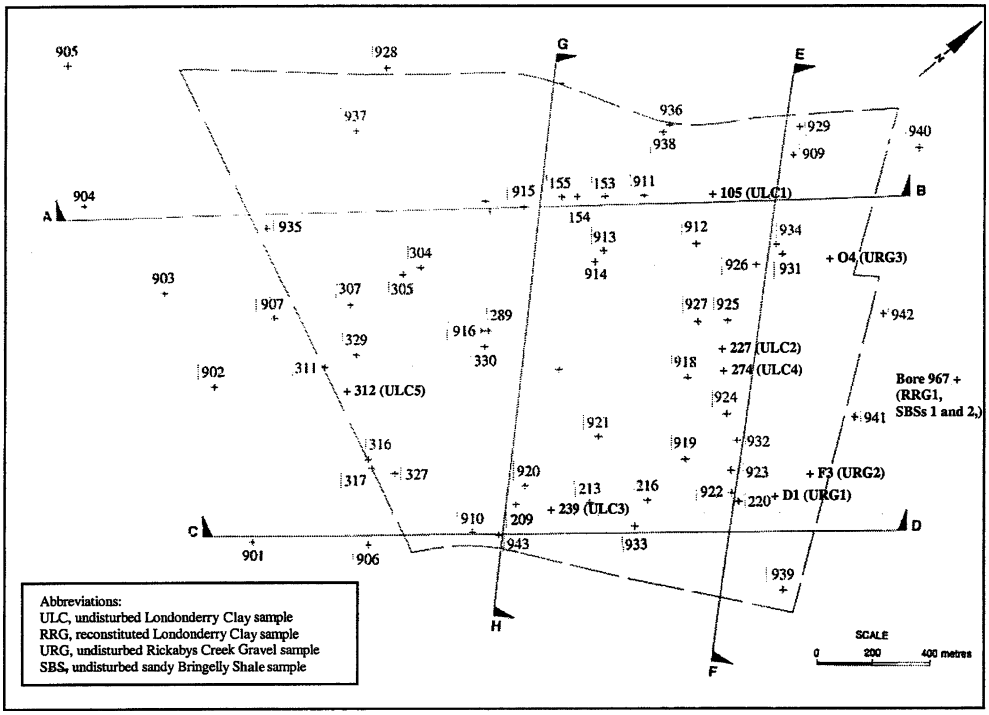


Fig. 3 Locations of monitoring bores and cross-sectional geological profiles

a range of apparently unrelated environmental health issues and a change in government philosophy led to the closure of the site in 1998.

To predict the long-term environmental integrity more information is needed on the soil properties influencing contaminant transport, such as conductivity, sorption, diffusion, dispersion and biodegradation, to complement the hydrological studies. The heterogeneity of the clay and gravel layers resulting from the alluvial deposition process is also an important factor which influences the contaminant transport at the site. The influence of the heterogeneity on hydraulic conductivity and other properties has only been investigated for a few aquifers (e.g. MacIntyre et al. 1998) and none with clay contents similar to those at the Castlereagh site. Many geotechnical investigations have been carried out at the site as well as reviews of the data. In this paper some new data are presented and these, together with existing data, are used to explore the heterogeneity of the site and its influence on the hydraulic conductivity.

Geology and groundwater

Geology

Existing geological studies of the western Sydney area including the site area were summarised by Jones and Clark (1991). The site lies in the Penrith Basin which contains a Tertiary alluvial sequence, comprising the Londonderry Clay and the Rickabys Creek Gravel. These two layers are apparently undifferentiated geological units, marked by an increase in coarseness of grain size with increasing depth. A generally thin Quaternary sandy surficial layer overlies the clay layer at the site. The sandy layer has been widely disturbed and was routinely removed during waste cell construction. Cross-sectional and longitudinal profiles of the geology at the site are shown in Figs. 3 and 4a–d. Figure 3 also shows the sampling locations of specimens tested for measurement of hydraulic conductivity. Details are discussed below.

The clay layer has a varying thickness ranging from 5 to 16 m as determined from borehole data; its average thickness is estimated to be 10 m (Jefferies 1985). The clay indicates evidence of laterisation and is heavily iron-stained, down to a depth of about 8 m. The clayey sediments are generally stiff to hard and the stained regions are partially cemented (Dames and Moore 1991). The colours of the soil range from brown to grey with redbrown staining associated with iron concentrations. The Londonderry Clay is typically categorised as a sandy to silty clay containing some fine to coarse sand particles and a trace amount of fine to coarse gravels. Sand dominant zones are known to be present in the clay layer in Areas 2, 8, 9 and 11. It has been suggested that these sandy zones are associated with old river courses (Golder Associates 1991a). The continuity of these zones is uncertain, but their presence suggests the possibility of preferential water flow paths and these

Table 2 Organic compounds and their maximum concentrations detected under the waste cells in the groundwater at the Castlereagh depot (Woodward-Clyde 1994)

Detected compounds	Concentration (µg/l)
Monocyclic aromatics	
Benzene	860
Toluene	8,900
Ethylbenzene	670
m- and *p*- Xylene	1,300
o-Xylene	680
Isopropylbenzene	30
n-Propylbenzene	24
1,2,5-Trimethylbenzene	200
1,2,3-Trimethylbenzene	170
p-Isopropyltoluene	24
Oxygenated compounds	
Methyl ethyl ketone	47,000
Methyl isobutyl ketone	3,400
2-Hexanone	120
Halogenated compounds	
Chloromethane	1,100
Chloroethane	270
1,1-Dichloroethene	52
1,1-Dichloroethane	61
cis-1,2,-Dichloroethylene	7.5
Chloroform	68
1,1,1-Trichloroethylene	21
Carbon tetrachloride	15
Trichloroethylene	95
1,2-Dichlorobenzene	160
1,3-Dichlorobenzene	12
1,4-Dichlorobenzene	33
Phenols	
Phenol	160
2-Methylphenol	420
4-Methylphenol	2,000
2,4-Dimethylphenol	170
2,4-Dichlorophenol	140
4-Chloro-3-methylphenol	150
Polynuclear aromatics	
Naphthalene	81
2-Methylnaphthalene	2.2
Phthalate esters	
Dimethyl phthalate	2.6
Diethyl phthalate	230
di-n-Butyl phthalate	6.4
di-n-Octyl phthalate	19
bis-(2-Ethylhexyl) phthalate	32
Nitroaromatics and cyclic ketones	
Acetophenone	44
Isophorone	15
Nitrobenzene	11

areas have tended to be where contamination of the underlying groundwater has been detected. It is known that complicated stratifications can be formed as a result of meandering river courses because of cyclic processes of cutting and filling previous deposits (e.g. Palmer 1996). Because of these processes, coarser grains can accumulate in deep channel incisions and later be filled with fine particles when floodwaters become slack. The

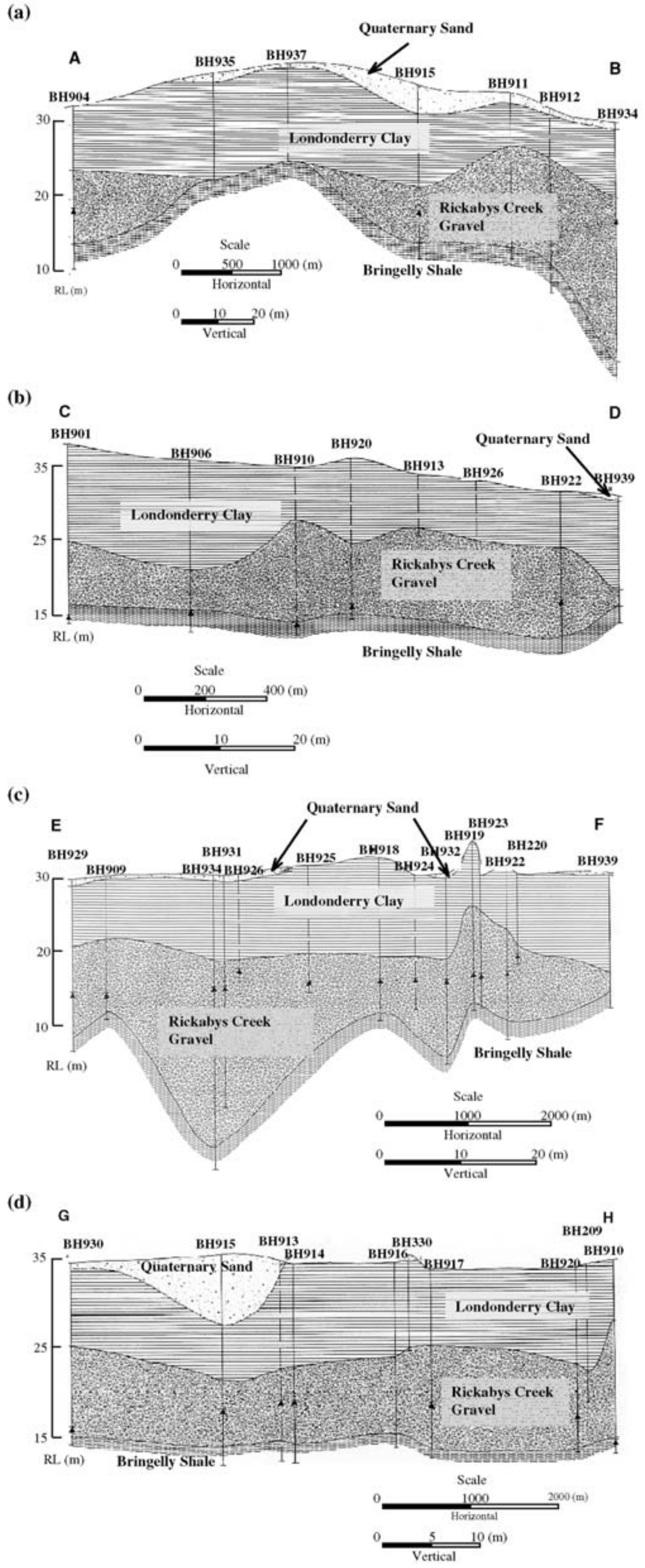


Fig. 4 **a** Geological section A–B. **b** Geological section C–D. **c** Geological section E–F. **d** Geological section G–H

resulting fine-grained sand laminae are generally thin and not regionally extensive.

The thickness of the Rickabys Creek Gravel ranges from 0 to 20 m, averaging 10 m. The layer is inclined to pinch out to the southwest side of the site where the Londonderry Clay directly overlies the Bringelly Shale and to thicken up to 20 m to the north. The gravel layer locally contains a large amount of cobbles and boulders (Dames and Moore 1991) and has been used as a gravel resource to the north of the site.

The Tertiary sequence is underlain by the highly weathered palaeo-surface of the Triassic Bringelly Shale. The thickness of the Shale at the site is unknown, but is believed to be of the order of 150 m (Dames and Moore 1991). The Shale belongs to the Wianamatta geological group, which is dominated by argillaceous rocks. The Shale's origins are as a coastal alluvial plain sequence, grading from a lagoonal-coastal marsh sequence to alluvial plain sediments towards the top, resulting from seawater transgression and regression (Herbert 1979). The clay-dominated sediments have been highly compacted creating a strongly laminated structure with low porosity, $n = 0.1$. The Shale contains other sedimentary rocks including siltstone, sandstone, coal and tuff (Jones and Clark 1991; Dames and Moore 1991) and some of these have been detected at the site.

Groundwater

The groundwater levels at the site have exhibited a rising trend since the commencement of landfill operations. This trend is believed to result from rainwater infiltrating into the ground due to the waste disposal operations. The nature of the clay materials and the flat topographical character of the site make effective management of surface water drainage and re-vegetation programmes difficult, causing waterlogging problems (Dames and Moore 1991). Slightly lower groundwater levels are observed on the northwestern and northeastern sides of the site and are possibly related to the old river courses that were mentioned earlier.

Groundwaters in the Penrith Basin, which include the groundwater at the site, are saline (Old 1942). The salinity is considered to originate from the Bringelly Shale (Emerson and Hallett 1994). Because of the salinity, the local groundwater is not utilised in the area. The local groundwater to the south of the site is highly saline with electrical conductivities (EC) up to 25,000 μS/cm whereas to the northeast and east of the site the groundwater becomes less saline (e.g. IT Environmental 2001). The pH values show a similar pattern to the EC values with values as low as 4 to the south and up to 7 to the northeast of the site. A typical stiff-diagram for the major ions in the groundwater is shown in Fig. 5. The up-coning pattern shown in Fig. 5 is seen throughout the site. The amount of Na^+ shown as a broken line indicates that this ion is the dominating univalent cation. The most dominant anion is Cl^-. The second most prevalent cation is Mg^{2+}, followed by Ca^{2+}. The groundwater contains essentially no K^+ or SO_4^{2-}.

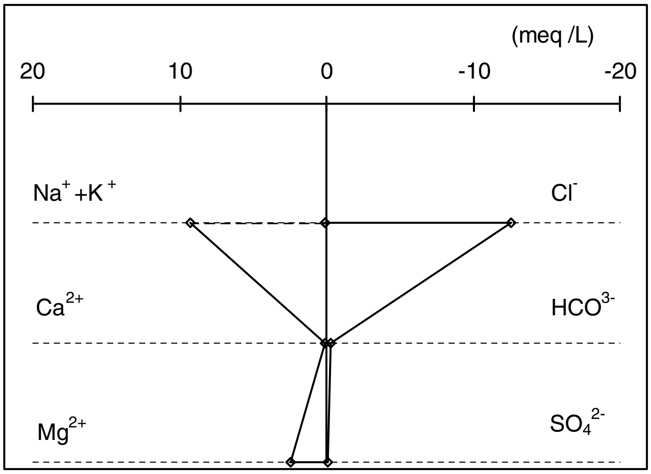


Fig. 5 A typical Stiff diagram pattern for the groundwater chemistry at the site

Soil mineralogy

X-ray diffraction and energy dispersive X-ray spectroscopy methods have been used to identify the major minerals and in particular the clay minerals present in the different soils. For both the clay and gravel layers these have shown that quartz and kaolin are the dominant minerals. A typical diffraction pattern for the clay fraction (<2 µm) of a Londonderry Clay specimen is shown in Fig. 6. The clay fraction consists mainly of kaolinite with some illite and quartz. In other specimens montmorillonite and illite-montmorillonite mixed layer clays have been detected, but in all cases kaolin has been the dominant clay mineral. The gravel shows a similar pattern with peaks for kaolinite and illite being evident (Itakura 1999). Haematite, titanium oxide and goethite have been found to be present at a trace level and in some cases high iron and manganese contents have been observed, consistent with the laterisation of the upper clay. Both layers have similar low organic carbon contents of approximately 0.0015. A mean cation exchange capacity of 15.4 cmol/kg was measured for the clay layer.

The Bringelly Shale underlies the alluvial deposits. Little data are available regarding the Shale at the site, however its properties have been investigated at a number of quarries in the region. The claystone, which is the dominant rock type of the Shale, typically comprises

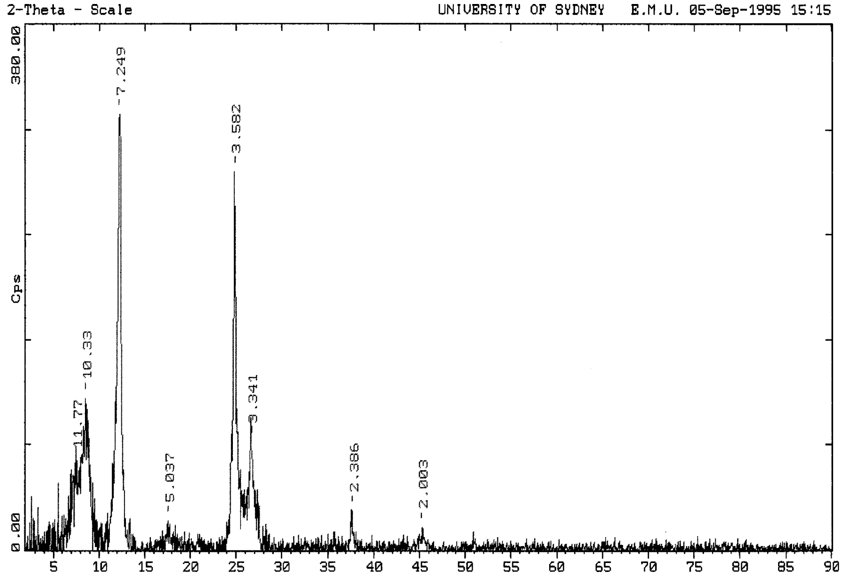


Fig. 6 A typical XRD analysis result for the Londonderry Clay

55% clay minerals and 45% quartz. The clay mineralogy changes with the degree of weathering as shown in Table 3. Illite-montmorillonite mixed layer clay is the dominant clay mineral in the Shale and this trend becomes more pronounced as the weathering process progresses. These characteristics suggest that the Shale may be inclined to swell and be susceptible to changes in pore water chemistry. Properties of the other rock types in the Shale are unknown, but are not believed to be important because these rocks are of limited lateral and vertical extent.

Particle size analyses

Particle size analyses have been performed for many depths and locations across the site. Typical particle size distributions for the clay and gravel layers in Area 8 are shown in Fig. 7. Previously collected data are classified into the two geological groups and are then averaged every 2 m. The data show considerable variability. In some cases, high percentages of sand and gravel are present, indicative of sandy patches within the

Table 3 Clay minerals of Bringelly Shale samples (William and Airey 1999)

Mineral	Fresh (%)	Extremely weathered (%)
Kaolinite	30.0	28.2
Mixed layered clay (illite + montmorillonite)	34.0	53.3
Montmorillonite	–	2.5
Illite	17.7	11.9
Chlorite	18.3	4.1

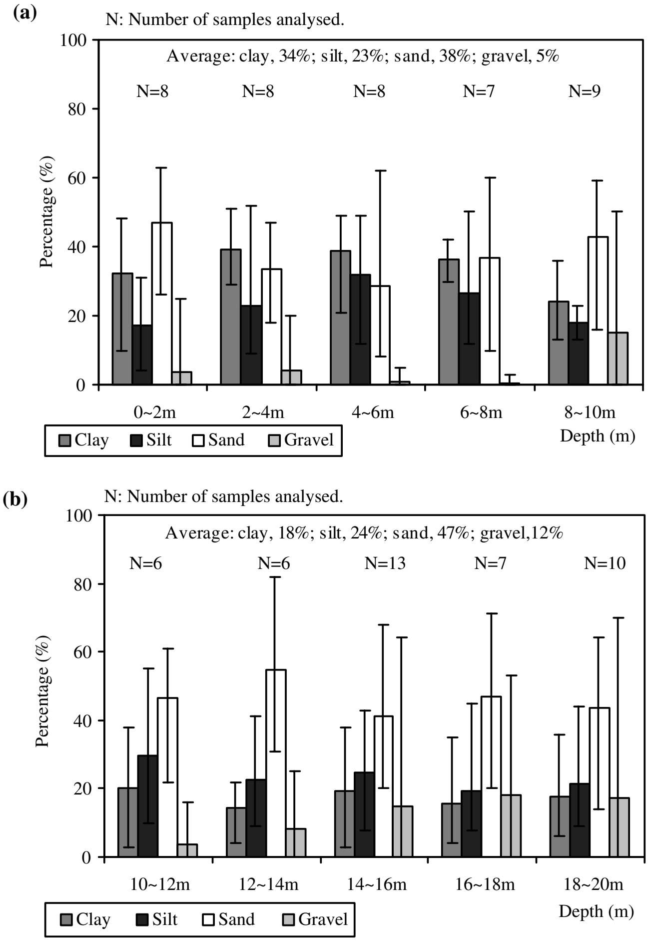


Fig. 7 **a** The particle size distribution patterns of Londonderry Clay in Area 8. **b** The particle size distribution patterns of Rickabys Creek Gravel in Area 8

Londonderry Clay. From the data in Fig. 7 it appears that clay particles slightly decrease and other coarser particles increase with depth, in agreement with the suggestion that the clay and gravel layers are undifferentiated and marked only by an increase in coarseness of grain size with increasing depth.

It may be anticipated that the type and percentage of finer soil particles will have the greatest influence on the properties that are of most interest for contaminant transport, that is the conductivity and sorption. Data showing the clay contents as a function of depth below the surface are presented in Fig. 8.

In the Londonderry Clay layer clay contents vary from 19 to 72% with a mean of 46%. Borehole logs indicate a predominantly clay layer with occasional sand lenses; however even within the clay units there are significant variations in the contents of sand and coarser particles.

In the Rickabys Creek Gravel layer clay contents vary from 3 to 39% with a mean of 23%. There is only a very slight trend for clay content to reduce with depth in both layers.

Particle size analyses for crushed Shale samples have been reported by Golder Associates 1981. These have indicated clay contents of over 50% for claystone and a fines content (<75 μm) of 34% for a sandstone member in the Shale.

Consistency limit tests

The results of consistency limit tests for Londonderry Clay and Rickabys Creek Gravel are summarised by the relation between plasticity index (I_P) and liquid limit (w_L) in Fig. 9, respectively. The data points for the Londonderry Clay are located parallel to and slightly above the A line. There is a wide range in the data with I_P values from 10 to 80. When the data are broken down into areas of the site shown on Fig. 1 there is no apparent difference from area to area (Itakura 1999). The data indicate that the Londonderry Clay would be categorised as CL, CH and occasionally SC in the Unified Soil Classification System. It is interesting to note that the data are also consistent with a relation observed by Young and Parmer (1999) to apply to over 300 sites within the Sydney region. The Rickabys Creek Gravel specimens have a lower plasticity and a smaller variability than the Clay. Considering that the Gravel layer contains a significant amount of coarse material (>425 μm) that is excluded from the consistency limit tests the Gravel may be categorised as SC, GC or occasionally CL.

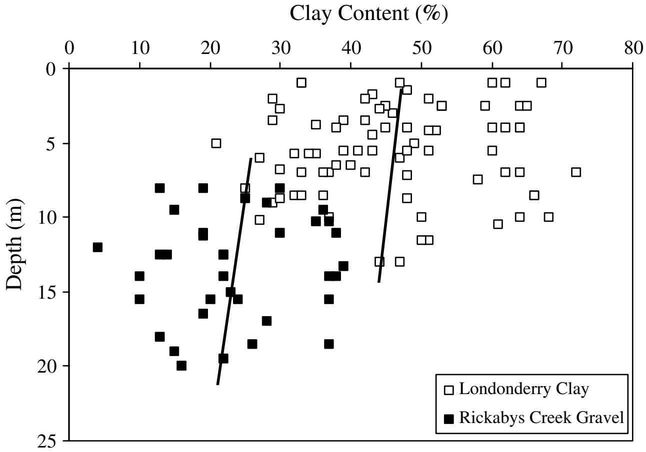
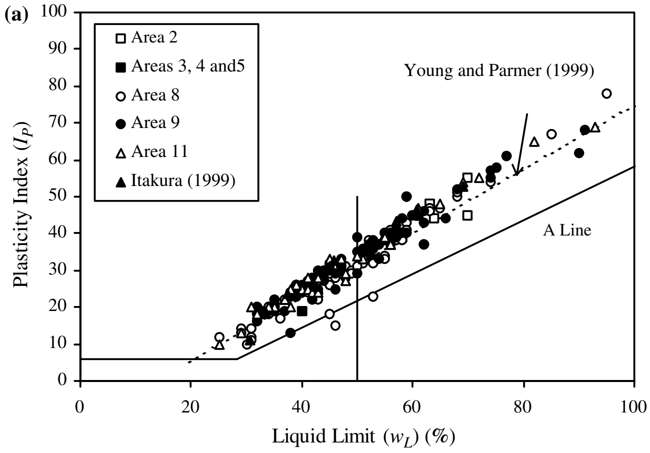


Fig. 8 Influence of depth on clay content



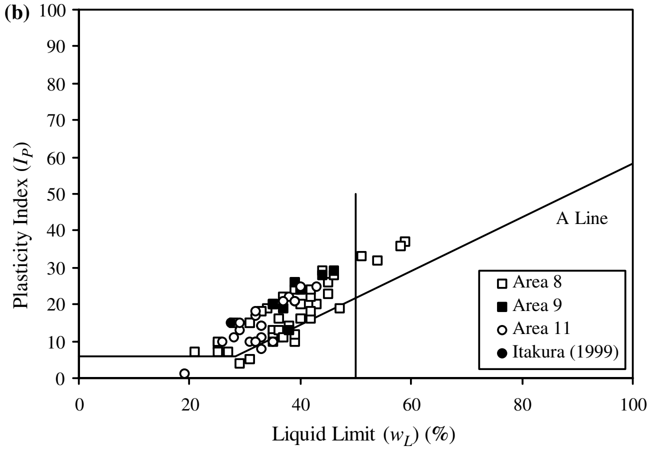


Fig. 9 a The consistency limit values of the Londonderry Clay. **b** The consistency limit values of the Rickabys Creek Gravel

Possible reasons for the variability in index properties are differences in grading and mineralogy. Figure 10 shows the relationship between I_P and clay content. There is a clear trend for I_P to increase with clay content; however, there is also considerable variability in the data. The ratio of I_P to clay content is known as the

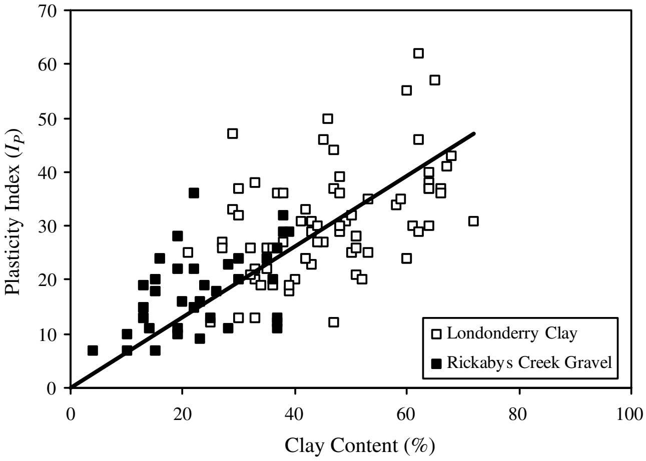


Fig. 10 Relation between plasticity index and clay content

activity and is related to the mineralogy. An average activity of 0.65 is indicated, which is typical of a kaolin/illite soil, as is the location of the data on the plasticity chart (Fig. 9). Activity values range from 0.35 to 2, apparently indicating a range of minerals, but this is not supported by the X-ray data, which although limited show little variation. Figure 11 shows that I_P reduces with depth, even though the clay content remains constant. This may be related to the laterisation that has affected the upper 8 m of the soil. High Fe contents, up to 5% of the soil, have been measured and it is known that the associated sesquioxides can influence the index parameters (Gidigasu 1976).

For the Bringelly Shale, only a limited number of consistency values are available. In other outcrops the I_P value of the Shale increases from 10 to 40 as the degree of weathering increases (e.g. William and Airey 1999). Data for the Shale at the site (Golder Associates 1979) cover a similar range suggesting that the Shale is extremely weathered at the surface, as also reported by Emerson and Hallett (1994). The consistency limit difference between the fresh and weathered samples results from the alteration of major minerals of the Shale during weathering.

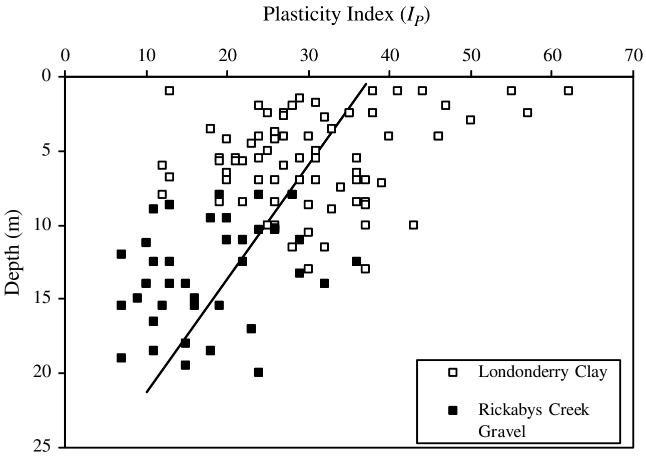


Fig. 11 Influence of depth on plasticity index

In-situ moisture content and state

Undisturbed samples collected for this study indicated void ratios in a small range from 0.45 to 0.55 for both soil layers. If the soil were saturated this would imply moisture contents of 17–20%. Several hundred moisture content measurements have been taken during the site's operation. These show moisture contents varying from 7 to 25%, with a mean of about 16%. It appears that the void ratio is reasonably constant through both soil layers and the lower moisture content values reflect the variable saturation above the water table. In the current study samples obtained from the upper 5 m of the clay layer had degrees of saturation that varied from 60 to 100%.

One-dimensional compression tests of reconstituted and undisturbed samples have indicated overconsolidation ratios of between 3 and 9 (Itakura 1999). The geological age and history of these Tertiary deposits is not known accurately, but it is believed that they have not experienced significant overburden.

Saturated hydraulic conductivity

Over 100 conductivity measurements have been recorded from laboratory and in-situ tests. A chart summarising these measurements is shown in Fig. 12. These measurements have been obtained from rising and falling borehole water levels and indirectly from 1D consolidation tests. Additional tests on reconstituted and undisturbed cores were conducted in the present study to try to obtain a better understanding of the factors influencing the conductivity. Tests were carried out in a triaxial cell to directly measure the saturated hydraulic conductivity (k) of undisturbed and reconstituted samples. Results from these tests are included in Fig. 12.The sampling locations of the specimens used for the conductivity measurement are described in Table 4. The bore locations are indicated in Fig. 3.

Reconstituted Londonderry Clay (RLC) samples were obtained from various locations in Area 10 during the excavation of waste cells over a 7 year period. Five undisturbed Londonderry Clay samples (ULC) were collected from Areas 2, 9 and 11. One reconstituted sample (RRG1) and three undisturbed samples (URG1, 2 and 3) of the Rickabys Creek Gravel were collected

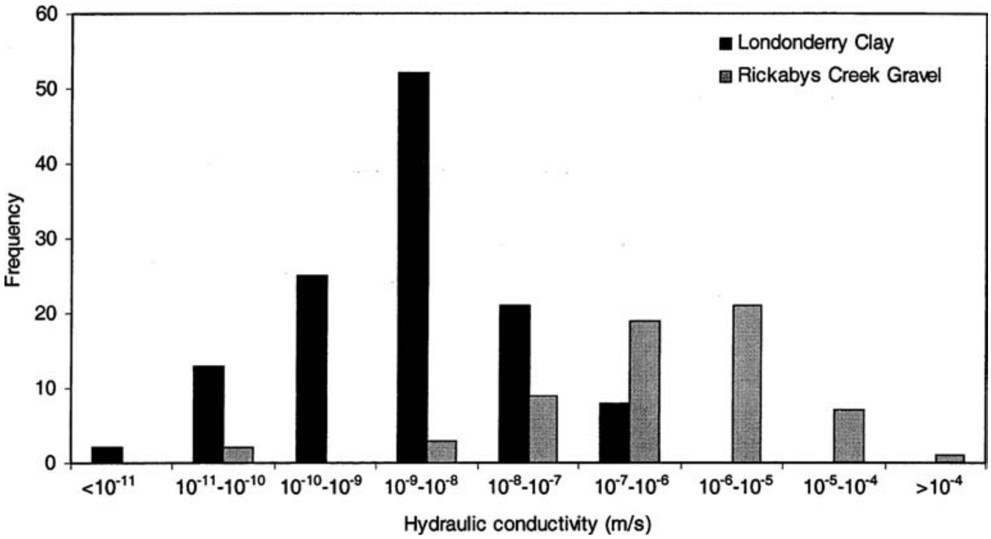


Fig. 12 Summary of hydraulic conductivity measurements

from Area 11. Four Bringelly Shale samples were tested. Two highly weathered sandstone samples, a minor constituent of the Shale, were obtained from Area 11 (SBS1 and SBS2) near the Gravel/Shale boundary. In most locations bores extended into the Shale showed a dark grey claystone. Because core recovery in the Shale was poor, claystone block samples of Bringelly Shale were obtained from a landfill located 15 km to the southwest of the Castlereagh site. Two samples (CBS1 and CBS2) were prepared.

Method

Samples were saturated for 24 h under an effective confining stress of 50 kPa and back pressure of 500 kPa, followed by a B-value test to confirm the saturation. The samples were consolidated in stages, to a range of effective confining stresses. When consolidation was completed at each stage, a k value was measured. This was achieved by providing equal and opposite flow rates to the top and bottom drains and measuring the differential pressure. The flow was applied in both downward and upward directions and in some cases water was pumped at various flow rates in order to investigate the validity of Darcy's law. The conductivity was calculated from:

$$k = \frac{QH\gamma_w}{A\Delta P} \tag{1}$$

where Q is flow rate, A is area of the sample, H is sample height, ΔP is pressure difference, γ_w is the unit weight of water.

Table 4 Sampling location of specimens tested for hydraulic conductivity measurement

Sample No.	Bore No.	Area No.	Depth (m)
Londonderry Clay			
RLC	NA	10	5.00–6.00
ULC1	105	2	6.50–6.65
ULC2	227	11	5.30–5.54
ULC3	239	11	7.38–7.46
ULC4	274	11	8.35–8.45
ULC5	312	9	11.88–11.95
Rickabys Greek Gravel			
RRG1	967	11	13.00–18.00
URG1	D1	11	11.00–11.50
URG2	F3	11	9.00–9.50
URG3	O4	11	7.00–7.50
Bringelly Shale			
SBS1 and SBS2	967	11	20.45
CBS1 and CBS2	NA	NA	8.00

NA not applicable

Londonderry clay

Figure 13a shows the relation between conductivity and void ratio for RLC samples. The data fall into a small band despite the fact that the samples were collected from various locations. The soil with the higher void ratio was obtained close to the surface and had a higher clay content than the others. As the in-situ void ratio is about 0.5 a conductivity of between 1.0×10^{-11} and 4.0×10^{-11} m/s can be expected from these tests.

The void ratios of the reconstituted samples are outside the range of previous studies for reconstituted kaolinitic clays, but lie close to an extension of the relation given by Mesri and Olson (1971) for kaolinitic clay samples with similar consistency limit values.

A wide range of conductivities, from 1.08×10^{-11} to 1.28×10^{-7} m/s, was measured for the undisturbed

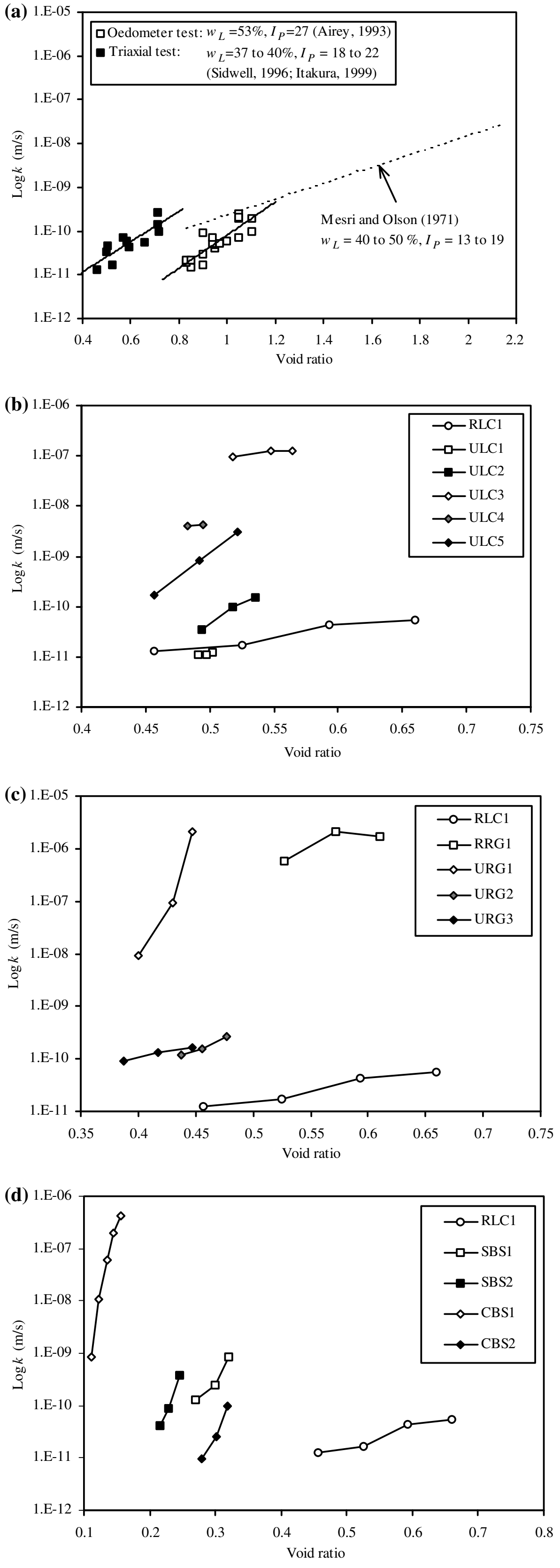


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Fig. 13 **a** Relation between void ratio and *k* for the reconstituted Clay samples. **b** Relation between void ratio and *k* for the undisturbed Clay samples. **c** Relation between void ratio and *k* for the Gravel samples. **d** Relation between void ratio and *k* for the Shale samples

samples (ULC) as shown in Fig. 13b. Results for one of the reconstituted samples (RLC1) are shown for comparison. The effective confining stresses were increased from 50 to 400 kPa to cover the possible in-situ stress states and this resulted in void ratios that ranged from 0.46 to 0.56. Samples ULC1, 2 and 5 had gradings and clay contents that could be considered representative of the Clay layer, and similar to the reconstituted samples. Sample ULC1 is similar to the reconstituted sample (clay content of 68% compared to 40%). For samples ULC2 and ULC5 the conductivity dropped rapidly as the confining stress increased, indicating fracture flow and the closing of micro-fissures in response to increasing stresses. This is believed to be an artefact of the sampling process as there is little reported evidence of fracturing in-situ, but attempts to trim the stiff clay from blocks in the laboratory always led to fracturing. Higher *k* values were measured for samples ULC3 and ULC4 that had higher sand contents. Sample ULC4 was obtained from a sand lens with 70% sand and 20% clay, an extreme of the reported gradings. However, sample ULC3 with only 40% sand gave a much higher conductivity. This was related to the distribution of sand in the samples. In ULC4, sand was uniformly distributed, but in ULC3 there was evidence of a sand filled root hole.

Table 5 shows comparison of field measured *k* values with laboratory measured *k* values of the ULC samples. The field-measured values have been obtained from bores adjacent to the sampling locations of the ULC samples (within a distance of 10 m). The table indicates that the field *k* values are generally greater than the laboratory measured values. The only exception was sample ULC3, which, as discussed above, contained a sand filled root hole. As has been widely reported in other studies (e.g. Daniel 1984) the laboratory measured *k* values are lower than those measured in the field. Laboratory values are suspect because they may miss hydraulic features such as fissures and root holes, whereas the interpretation of the field data is complicated by differences in sample saturation and the heterogeneity of the soils. Because of the heterogeneity of the soil and the different volume of soil involved in the laboratory and field tests, differences between field and laboratory values are inevitable.

From consideration of the laboratory data, it appears that the conductivity of most of the Londonderry Clay lies in the range of 1.0×10^{-11} to 1.0×10^{-10} m/s and only in the sand lenses does this increase to 4×10^{-9} m/s. The

Table 5 Comparison between laboratory and field *k* measurements for the Londonderry Clay

Sample	*k* in the laboratory (m/s)	*k* in the field	*k* (field)/*k* (lab)
ULC1	1.1×10^{-11}	1.30×10^{-9} m/s (1–6.7 m) (Golder Moss Associates 1974)	118
ULC2	3.6×10^{-11}	1.26×10^{-6} m/s (2.05–5.5 m) (Dames and Moore 1996)	35,000
ULC3	9.4×10^{-8}	3×10^{-8} m/s (2.0–8.4 m) (Golder Associates 1979)	0.32
ULC4	4.1×10^{-9}	5×10^{-8} m/s (2.0–8.3 m) (Golder Associates 1979)	12.1
ULC5	1.7×10^{-10}	3×10^{-9} m/s (1.0–5.5 m) (Golder Associates 1979)	17.6

field data show an approximately log-normal distribution with a mean of 3×10^{-9} m/s, which correlates with the conductivity in the sand lenses. This suggests that the sand lenses may be more widespread than is evident from the available borehole logs. The field tests involve predominantly lateral flow, whereas flow in the Londonderry Clay is in a predominantly vertical direction; the vertical connection between sand lenses is largely unknown. It should also be noted that in recent years investigation has been biased towards areas where groundwater contamination has occurred.

Rickabys Creek Gravel

Figure 13c shows the relation between conductivity and void ratio for reconstituted and undisturbed Gravel samples. The three nominally undisturbed samples (URG1, 2 and 3) had similar gradings with a wide range of particle sizes (70 to <2 μm) and clay contents from 10 to 20%. The reconstituted sample (RRG1) was 80% sand and 20% fines. Because of the presence of cobbles, relatively thick sample tubes were necessary to obtain "undisturbed" samples. In the case of sample URG1, some damage to the tube occurred and this appears to have fractured the sample and is believed to explain the fracture flow type of behaviour. The other two undisturbed samples give very similar conductivities of 1.0×10^{-10} m/s. The reconstituted sample has a conductivity of 1.0×10^{-6} m/s, four orders of magnitude greater. The most significant difference appears to be the fines content, which varies from 20% for RRG1 to 40% for URG2 and 3. The *k* values for the undisturbed samples are significantly lower than the corresponding field values, 1.4×10^{-6} m/s for URG2 and 3.1×10^{-5} m/s for URG3 (Golder Associates 1991b). Borehole logs indicate a uniform soil layer and data from gradings indicate a mean fines content of around 40%, similar to the undisturbed samples. However, the lowest field conductivity data are two orders of magnitude greater than the laboratory values, suggesting that there must be significant differences in fines content and considerable heterogeneity in the Gravel layer. The sensitivity of the Gravel layer's conductivity to particle grading is not unexpected, as previous attempts to correlate these properties have proven difficult (e.g. Hatanaka et al. 2001; MacIntyre et al. 1998).

Bringelly shale

The variations of conductivity with void ratio for the Shale samples are shown in Fig. 13d. All samples show a marked decrease in conductivity with increasing confining stress, indicating flow through fissures. One of the claystone samples (CBS1) had high conductivities. This was a result of swelling during saturation, which occurred under an effective stress of 50 kPa. During free swell tests in water, volume strains of up to 8% have been measured, followed by disintegration of the Shale (William and Airey 1999). The second claystone sample (CBS2) was saturated under an effective stress of 400 kPa to minimise swelling and this resulted in conductivities 3 orders of magnitude lower. The claystone is characterised by a laminated structure and the limited porosity is mostly in the form of micro-cracks that are more pronounced with weathering and open up on swelling (William and Airey 1999).

The laboratory tests indicate conductivities of at least 1×10^{-10} m/s in the intact rock. The extent of fissuring in the Shale is unknown, but the units tend to be massive. It is therefore surprising that the laboratory values are much lower than the few field *k* values previously reported, which range from 1×10^{-9} to 1×10^{-7} m/s. In most of these field tests time was allowed for bore saturation, which might have enabled the Shale to swell and possibly to disintegrate, which could result in an over-estimate of the in-situ conductivity. In previous hydrogeological and contaminant migration studies it has been assumed that the Shale is an aquitard. However, there is little information on the extent of sandstone, the influence of weathering at the Shale surface and the extent of fracturing in the rock.

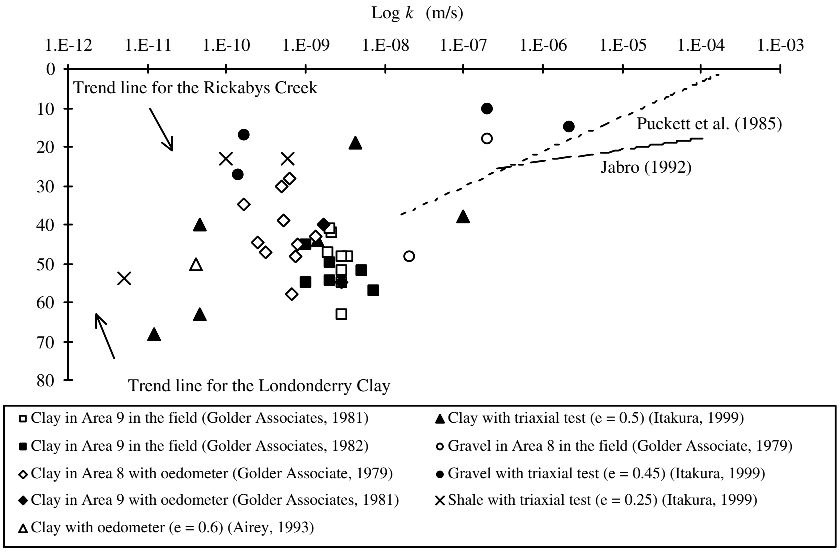

Fig. 14 Relation between *k* value and clay content

Correlations with conductivity

Figure 14 shows the relation between clay content and hydraulic conductivity for all the laboratory tests conducted in this and previous studies. There is a general trend for *k* to decrease with an increase in clay content, as might be expected, but no useful correlation is evident. Attempts were made to correlate the *k* values to other soil properties such as plasticity index, but none produced useful correlations. In other studies relationships between clay content and *k* have been reported; two of these are shown on Fig. 14. It has been noted above that the mineralogy is similar throughout the site and therefore differences in conductivity can be related to differences in the shape of the grading curve and structure. For coarser grained soils many relationships have been proposed between grading and conductivity, but particularly when gravel sized particles are present, these correlations do not appear to be useful (e.g. Hatanaka et al. 2001)

Summary

Consideration of the type and nature of the sediments suggests that the alluvial deposit is comprised of an alluvial fan, Rickabys Creek Gravel, overlain by an alluvial plain deposit, Londonderry Clay. Both layers have similar mineralogies but are characterised by considerable heterogeneity that is evident in variations in grading, limit indices and hydraulic conductivity. In both layers measured hydraulic conductivities varied by seven orders of magnitude.

Predictions of contaminant transport are strongly dependent on the hydraulic conductivity and for the Clay layer in particular this has been found to be very dependent on slight changes in the physical properties. A further complicating factor is that the in-situ tests tend to measure lateral flow and do not give an indication of the vertical connection between sand lenses. A range of hydraulic conductivities can be proposed for vertical flow from 10^{-10} to 10^{-8} m/s depending on the assumed degree of vertical connection between the sandier zones. The observation of groundwater contamination in some boreholes in the underlying Gravel layer indicates that in some locations the effective conductivity is at the high end of this range.

The *k* values in the clay layer imply that advection and diffusion are both important when contaminant transport at the site is assessed. Measurements of diffusion and sorption coefficients for organic contaminants were in a small range for both reconstituted and undisturbed samples (Itakura et al. 2002). This is in contrast to the hydraulic conductivity, which varied widely. Accurate predictions of contaminant transport require greater understanding of the reasons for the conductivity variability. Further study of the heterogeneity, particularly in the Gravel layer, is needed to assess the continuity of the more permeable zones.

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