Clay Minerals, (2016) **51**, 517–528

Halloysite behaving badly: geomechanics and slope behaviour of halloysite-rich soils

VICKI MOON*

School of Science, University of Waikato, Private Bag 3105, Hamilton 3240, New Zealand

(*Received 20 November 2015; revised 23 March 2016; Guest editor: Jock Churchman*)

ABSTRACT: Halloysite-rich soils derived from *in situ* weathering of volcanic materials support steep stable slopes, but commonly fail under triggers of earthquakes or rainfall. Resulting landslides are slide-flow processes, ranging from small translational slides to larger rotational failures with scarps characteristic of sensitive soils. Remoulding of failed materials results in high-mobility flows with apparent friction angles of 10–16°. The materials characteristically have high peak-friction angles (~25–37°), low cohesion (~12–60 kN m^{-2}) and plasticity (plasticity index ~10–48%), and low dry bulk density (~480–1,080 kg m^{-3}) with small pores due to the small size of the halloysite minerals. They remain saturated under most field conditions, with liquidity indexes frequently >1. Remoulded materials have limited cohesion (<5 kN m^{-2}) and variable residual friction angles (15°–35°). Halloysite mineral morphology affects the rheology of remoulded suspensions: tubular minerals have greater viscosity and undrained shear strength than spherical morphologies.

KEYWORDS: halloysite, landslide, shear strength, sensitivity, Atterberg limits.

Halloysite clay minerals are present in many soils derived from weathering of volcanic materials, particularly but not exclusively, in materials formed from pyroclastic deposits. With their small mineral sizes and varied morphologies, halloysite clay minerals create soils with engineering properties that are distinctly different from those normally encountered in soils derived from sedimentary deposits. Allophane, being a nano-crystalline mineral also formed from weathering of volcanic glass, likewise displays engineering properties akin to those of halloysite, so these two minerals are often treated as analogous in discussions of residual soils formed from volcanic ashes. However, since early work by Wesley (1973, 1977) where the properties of both allophane and halloysite were measured and described, allophane seems to have become labelled as the 'culprit' material for difficult soil behaviour. Allophane has thus become the primary focus of more recent work (Wesley, 2001, 2009, 2010), and most recent publications have tended to focus on allophanic soils, though it is not always apparent that identification of the appropriate clay mineral in each soil has been made. This review is limited to papers in which it is clear that halloysite is the dominant clay mineral considered. A number of other papers that discuss 'allophanic soils' in general may actually be including soils rich in halloysite, but these have not been included in the discussion here.

This paper reviews published engineering data for halloysite-rich soils, particularly those formed from weathering of pyroclastic-derived materials. Consideration is given to behaviour in the natural environment, particularly the influence of halloysite on landslide generation and runout behaviour, as well as laboratory-measured physical parameters such as Atterberg limits and shear strength.

LANDSLIDES

Many soils rich in halloysite are formed in a pyroclastic environment and landslides are commonly reported for these materials. Studies from Japan (Ishihara & Hsu,

*E-mail: v.moon@waikato.ac.nz
DOI: 10.1180/claymin.2016.051.3.09

© 2016 The Mineralogical Society
https://doi.org/10.1180/claymin.2016.051.3.09 Published online by Cambridge University Press

1986; Chigira & Yokoyama, 2005; Chigira *et al.*, 2012; Wang *et al.*, 2014), Indonesia (Nakano *et al.*, 2013), and New Zealand (Gulliver & Houghton, 1980; Keam, 2008; Tonkin & Taylor, 2011a,b) discuss landslides in soils containing halloysite. Many of these landslides begin as a planar slide failure, often along boundaries developed within the stratigraphy by depositional or weathering processes. As the material remoulds and moves downslope the landslides develop into flows which spread onto the depositional area (a complex slide-flow, Cruden & Varnes, 1996). They are characterized by high mobility, with apparent friction angles of ~10–16° (Chigira *et al.*, 2012). Typically these landslides are relatively small features (<100,000 m^3). Triggering of the landslides is often attributed to elevated pore-water pressures (or reduced matric suctions, the suction associated with capillary effects in unsaturated soils, defined as the difference between pore air and water pressures) occurring during storm events, or earthquakes. In both of these cases there may be a number of similar landslides generated in a small area during one event.

High mobility is a common characteristic described for these landslides. Corominas (1996) presents apparent friction angles for many different types of landslides and shows that for small events of 10^3–10^5 m^3 values of the apparent friction angle span a range of 6–60°. Thus the landslides in halloysite-rich soils are at the mobile end of this range. However, they show much lower mobility than the sensitive clay landslides of the Northern Hemisphere where typical earthflows resulting from sensitive soil failure have average apparent friction angles of 2.4° (Quinn *et al.*, 2011).

It is important to note that landslides with similar morphologies are reported from Italy (Fiorillo & Wilson, 2004; Vingiani *et al.*, 2015) and El Salvador (Crosta *et al.*, 2005), but it is not clear whether or not halloysite is involved in these failures. Indeed, Crosta *et al.* (2005) noted that long runout is common for volcanic materials, and Hayashi & Self (1992) observed statistically longer runout characteristics in volcanic materials compared with non-volcanic materials for a variety of flow processes. Iverson *et al.* (1997) discussed mobilization of debris flows and noted that many interacting processes result in mobilization, including pore-fluid pressures generating liquefaction, and vibrational energy of the grains. Halloysite mineralogy, and the way it affects soil structure, may provide one pathway for establishing the conditions in which liquefaction of the material can occur as the landslide remoulds.

Landslides induced by earthquakes have been described by a number of authors. Ishihara & Hsu (1986) reported on a number of landslide-inducing earthquake events in Japan and Italy, noting in particular that for the Nagano-seibu (Japan) earthquake of 1984, highly porous pumiceous silts containing halloysite were responsible for triggering large landslides. Chigira *et al.* (2012) and Wang *et al.* (2014) described a number of landslides triggered by the 2011 Tohoku Earthquake in Japan. Both describe slide-flow processes on gentle slopes (13–23°) with depths of 3–9 m and high mobility of the debris. Displaced material consisted of a sequence of pyroclastic deposits, but all the landslides described were based in a halloysite-rich palaeosol layer underlying pumiceous materials. Wang *et al.* (2014) concluded that the seismic accelerations induced high pore-water pressures within the halloysite-rich palaeosol, which formed the initial slide surface. Nakano *et al.* (2013) drew very similar conclusions for earthquake-induced landslides in Tandikat, Indonesia, following the Padang Earthquake of 2009. In this case nearly 1000 landslides were triggered by the earthquake and Nakano *et al.* (2013) found that the sliding surfaces developed in a layer of mixed pumice-palaeosol, rich in halloysite. Tanaka (1992) in an early review of a number of such earthquake-induced landslides in pyroclastic materials in Japan, observed that spherical (ball-type) halloysite was found in the rupture surfaces of many of these landslides. He drew the very specific conclusion that “Halloysite is the key mineral of these landslides.”

Rainfall-triggered landslides are less frequently reported, but several studies note their occurrence. Chigira & Yokoyama (2005) describe weathering profiles and matric suction measurements in non-welded ignimbrite (Shirasu) exposures in Japan. They note an increase in halloysite in weathered Shirasu compared with the underlying fresh rock as volcanic glass is altered. They interpret the halloysite as migrating downwards through the porous rock, to collect in bands. As weathering proceeds the grain size of the weathered material decreases, and Chigira & Yokoyama (2005) infer that this causes a capillary barrier effect which prevents downward drainage of a pore-water pulse resulting from rainfall events, resulting in increased mass and reduced matric suction and leading to landslides from lowered effective stress.

During May 2005 significant rainfall events triggered slide failures and debris flows at Matata (McSaveney *et al.*, 2005) and Tauranga in the Bay of Plenty, New Zealand. Within Tauranga City a number

https://doi.org/10.1180/claymin.2016.051.3.09 Published online by Cambridge University Press

of small slide-flow events caused damage to houses and infrastructure. Geomorphic evidence suggests that the area is prone to such events. One particularly well studied area is the Omokoroa Peninsula in Tauranga Harbour where a number of large landslides have been recorded (summarized by Garae, 2015), and geomorphic evidence points to many pre-historic events. The evacuated landslide scars show a variety of forms, similar to those described for sensitive soils in Canada by Quinn *et al.* (2011). These range from small, planar scars on steep coastal margins, through small (<20 m diameter) roughly equidimensional scars indicative of rotational failure mechanisms, to large scars with a steep headscarp and relatively low-angle base of the failure. Most of the scars exposed are largely devoid of debris, but some remain as ridges on the low-angle base of the failures. The landslide at Bramley Drive, Omokoroa, originally occurred in 1979 (Gulliver & Houghton, 1980) and has since shown slow retrogression over ~30 y, developing an elongate crater form as defined by Quinn *et al.* (2011) with a narrowed outlet zone as successive failures widen the scarp, yet so far the outlet has remained unchanged. The scarp, at present, is ~50 m long, 48 m wide, and 25 m deep. The original runout was unconfined, and extended across the flat shore platform with a length exceeding 150 m (Gulliver & Houghton, 1980), giving an apparent friction angle of ~12°. Later failure events (Tonkin & Taylor, 2011a) have been smaller than the original failure and involved shorter runout distances up to 130 m (apparent friction angle of ~14°). The mobility of these flows is thus in keeping with the range observed by Chigira *et al.* (2012) for landslides in halloysite-rich soils in Japan.

We have identified halloysite as the principal clay mineral in the pyroclastic sequence at the level of the failure surface of the recent reactivations of the landslide at Bramley Drive (Moon *et al.*, 2013, 2015a,b), confirming the original conclusions of Gulliver & Houghton (1980) and Smalley *et al.* (1980). The halloysite occurs within material with a loose, open structure formed during the depositional and weathering processes, which results in high porosity and large natural water contents. The halloysite in the profile at Bramley Drive shows a range of morphologies from tubular, to platy, spherical, and book forms (Wyatt *et al.*, 2010; Moon *et al.*, 2015b), and we suggest that these different morphologies provide important controls on the behaviour of the materials. Smalley *et al.* (1980) originally noted that the high sensitivities developed in the Bramley Drive landslide were associated with spherical halloysite minerals, in keeping with the observation of Tanaka (1992) of “ball-type” halloysite in earthquake-induced landslides in Japan. Initial research relating peak and remoulded undrained shear strength of layers within the pyroclastic sequence at Bramley Drive (Kluger *et al.*, under review) suggests that the peak and remoulded strengths are lower for spherical halloysite than for the other morphologies. While the materials exhibit considerable run-out distances, they are not as great as those for sensitive soils of the Northern Hemisphere (*e.g.* Geertsema *et al.*, 2006), and we suggest that the variable clay morphologies result in more complex interactions between grains compared with the fully hydrated face-to-face arrangements of platy clay minerals in glaciogenic sensitive soils.

Finally, kaolin clays, including halloysite, have also been implicated in completely different landslide types when these clays form the infill material along discontinuity surfaces in weathered rock masses. Examples of these failures are reported from Hong Kong by Kirk *et al.* (1997), Campbell & Parry (2002) and Parry *et al.* (2004).

Kirk *et al.* (1997) described two deep-seated landslides, at Fei Shui and Shum Wan Roads. They inferred that a bedding-parallel, highly to completely weathered layer containing kaolin provided the failure surface for the landslide at Fei Shui Road. At Shum Wan Road, Kirk *et al.* (1997) noted a zone of steeply dipping foliation, together with widespread, closely spaced jointing with kaolin infills. Complex microstructures within these joint infills suggest multiple stages of minor shearing, and perched water tables were associated with clay layers. In both landslides, slip surfaces occurred in zones of kaolin-filled joints. The proportions of halloysite and kaolinite in the kaolin-filled zones varies, but at Fen Shui Road Kirk *et al.* (1997) report halloysite as the dominant kaolin mineral in the slipped clay, and at Shum Wan Road halloysite formed 80% of the white clay along the surface of rupture. Kirk *et al.* (1997) concluded that their observations confirmed Tanaka’s (1992) thesis that halloysite is a key mineral associated with the development of landslides.

Following these landslides, wider research into the extent and impact of kaolin-rich zones in Hong Kong was undertaken by the Geotechnical Engineering Office of The Government of Hong Kong (Campbell & Parry, 2002; Parry *et al.*, 2004). Those authors developed a model for the formation of kaolin-rich zones in Hong Kong, and confirm the presence of kaolin in the weathered zone, most commonly infilling relict discontinuities and showing signs of multiple

https://doi.org/10.1180/claymin.2016.051.3.09 Published online by Cambridge University Press

stages of shearing during formation. Wen & Aydin (2003) examined some of these clay seams microscopically, and observed complex seams consisting of mixtures of halloysite, kaolinite and illite. Their observations suggest movement concentrated in the higher-kaolinite portion (41%–54%) of a clay seam, and that portions dominated by halloysite (71%–80%) show little evidence of involvement in landsliding, contradicting the conclusion of Kirk *et al.* (1997) from field observations.

Campbell & Parry (2002) and Parry *et al.* (2004) reported results of shear-strength testing on commercially prepared samples of kaolinite and halloysite (see "Shear Strength" section below) and note that kaolinite has lower peak and residual shear strengths for the samples tested, with the shear strength of mixtures reducing as the proportion of kaolinite increases. They associate the greater shear resistance of halloysite to the tubular morphology of the commercially prepared minerals. However, Duzgoren-Aydin & Aydin (2006) noted that the morphology of halloysite in a weathering profile in Hong Kong is not always tubular, but varies from spheroidal clusters to tubular aggregates. Churchman *et al.* (2010) also note variability in the morphology of halloysite minerals in this region, particularly varying from long, fibrous bunches to tubes of varying lengths.

The work of Campbell & Parry (2002) and Parry *et al.* (2004) indicated that a complex relationship exists between weathering processes, the location of kaolin-rich zones, and groundwater movement. Detailed engineering-geology investigation is required to assess the stability of slopes (Parry *et al.*, 2004). Churchman *et al.* (2010) inferred that halloysite forms preferentially along surfaces that remain wet (poorly drained), as opposed to kaolinite that forms when drying occurs. This drainage difference may, in part, explain why halloysite is implicated in some slope failures in Hong Kong as described by Kirk *et al.* (1997), despite the greater shear strength compared with that of kaolinite. The variable morphology observed for halloysite minerals may also impact on the local shear strength in any kaolin-rich zone, as observed by Kluger *et al.* (under review) (see above).

SENSITIVITY

The significant mobility of many of the landslides discussed above is associated with, and evidence for, sensitivity in the materials. Sensitivity represents a loss of strength upon remoulding, and is quantified as the ratio of undisturbed to remoulded undrained strength where both strengths are determined at the same moisture content. Values of <2 are insensitive, 4–8 are sensitive, 8–16 are extra sensitive, and >16 are considered "quick" (Skempton & Northey, 1952).

Sensitive soil behaviour is classically described from glacial outwash deposits in Norway and Canada, where low-activity illite clays collapse from an open, cardhouse structure following leaching of Na cations and consequent loss of cohesion between clay minerals. In these soils, sensitivity can reach values of 150 (Skempton & Northey, 1952). Early work on sensitive soils in New Zealand reported sensitivities up to 140 in rhyolitic deposits at Bramley Drive, Omokoroa, and attributed the high sensitivity to hydrated halloysite clays (Smalley *et al.*, 1980). The halloysite in this case was seen to have a spherical morphology and the authors inferred that this gave minimal interparticle interactions, particularly long-range interactions, accounting for an initial brittle breakdown of the slope materials.

Jacquet (1990) considered the cause of sensitivity in a range of tephra-derived soils in New Zealand, including samples dominated by both allophane and halloysite clay minerals. The sensitivities of the soils studied ranged from 5 to 55, and the measured sensitivity could not be seen to relate readily to mineralogical compositions or bulk properties of the materials. However, Jacquet (1990) noted that the halloysite mineral aggregates were larger than the allophane aggregates and hence had fewer contacts, making the halloysite aggregates less stable than those in the allophane-dominated soils.

Moon *et al.* (2015b) summarized recent thesis research on sensitive soils from the Tauranga region of New Zealand, including the Omokoroa site discussed above. Sensitivities range from 5 to 20, and all soils considered are clayey silts to silty clays with halloysite as the dominant clay mineral. The original deposition of the materials was from a pyroclastic source (airfall or pyroclastic flow) with likely redeposition of some of the materials in lacustrine or estuarine environments. The sampled materials range from depths of several metres to several tens of metres within the modern stratigraphic sequence. In parallel with the northern hemisphere, it is suggested that cations derived from early-stage weathering of the volcanic glasses provide cohesion amongst clay minerals that allow retention of a flocculated structure as secondary clay minerals (halloysite) develop. With continued weathering the supply of cations becomes exhausted (incorporated into clay crystal lattices or into other insoluble

https://doi.org/10.1180/claymin.2016.051.3.09 Published online by Cambridge University Press

TABLE 1. Bulk physical properties for weathered pyroclastic-derived halloysite-rich soils.

Location	ρ_{dry} (kg m^{-3})	η (%)	w_{field} (%)	Sat. (%)	k*10^{-9} (m s^{-1})	Source
Indonesia			31–51	100	1–13	Wesley (1973, 1977)
New Zealand			60–100			Smalley *et al.* (1980)
New Zealand			60–89			Jacquet (1990)
New Zealand	759–972	59	76–106			Keam (2008)
New Zealand	680–1080	33–70	54–101			Arthurs (2010)
New Zealand	688–1030	61–71	64–109	91–109	3–111	Moon *et al.* (2013, 2015a,b)
Japan	480–660		94–160			Wang *et al.* (2014)

ρ_{dry}, = dry bulk density; η = porosity; w_{field} = field moisture content; Sat. = field saturation; k = permeability coefficient.

components) or leached from the system. A low cation exchange capacity (CEC) of halloysite (Joussein *et al.*, 2005; Churchman & Lowe, 2012), in conjunction with low cation-concentration soil solutions, leads to loss of cohesion across clay contacts. This material fails with increased stress (reduced effective stress) and remoulds to form a flow.

BULK SOIL PROPERTIES

Bulk density and permeability

Table 1 summarizes published bulk physical properties of halloysite-rich soils; all of the values compiled here are from weathered pyroclastic-derived soil materials. Of particular note is the very low dry bulk-density values for all measured soils. As a result, porosity and void ratio values are high. Many authors report that pore spaces are small, a function of the small size of the halloysite clay minerals (Allbrook, 1992; Keam, 2008; Wyatt, 2009; Arthurs, 2010; Cunningham, 2012; Moon *et al.*, 2013, 2015b). Natural moisture content is high, and the soils are characteristically at or close to saturation in their normal field conditions (Wesley, 1973), with saturation levels remaining close to 100% with little variation throughout the year.

Permeability is reported infrequently in the literature for these soils. Wesley (1977) reported permeabilities of 1–13 × 10^{-7} m s^{-1} for Indonesian residual soils with halloysite as the predominant clay mineral. These, he noted, are comparatively high values compared with London Clay (a sedimentary deposit with smectite, illite, kaolinite and chlorite clay minerals (Kemp & Wagner, 2006)). Recently reported results for pyroclastic soils in New Zealand (Moon *et al.*, 2013, 2015a, b) indicate rather lower permeabilities, in the range 10^{-7} to 10^{-9} m s^{-1}, with the most reliable measurements giving a value of 4 × 10^{-9} m s^{-1} (Moon *et al.*, 2015b). In this case the materials are clayey silts to silty clays, with median clay percentages of only 6.5%. This is a very low permeability for a silty material and again reflects the small pore size resulting from the small size of the halloysite minerals and resulting tortuosity of the pathways for water movement.

Atterberg limits

Early reports of the Atterberg limits of halloysite clays (Bain, 1971) and halloysite-rich soils (Wesley, 1973) report high liquid and plastic limits in comparison with "normal" clay soils (derived from sedimentary materials) (Table 2). These early papers also noted that despite the high actual plastic and liquid limits, the clays display low plasticity indexes. In the case of the pure clays considered by Bain (1971) the plasticity index is very low (10%–15%, Table 2). In contrast, the plasticity index is somewhat elevated in the soils considered by Wesley (1973), possibly reflecting impurities within the natural soil. Both Bain (1971) and Wesley (1973) illustrated that materials containing halloysite plot below the A-line of the classic Casagrande plasticity chart as "high compressibility silts" (Fig. 1). Wesley (1973) defined representative zones for these soils on the Casagrande chart: halloysite generally plots below but parallel to the A-line.

More recent data from a range of halloysite-dominated soils from throughout the globe fall within the ranges defined by these two initial studies (Table 2) and largely confirm the zone presented by Wesley (1973) for halloysite, but extend it to lower liquid limit values where the results still lie below, but parallel to, the A-line (Fig. 1).

https://doi.org/10.1180/claymin.2016.051.3.09 Published online by Cambridge University Press

High plastic and liquid limits mean that, compared with platy clays, a large amount of water is contained within a soil paste before the key rheological changes that define the limits are observed. This implies that the water is in positions that do not either physically lubricate the contacts between the clay minerals, or interact with the clay surfaces through chemical and electrostatic effects. High limit values are to be expected from the fact that the structural formula for hydrated halloysite contains water molecules that are readily driven off by oven drying such as is employed in measuring the Atterberg limits (Bain, 1971). Comparison with kaolinite clays suggests that this additional water should result in enhanced plastic and liquid limits of 14%, while the plasticity index will remain unaffected (Bain, 1971). In reality, the plastic and liquid limits are enhanced by more than this, implying that the morphology of the halloysite clay minerals, specifically tubular morphologies, results in additional water held within the structure (adsorbed on internal surfaces) which does not contribute to the development of plasticity in the materials (Bain, 1971).

The low plasticity indexes for halloysite indicate low-activity materials, which is confirmed by their plotting as “silt” materials below the A-line; a low activity reflects low shrink/swell potential. Plasticity relates to interaction between clay mineral surfaces and the cations in the double-layer water, and hence the capacity of individual clay minerals to interact electrostatically with one another. Thus the low plasticity of these materials is a reflection of the relatively low CEC. Because of their low CEC, low-activity clays such as kaolinite and halloysite have low values of plasticity (Kirchhof, 2006), and display a marked lack of cohesion when moulded (Bain, 1971).

A low shrink/swell capacity is generally seen as positive for engineering as volume change with moisture content changes is unlikely to be a problem. However, dehydration of halloysite will lead to irreversible shrinkage and halloysite-rich soils have been observed to experience significant shrinkage (Allbrook, 1992; Gray & Allbrook, 2002). Swelling is unlikely to be a problem as dehydration of halloysite is irreversible, and Allbrook (1992) suggested that the shrinkage is unlikely to be enough to initiate cracks in dry conditions.

As a result of the low-plasticity index but large natural moisture contents noted above, the soils characteristically have very high liquidity indexes, reaching >2 at times (Table 2). This means that their moisture content under normal field conditions is greater than the liquid limit of the remoulded soil. The small pore size and clay mineral morphologies allow this very high moisture content to be held within the structured soil.

SHEAR STRENGTH

Peak shear strength

Many authors have determined Mohr-Coulomb shear strength parameters of halloysite-rich soils using various testing methods (Table 3). Peak cohesion values measured on undisturbed samples are characteristically low, though they cover a wide range from 0 to 70 kN m^{-2}. Values from a number of authors reported by Moon *et al.* (2015b) range from 12 to 18 kN m^{-2}, and are in keeping with the value of 14 kN m^{-2} originally reported by Wesley (1977).

Peak strength values measured on undisturbed specimens show high friction angle values (Table 3), typically between 25 and 37°, but notable outliers from this are the values of Jacquet (1990) and Keam (2008) with values <9° and >50° respectively. An effective friction angle of 30° measured using reconstituted samples prepared from commercially sourced pure halloysite is within the range of values derived for undisturbed specimens.

Wesley (1977) referred to high values of c' and ϕ' for both disturbed and undisturbed samples of allophanic and halloysitic soils, and relates this to high slope angles observed. Comparison of friction angles between clays is often undertaken with respect to plasticity index (*e.g.* Terzaghi *et al.*, 1996). Figure 2 shows values of peak effective friction angle values obtained using unconsolidated, undrained triaxial testing for samples positively identified as containing halloysite. When compared with published plots for sedimentary clays presented by Holt in 1962 (from Kanji, 1974), Wesley (1977) and Terzaghi *et al.* (1996), the halloysite samples show a spread of results surrounding, but in general falling above the correlation lines presented. Thus friction angles overall are elevated when compared with those of platy clay minerals.

A high frictional resistance for the materials has variously been attributed to the particle shape of the halloysite clay minerals (tubular) and aggregation of the clay minerals (González de Vallejo *et al.*, 1981; Campbell & Parry, 2002). In order to shear, particle realignment occurs (Skempton, 1964; Morgenstern & Tchalenko, 1967; Gylland, 2013, 2014), which is readily achieved with hydrated platy clay minerals, but

https://doi.org/10.1180/claymin.2016.051.3.09 Published online by Cambridge University Press

TABLE 2. Published Atterberg limit data for halloysite clays (Bain, 1971) and halloysite-rich soils (all others).

Location	PL (%)	LL (%)	PI (%)	LI	Source
Various	60–70		10–15		Bain (1971)
Indonesia	55–75	70–110	20–45		Wesley (1973)
Cameroon	18–29	34–77	16–48		Simon *et al.* (1975)
New Zealand		65–80	15–30		Smalley *et al.* (1980)
Canary Islands	29	71	42		González de Vallejo *et al.* (1981)
Italy			20–45		Ishihara & Hsu (1986)
New Zealand	46–67	68–99	22–46	0.3–0.8	Jacquet (1990)
New Zealand	39–48	55–72	10–33	1.0–2.1	Keam (2008)
New Zealand	29–66	42–98	11–40	0.5–2.4	Arthurs (2010)
New Zealand	35–49	52–89	15–44	1.1–2.2	Moon *et al.* (2013, 2015a,b)

PL, plastic limit; LL, liquid limit; PI, plasticity index; LI, liquidity index.

rather more challenging with odd-shaped minerals. Hence the angularity of particles affects peak friction angle in constant volume shear (Santamarina & Cho, 2004). The relatively high peak friction angles measured for these materials probably represent the irregular morphologies of the halloysite minerals and their aggregates.

The high frictional resistance, and hence relatively high peak strength, of halloysite-rich soils means that they remain stable at high slope angles (Wesley, 1977). In an engineering sense they are thus compliant materials compared with "normal" platy clay materials weathered from sedimentary rocks. As these halloysite-rich soils have generally weathered *in situ* and the materials have not experienced elevated overburden stresses, they remain normally consolidated in most conditions.

Remoulded shear strength

Reported residual shear strengths for halloysite-rich soils are compiled in Table 3. Typical values of residual cohesion are <5 kN m^{-2}, while the residual friction angle ranges from 15 to 35°. Rigo *et al.* (2006) discussed the residual shear strength of tropical soils and classified the residual friction angle based on plasticity index and

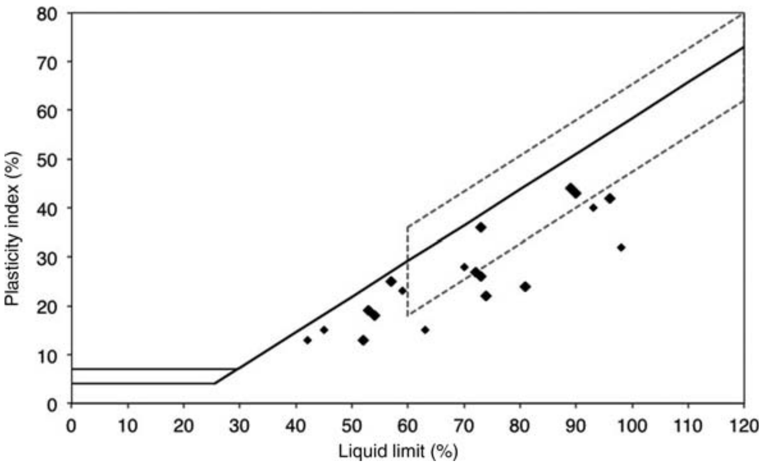

FIG. 1. Atterberg limits plotted against the A-line of the plasticity chart. The dashed box indicates the halloysite zone defined by Wesley (1973). Data points for recent measurements from pyroclasic-derived halloysite-rich soils from the Bay of Plenty, New Zealand are superimposed (Keam, 2008; Wyatt, 2009; Arthurs, 2010; Cunningham, 2012).

https://doi.org/10.1180/claymin.2016.051.3.09 Published online by Cambridge University Press

TABLE 3. Strength parameters reported for a number of halloysite-rich soils.

Location	S_t	Peak (kN m^{-2})		Residual (kN m^{-2})		Source
		c' (c)	ϕ' (ϕ)	c' (c)	ϕ' (ϕ)	
Bay of Plenty, NZ	<140					Smalley *et al.* (1980)
Indonesia[a]		14–23	31–38	5*	25*	Wesley (1973, 1977)
Japan[a]		20–50	31	0–10	9–13	Ishihara & Hsu (1986)**
Bay of Plenty, NZ[a]	8–23	0–70	25–37	0–3	15–35	Arthurs (2010)
Auckland, NZ[a]	6–18	23–48	21–32	0–13	15–19	Arthurs (2010)
Bay of Plenty, NZ[a]	10–13	12–18	29–41			Moon *et al.* (2015b)
Bay of Plenty, NZ[b]	9–16	0–43	50–56	0–4	17–31	Keam (2008)
Japan[b]		37.4	33	2.7	34.2	Wang *et al.* (2014)
New Zealand[c]	5–39	55–60	2–8.5			Jacquet (1990)
Bay of Plenty, NZ[d]				0–5	19–33	Wyatt (2009)
Dominica[e]					28.9°–34.2°	Reading (1991)
Commercial pure halloysite[e]		0	30	0	21	Campbell & Parry (2002); Parry *et al.* (2004)

S_t = undrained shear strength from *in situ* shear vane testing; c' (c), ϕ' (ϕ): effective (total) strength parameters (cohesion, friction angle).

[a] Effective stress from consolidated, undrained triaxial tests.

[b] Effective stress from consolidated, drained triaxial tests.

[c] Total stress from unconsolidated, undrained triaxial tests.

[d] Total stress from ring shear tests.

[e] Effective stress from direct and ring shear tests.

*Compacted.

**Not positively identified as halloysite.

soil type. They showed volcanic ash-derived soils as plotting in a group with residual friction angle higher than those for soils derived from sedimentary materials with similar plasticity index. This is primarily based on the graph presented by Wesley (2003) for which the volcanic ash soils are largely from New Zealand and are assumed to contain either halloysite or allophane, though complete mineralogical analysis was not undertaken. Thus, relatively high residual friction angles may be expected for halloysite-containing materials, and high values are indeed reported by Reading (1991) and Wang *et al.* (2014).

However, from the data presented in Table 3, the residual friction angle may be considerably lower than the peak friction angle; in many samples the friction angle is relatively unaffected by remoulding, but in others it is reduced to approximately half that of the peak value. Many of these remoulded shear strengths are reported from the pyroclastic-derived soils of the Bay of Plenty, New Zealand. These soils are known to be sensitive (see the 'Sensitivity' section above), and were sampled on the basis of sensitivity identified in field vane shear testing. Thus the reduced residual friction angle values compared with the peak friction angle may be biased towards low results on the basis of the sampling protocol. The one set of data from Indonesian soils that are reported to be insensitive (Wesley, 1977) indicated a similar loss in cohesion and friction angle to the more sensitive New Zealand examples. Data from Campbell & Parry (2002) and Parry *et al.* (2004) indicate a loss in effective friction angle from 30 to 21° on remoulding for reconstituted samples of pure halloysite; this loss is of a similar magnitude to that observed for pure kaolinite (22 to 14°) under the same testing conditions.

It is recognized that changes in the chemistry of the constituent pore water cause corresponding changes in sensitivity and residual shear strength (Moore, 1991; Andersson-Skold *et al.*, 2005; He *et al.*, 2015) of soil materials containing clays because of the importance of cation interaction with the charged clay surfaces. Hence, weathering and water movement through the soil profile will be expected to impact on the rheological characteristics of halloysite-dominated sensitive soils.

https://doi.org/10.1180/claymin.2016.051.3.09 Published online by Cambridge University Press

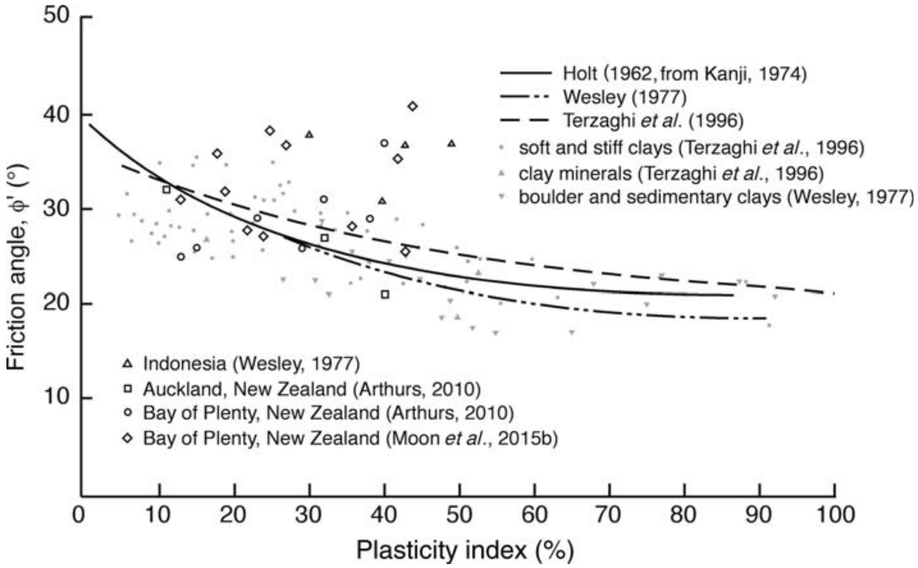

FIG. 2. Effective peak-friction angle *vs.* plasticity index for consolidated, undrained triaxial tests. Published correlations derived for platy clay minerals in sedimentary environments are compared with data for halloysite-rich soils from Indonesia and New Zealand. While scatter exists in the results, the halloysite samples show generally high peak-friction angles.

Theng & Wells (1995) studied the rheology of suspensions of halloysite from New Zealand, considering samples with different clay mineral morphologies (long tubules, short thin laths, spherules). They observed different shear stress *vs.* shear rate relationships associated with the different morphologies (psuedo-plastic for tubes and laths, Newtonian for spherules), together with a yield stress dependency on ionic concentration and pH for psuedo-plastic samples. Theng & Wells (1995) concluded that the psuedo-plastic behaviour is typical of flocculated clays, and indicates development of a network structure in the tubular and lath-like halloysites formed by edge-to-edge and edge-to-face contacts between clay mineral particles. In contrast, clays with spheroidal morphology interact as a string of beads and do not develop networks. Theng & Wells (1995) also observe that changes in pH and electrolyte concentration affect yield strengths by changing surface-charge characteristics and hence altering the nature of the particle contacts. Itami & Fujitani (2005), in a study on dispersibility of soil colloids, concluded that surface-charge characteristics of halloysite are quite different from those of kaolinite, and that these impact on edge surface interactions that play a significant role in determining the flocculation behaviour of halloysite clays. They noted that little work has been done on these characteristics of halloysite, and more investigation is needed to elucidate its charge characteristics and flocculation behaviour.

Cone-penetration resistance

The strength measured *in situ* is low, somewhat in contrast with the laboratory results discussed above. Few *in situ* measurements have been reported: Moon *et al.* (2013, 2015b) and Jorat *et al.* (2014) reported on a cone-pentration test (CPTu) undertaken on the scarp of the landslide at Bramley Drive, Omokoroa; Jorat *et al.* (2014) also presented a CPTu sounding from nearby Pyes Pa, Tauranga; and Nakano *et al.* (2013) noted that the pumice-palaeosol mixed layer containing halloysite showed the smallest cone resistance in the profile they considered, though they did not report absolute values.

In both of the Tauranga cases, low tip resistance (<2 MPa) was recorded, indicating a low *in situ* strength for these materials. This was accompanied by development of high excess pore-water pressures associated with penetration of the cone, confirming a low permeability. While large amounts of water can be contained within the open structure, the rate at which water can move within the small pore spaces is limited, so permeability is very low, and induced water pressures in CPTu testing rise to very high levels.

https://doi.org/10.1180/claymin.2016.051.3.09 Published online by Cambridge University Press

CONCLUSION

Soils rich in halloysite derived from weathering of volcanic glass show distinct engineering characteristics, many of which are markedly different from those observed in soils developed from sedimentary materials. In particular, high peak shear strength associated with high friction angles allows steep faces to remain stable. When failure is initiated, however, these materials frequently undergo a dramatic loss of strength on remoulding, to form flows with high mobility. The cause of this sensitivity is complex: the open microstructure, high porosity, and high natural moisture contents of the materials will encourage release of water on failure; the low cation exchange capacity, low cohesion and low plasticity of halloysite will contribute to its breakdown on failure; and the charge characteristics associated with the different morphologies of halloysite will result in variable flow behaviours that respond to changes in pH or electrolyte concentration. While we have a reasonable understanding of the strength and plasticity of the materials, the processes leading to initial slope failure are poorly understood, and only a small amount of work has so far been undertaken on the flow characteristics of the remoulded soil.

REFERENCES

Allbrook R.F. (1992) Shrinkage of some New Zealand soils and its implications for soil physics. *Australian Journal of Soil Research*, **31**, 111–18.

Andersson-Skold Y., Torrance J.K., Lind B., Odén K., Stevens R.L. & Rankka K. (2005) Quick clay – a case study of chemical perspective in Southwest Sweden. *Engineering Geology*, **82**, 107–118.

Arthurs J.M. (2010) *The nature of sensitivity in rhyolitic pyroclastic soils from New Zealand*. PhD thesis, University of Auckland, New Zealand.

Bain J.A. (1971) A plasticity chart as an aid to the identification and assessment of industrial clays. *Clay Minerals*, **9**, 1–17.

Campbell S.D.G. & Parry S. (2002) *Report on the Investigation of Kaolin-rich Zones in Weathered Rocks in Hong Kong.* GEO Report no. 132, Geotechnical Engineering Office, Hong Kong. Retrieved from http://www.cedd.gov.hk/eng/publications/geo_reports/geo_rpt132.html. 1 March 2016.

Chigira M. & Yokoyama O. (2005) Weathering profile of non-welded ignimbrite and the water infiltration behavior within it in relation to the generation of shallow landslides. *Engineering Geology*, **78**, 187–207.

Chigira M., Nakasuji A., Fujiwara S. & Sakagami M. (2012) Catastrophic landslides of pyroclastics induced by the 2011 off the pacific coast of Tohoku earthquake. Pp. 139–147 in: *Earthquake-Induced Landslides* (K. Ugai, H. Yagi & A. Wakai, editors). *Proceedings of the International Symposium on Earthquake-Induced Landslides.* Springer, Kiryu, Japan.

Churchman G.J. & Lowe D.J. (2012) Alteration, formation, and occurrence of minerals in soils. Pp. 20.1–20.72 in: *Handbook of Soil Sciences. 2nd edition. Vol. 1: Properties and Processes* (P.M. Huang, Y. Li & M.E. Sumner, editors). CRC Press (Taylor & Francis), Boca Raton, Florida, USA.

Churchman G.J., Pontifex I.R. & McClure S.G. (2010) Factors influencing the formation and characteristics of halloysites or kaolinites in granitic and tuffaceous saprolites in Hong Kong. *Clays and Clay Minerals*, **58**, 220–237.

Corominas J. (1996) The angle of reach as a mobility index for small and large landslides. *Canadian Geotechnical Journal*, **33**, 260–271.

Crosta G.B., Imposimato S., Roddeman D., Chiesa S. & Moia F. (2005) Small fast-moving flow-like landslides in volcanic deposits: The 2001 Las Colinas Landslide (El Salvador). *Engineering Geology*, **79**, 185–214.

Cruden D.M. & Varnes D.J. (1996) Landslide types and processes. Pp. 36–75 in: *Landslides: Investigation and Mitigation* (A.K. Turner & R.L. Schuster, editors). National Research Council, Transportation Research Board Special Report, 247, National Academy Press, Washington, D.C.

Cunningham M.J. (2012) *Sensitive rhyolitic pyroclastic deposits in the Tauranga region: mineralogy, geomechanics and microstructure of peak and remoulded states*. MSc Thesis, University of Waikato, New Zealand.

Duzgoren-Aydin N.S. & Aydin A. (2006) Chemical and mineralogical heterogeneities of weathered igneous profiles: implications for landslide investigations. *Natural Hazards and Earth System Science*, **6**, 315–322.

Fiorillo F. & Wilson R.C. (2004) Rainfall induced debris flows in pyroclastic deposits, Campania (southern Italy). *Engineering Geology*, **75**, 263–289.

Garae C.P. (2015) *Estimating patterns and rates of coastal cliff retreat around Tauranga Harbour*. MSc thesis, University of Waikato, New Zealand.

Geertsema M., Cruden D.M. & Schwab J.W. (2006) A large rapid landslide in sensitive glaciomarine sediments at Mink Creek, northwestern British Columbia, Canada. *Engineering Geology*, **83**, 36–63.

González De Vallejo L.I., Jimenez Salas J.A. & Leguey Jimenez S. (1981) Engineering Geology of the tropical volcanic soils of La Laguna, Tenerife. *Engineering Geology*, **17**, 1–17.

Gray C.W. & Allbrook R. (2002) Relationships between shrinkage indices and soil properties in some New Zealand soils. *Geoderma*, **108**, 287–299.

Gulliver C.P. & Houghton B.F. (1980) *Omokoroa Point Land Stability Investigation.* Report prepared by Tonkin & Taylor for Tauranga County Council (New Zealand).

https://doi.org/10.1180/claymin.2016.051.3.09 Published online by Cambridge University Press

Gylland A.S., Jostad H.P. & Nordal S. (2013) Experimental study of strain localization in sensitive clays. *Acta Geotechnica*, **9**, 227–240.

Gylland A.S., Rueslåtten H., Jostad H.P. & Nordal S. (2014) Microstructural observations of shear zones in sensitive clay. *Engineering Geology*, **163**, 75–88.

Hayashi J.N. & Self S. (1992) A comparison of pyroclastic flow and debris avalanche mobility. *Journal of Geophysical Research, Solid Earth*, **97**, 9063–9071.

He P., Ohtsubo M., Higashi T. & Kanayama M. (2015) Sensitivity of salt-leached clay sediments in the Ariake Bay area, Japan. *Marine Georesources and Geotechnology*, **33**, 429–436.

Ishihara K. & Hsu H-L. (1986) Considerations for landslides in natural slopes triggered by earthquakes. *Proceedings of Japan Society of Civil Engineers*, **376**, III-6.

Itami K. & Fujitani H. (2005) Charge characteristics and related dispersion/flocculation behaviour of soil colloids as the cause of turbidity. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, **265**, 55–63.

Iverson R.M., Reid M.E. & LaHusen R.G. (1997) Debris-flow mobilization from landslides. *Annual Review of Earth and Planetary Sciences*, **25**, 85–138.

Jacquet D. (1990) Sensitivity to remoulding of some volcanic ash soils in New Zealand. *Engineering Geology*, **28**, 1–25.

Jorat M.E., Mörz T., Schunn W., Kreiter S., Moon V. & de Lange W. (2014) Geotechnical Offshore Seabed Tool (GOST): CPTu measurements and operations in New Zealand. Pp. 217–223 in: *Proceeding, 3rd International Symposium on Cone Penetration Testing.* Las Vegas, Nevada, USA. http:www.cpt14.com/cpt14-papers.

Joussein E., Petit S., Churchman G.J., Theng B., Righi D. & Delvaux B. (2005) Halloysite clay minerals – a review. *Clay Minerals*, **40**, 383–426.

Kanji M.A. (1974) The relationship between drained friction angles and Atterberg limits of natural soils. *Géotechnique*, **24**, 671–674.

Keam M.J. (2008) *Engineering geology and mass movement on the Omokoroa Peninsula, Bay of Plenty, New Zealand*. MSc Thesis, University of Auckland, New Zealand.

Kemp S.J. & Wagner D. (2006) *The Mineralogy, Geochemistry and Surface Area of Mudrocks From the London Clay Formation of Southern England.* British Geological Survey, Nottingham, UK, 81 pp. (IR/06/060) (Unpublished). Available from: http://nora.nerc.ac.uk/7232/.

Kirchhof G. (2006) Plastic properties. Pp. 1311–1313 in: *Encyclopedia of Soil Science*, 2nd edition (R. Lal, editor). CRC Press (Taylor & Francis), Boca Raton, Florida, USA.

Kirk P.A., Campbell S.D.G., Fletcher C.J.N. & Merriman R.J. (1997) The significance of primary volcanic fabrics and clay distribution in landslides in Hong Kong. *Journal of the Geological Society*, **154**, 1009–1019.

Kluger M.O., Moon V., Kreiter S., Lowe D.J., Churchman G.J., Hepp D.A., Seibel D. & Mörz T. (under review). A new attraction-detachment model for explaining landsliding in clay-rich tephras. Submitted to *Geology*, September, 2016.

McSaveney M.J., Beetham R.D. & Leonard G.S. (2005) *The 18 May 2005 Debris Flow Disaster at Matata: Causes and Mitigation Suggestions.* GNS Science Client Report 2005/71.

Moon V.G., Cunningham M.J., Wyatt J.B., Lowe D.J., Mörz T. & Jorat M.E. (2013) Landslides in sensitive soils, Tauranga, New Zealand. Pp. 537–544 in: *Proceedings 19th New Zealand Geotechnical Society Symposium. Hanging by A Thread – Lifelines, Infrastructure, and Natural Disasters* (C.Y. Chin, editor). The Institution of Professional Engineers New Zealand, Queenstown, November 2013.

Moon V.G., de Lange W.P., Garae C.P., Mörz T., Jorat M. E. & Kreiter S. (2015a) Monitoring the landslide at Bramley Drive, Tauranga, New Zealand. Pp. 737–744 in: *ANZ 2015 Changing the Face of the Earth, Geomechanics and Human Influence, 12th Australia New Zealand Conference on Geomechanics.* Wellington 22–25 February 2015.

Moon V.G., Lowe D.J., Cunningham M.J., Wyatt J.B., Churchman G.J., de Lange W.P., Mörz T., Kreiter S., Kluger M.O. & Jorat M.E. (2015b) Sensitive pyroclastic-derived halloysitic soils in northern New Zealand: interplay of microstructure, minerals, and geomechanics. Pp. 3–21 in: *Volcanic Rocks and Soils. Proceedings of the International Workshop on Volcanic Rocks and Soils, Lacco Ameno, Ischia Island, Italy, 24–25 September, 2015* (T. Rotonda, M. Cecconi, F. Silvestri & P. Tommasi, editors). Taylor and Francis Group, London.

Moore R. (1991) The chemical and mineralogical controls upon the residual strength of pure and natural clays. *Géotechnique*, **41**, 35–47.

Morgenstern N.R. & Tchalenko J.S. (1967) Microscopic structures in kaolin subjected to direct shear. *Géotechnique*, **17**, 309–328.

Nakano M., Chigira M. & Lim C-S. (2013) Landslides of pumice fall deposits induced by the 2009 Padang earthquake and the formation of halloysite. *Japan Geoscience Union Meeting*, 19–24 May 2013, Makuhari, Chiba, Japan.

Parry S., Campbell S.D.G. & Churchman G.J. (2004) The origin and shear strength of kaolin-rich zones in Hong Kong and their implications for slope stability. Pp. 1342–1353 in: *Advances in Geotechnical Engineering: The Skempton Conference* (R.J. Jardine, D.M. Potts & K.G. Higgins, editors). Thomas Telford, London.

Quinn P.E., Hutchinson D.J., Diederichs M.S. & Rowe R.K. (2011) Characteristics of large landslides in sensitive

https://doi.org/10.1180/claymin.2016.051.3.09 Published online by Cambridge University Press

clay in relation to susceptibility, hazard, and risk. *Canadian Geotechnical Journal*, **48**, 1212–1232.

Reading A.J. (1991) Stability of tropical residual soils from Dominica, West Indies. *Engineering Geology*, **31**, 27–44.

Rigo M.L., Pinheiro R.J.B., Bressani L.A., Bica A.V.D. & da Silveira R.M. (2006) The residual shear strength of tropical soils. *Canadian Geotechnical Journal*, **43**, 431–447.

Santamarina J.C. & Cho G.C. (2004) Soil behaviour: the role of particle shape. Pp. 604–617 in: *Advances in Geotechnical Engineering: The Skempton Conference* (R.J. Jardine, D.M. Potts & K.G. Higgins, editors). Thomas Telford, London.

Simon A.B., Bidló G. & Liautaud G. (1975) On the black cotton soils of North Cameroon. *Engineering Geology*, **9**, 351–357.

Skempton A.W. (1964) Long-term stability of clay slopes. *Géotechnique*, **14**, 77–102.

Skempton A.W. & Northey R.D. (1952) The sensitivity of clays. *Géotechnique*, **3**, 30–53.

Smalley L.J., Ross C.W. & Whitton J.S. (1980) Clays from New Zealand support the inactive particle theory of soil sensitivity. *Nature*, **288**, 576–577.

Tanaka K. (1992) Slope hazards and clay minerals. *Journal of the Clay Science Society of Japan (Nendokagaku)*, **32**, 16–22.

Terzaghi K., Peck R.B. & Mesri G. (1996) *Soil Mechanics in Engineering Practice*, 3rd edition. Wiley, New York.

Theng B.K.G. & Wells N. (1995) The flow characteristics of halloysite suspensions. *Clay Minerals*, **30**, 99–106.

Tonkin & Taylor (2011a) *Bramley Drive Landslip Hazard Assessment.* Report prepared for Western Bay of Plenty District Council by Tonkin and Taylor Ltd. 851378.150 June 2011.

Tonkin & Taylor (2011b) *Landslip Assessment – Ruamoana Place, Omokoroa.* Report prepared for Western Bay of Plenty District Council by Tonkin and Taylor Ltd. 851378.150 August 2011.

Vingiani S., Mele G., De Mascellis R., Terribile F. & Basile A. (2015) Volcanic soils and landslides: a case study of the island of Ischia (southern Italy) and its relationship with other Campania events. *Solid Earth*, **6**, 783–797.

Wang G., Suemine A., Zhang F., Hata Y., Fukuoka H. & Kamai T. (2014) Some fluidized landslides triggered by the 2011 Tohoku Earthquake (Mw 9.0), Japan. *Geomorphology*, **208**, 11–21.

Wen B.P. & Aydin A. (2003) Microstructural study of a natural slip zone: quantification and deformation history. *Engineering Geology*, **68**, 289–317.

Wesley L. (1973) Some basic engineering properties of halloysite and allophane clays in Java, Indonesia. *Géotechnique*, **23**, 471–494.

Wesley L. (1977) Shear strength properties of halloysite and allophane clays in Java, Indonesia. *Géotechnique*, **27**, 125–136.

Wesley L. (2001) Consolidation behaviour of allophane clays. *Géotechnique*, **51**, 901–904.

Wesley L. (2009) Behaviour and geotechnical properties of residual soils and allophane clays. *Obras y Proyectos*, **6**, 5–10.

Wesley L.D. (2003) Residual strength of clays and correlations using Atterberg limits. *Géotechnique*, **53**, 669–672.

Wesley L.D. (2010) Volcanic soils. Pp. 189–222 in: *Geotechnical Engineering in Residual Soils.* Wiley, Hoboken, New Jersy, USA.

Wyatt J.B. (2009) *Sensitivity and clay mineralogy of weathered tephra-derived soil materials in the Tauranga region*. MSc Thesis, University of Waikato, New Zealand.

Wyatt J., Lowe D.J., Moon V.G. & Churchman G.J. (2010) Discovery of halloysite books in a ~270,000 year-old buried tephra deposit in northern New Zealand. Pp. 39–42 in: *Proceedings, 21st Biennial Australian Clay Minerals Society Conference* (G.J. Churchman, J.L. Keeling & P.G. Self, editors). 7–8 August 2010 QUT, Brisbane. (Available at http://www.smectech.com.au/ACMS/ACMS_Conferences/ACMS21/ACMS21.html).

https://doi.org/10.1180/claymin.2016.051.3.09 Published online by Cambridge University Press