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Landslides in sensitive soils, Tauranga, New Zealand

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ABSTRACT

In the Tauranga region sensitive soil failures commonly occur after heavy rainfall events, causing considerable infrastructure damage. Several notable landslides include a large failure at Bramley Drive, Omokoroa in 1979, the Ruahihi Canal collapse in 1981, and numerous landslides in May 2005; recently the Bramley Drive scarp was reactivated in 2011. These failures are associated with materials loosely classified as the Pahoia Tephras - a mixture of rhyolitic pyroclastic deposits of approximately 1 Ma.

The common link with extreme rainfall events suggests a pore water pressure control on the initiation of these failures. Recent research on the structure of the soils shows a dominance of halloysite clay minerals packed loosely in arrangements with high porosity (51 – 77 %), but with almost entirely micropores. This leads us to conclude that the permeability is very low, and the materials remain continuously wet. The formation of halloysite is encouraged by a wet environment with no episodes of drying, supporting this assumption.

A high-resolution CPT trace at Bramley Drive indicates induced pore water pressures rising steadily to a peak at approximately 25 m depth; this depth coincides with the base of the landslide scarp. We infer that elevated pore water pressures develop within this single, thick aquifer, triggering failure through reduced effective stresses. The inactive halloysite clay mineral results in low plasticity indices (13 – 44 %) and hence high liquidity indices (1.2 – 2.4) due to the saturated pore space; remoulding following failure is sudden and dramatic and results in large debris runout distances.

1. INTRODUCTION

In the Tauranga region sensitive soil failures commonly occur after heavy rainfall events, causing considerable infrastructure damage. A history of large landslides over the past 35 years includes:

- a large failure at Bramley Drive, Omokoroa in 1979, as a result of which 5 houses were removed (Gulliver and Houghton, 1980);
- the collapse of the Ruahihi Canal in 1981 which resulted in more than 1 million m^3 of material being eroded and transported into the Wairoa River (Hatrick, 1982); and
- a series of landslides in various parts of Tauranga City and its surroundings in May 2005.

Recently, the Bramley Drive scarp, which had remained essentially stable for 30 years and had developed a good vegetation cover, was reactivated in 2011, and continued regression of the scarp face has occurred throughout 2012 (Figure 1).

Figure 1: Reactivated landslide at Bramley Drive, Omokoroa, January 2013.

A striking feature of these landslides is the long run-out distance of the debris and apparent fluidity of the debris flow. This long runout is associated with, and evidence of, the sensitive nature of many materials in the Tauranga region (Keam, 2008, Wyatt, 2009, Arthurs, 2010, Cunningham, 2013). Sensitivity is recognised as 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 considered sensitive, 8 – 16 are "extra sensitive", and > 16 are referred to as "quick clays" (New Zealand Geotechnical Society, 2005).

Sensitive behaviour is well described from glacial outwash deposits in Norway and Canada, where leaching of salt from an open, flocculated structure in low activity illite clay minerals results in a loss of cohesion of the soils, which are then prone to failure in response to a weak trigger. Characteristic failures are spreads and flows as the loose structure contains large quantities of water that is released upon remoulding. In Tauranga however, we do not have glacial clays, and the sensitivity is developed in sequences of rhyolitic pyroclastic materials, including primary pyroclastic fall deposits (tephra), pyroclastic flow deposits (ignimbrite), and a wide variety of reworked pyroclastics including slope wash, fluvial, and aoelian variants. A different origin for the development of sensitivity in these materials is thus needed. This paper considers the microstructural influences on the properties of the soils leading to sensitivity.

2. MATERIALS

The stratigraphic sequence seen in the Tauranga area is complex, but an overall stratigraphy recognizes several "packages" of material that are well exposed in the present scarp of the Bramley Drive failure at Omokoroa where the sequence is very thick (Figure 2). At the top are Pleistocene and Holocene materials representing recent eruptives, predominantly from the Taupo Volcanic Zone, and modern soil materials; the base of this unit is comprised of the Rotoehu Ash of approximately 60,000 years (Briggs *et al.*, 1996). The Rotoehu Ash lies on a very distinctive paleosol formed on the Hamilton Ashes. The Hamilton Ashes are comprised of a series of tephra deposits with intercalated paleosols ranging from ~0.08 to 0.38 Ma (Lowe *et al.*, 2001). At Bramley Drive the Hamilton Ashes reach a total thickness of ~ 9 m; this thickness is variable around the region. The Hamilton Ashes lie on top of another very well developed, dark brown paleosol (Figure 2) which marks the top of the Pahoia Tephra sequence – a poorly defined sequence of primary and reworked rhyolitic volcaniclastic materials ranging in age from approximately 0.35 to 2.18 Ma (Briggs *et al.*, 1996). The Pahoia Tephras are part of the Matua Subgroup which is a widespread, complex unit throughout the Bay of Plenty (Briggs *et al.*, 1996). At the Bramley Drive site, the Pahoia Tephras include at least 6 units to a thickness of > 12 m. Below this is believed to be the Te Puna Ignimbrite (Briggs *et al.*, 1996, Gulliver and Houghton, 1980) based on nearby exposures, which in turn is underlain by a lignite deposit at shore platform level.

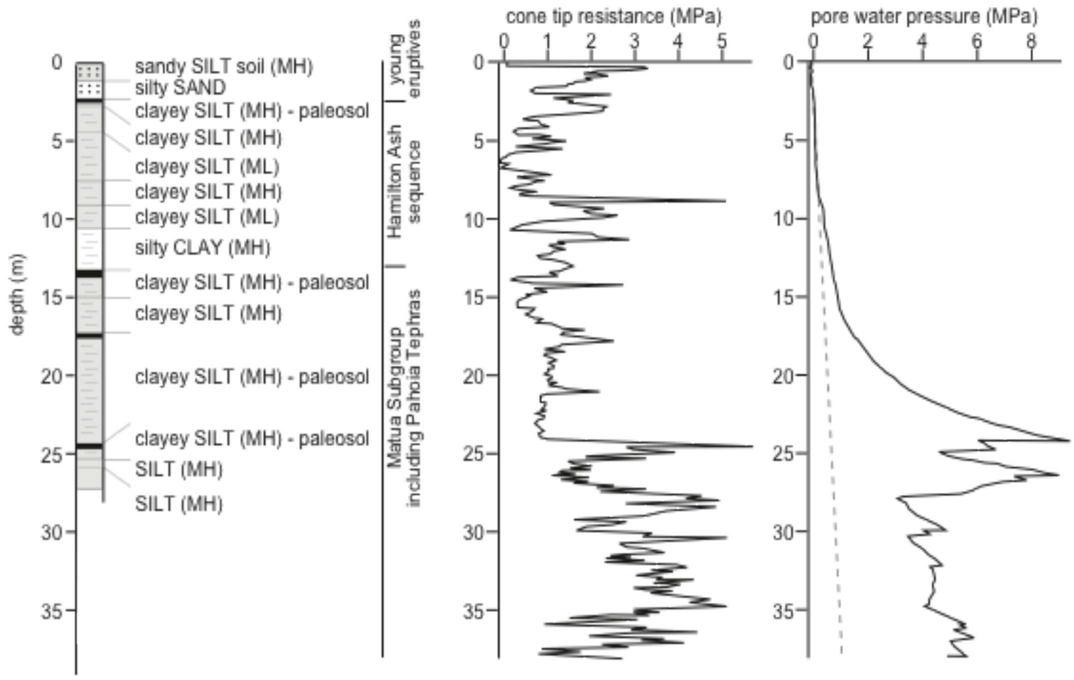

Figure 2: Profile log and cone penetrometer trace from the scarp of the Bramley Drive landslide. CPT trace measured in March 2012, profile log described in January 2013; textural descriptions are from particle size analysis, classification from Atterberg limits.

It is the Pahoia Tephras that are associated with the sensitive soil failures observed in the Tauranga region. This sequence is in places very thick, but thinner in others, and it is difficult to correlate single layers across any significant distance. It is likely that many of the units are formed by local reworking of primary pyroclastic material, and hence have small lateral extents. In this paper, materials from individual units within the Pahoia Tephras at Omokoroa Peninsula (OMOK1 and OMOK2), Pahoia Peninsula (PAHO1), Te Puna (TEPU1), Otumoetai (OTUM1, OTUM2, OTUM3 and OTUM4), and Tauriko (TAUR1, TAUR2 and TAUR3) were sampled and tested. Site locations are presented in Table 1, and further details of site stratigraphy and sample locations can be found in Wyatt (2009) and Cunningham (2013).

Sampling was undertaken based on recognition of sensitive layers in the field from vane shear tests following standard methods (New Zealand Geotechnical Society, 2001). A selection of data from sensitive units is presented in Table 1. Mineralogy was determined from XRD analysis of both bulk samples and clay separates. Natural water content, dry bulk density, and Atterberg limits were determined following ISO standards (ISO/TS 17892-1:2004(E), ISO/TS 17892-2:2004(E), ISO/TS 17892-12:2004(E)), except that specimens were not allowed to dry when preparing for Atterberg limits tests; and particle density was determined using density bottles following the method outlined by Head (1992). Effective cohesion and friction angle from consolidated, undrained triaxial testing were measured following standard BS 1377-8:1990. Coefficients of consolidation (c_{vi}) and volume compressibility (m_{vi}) were determined for each applied loading in consolidation stages of the triaxial testing (BSI, 1999), and the coefficient of permeability was estimated using the method described by Head (1986).

Texturally, the samples are identified in the field as clayey silts or silty clays. This is in keeping with a pyroclastic fall (tephra) origin, but does not preclude reworking of initial tephra deposits as suggested by Arthurs (2010). Mineralogically the samples are dominated by glass or alteration products of volcanic glass (Table 1). The clay mineralogy is in all cases dominated by halloysite clay minerals, with some kaolinite also identified in OTUM3 and OTUM4 samples. Allophane was not identified in any of the samples. Sensitivity values (Table 1) show generally "sensitive" to "extra sensitive" materials (New Zealand Geotechnical Society, 2005). These values are comparable with others measured on volcanic soils in NZ, both in Tauranga (Wesley, 2007, Keam, 2008, Arthurs, 2010) and more widely (Jacquet, 1990). Dry bulk density is typically very low (Table 1), with associated high porosity and void ratio values. Natural moisture content is high, meaning that the soils are characteristically at or close to saturation in their normal field conditions (Table 1).

Atterberg limits (Table 1) are high, but are in keeping with those measured on halloysite-dominated soils in Indonesia by (Wesley, 1973), though values of the plastic and liquid limits and plasticity index all extend to lower values than the ranges given by Wesley (1973) suggesting the inclusion of some dehydrated halloysite. All samples plot below, but parallel to, the A-line in the same range as shown for halloysite soils by Wesley (1973); they are classed as high compressibility silts (MH). Likewise, effective strength parameters (c', ϕ') are also high; they span a range for the soils measured, but averages of c' = 15 kN m^{-2} and ϕ' = 33° are in agreement with Wesley's (1973) values.

Estimated coefficients of permeability are generally within the range of 10^{-8} to 10^{-9} m s^{-1}, in keeping with Wesley's (1977) results in the range of 10^{-7} cm s^{-1}. Wesley interprets this as a high permeability given that the soils he was considering were dominantly clay materials. In this case, however, the soils have a very large silt component, and the measured coefficients of permeability are much lower than might be anticipated.

3. MICROSTRUCTURE

Components of the microstructure include:

- glass fragments which are generally angular and show pumice vesicle wall forms indicating the fragmental pyroclastic origin (Figure 3A) - these are generally of silt to fine sand sizes;
- occasional sand-sized quartz and plagioclase crystals; and
- ubiquitous fine clay-size (< 2 μm) material (Figure 3B).

Halloysite is commonly envisaged as a tubular mineral (Joussein *et al*., 2005). However, in the halloysites identified here a wide range of morphologies is seen, including tubes (Figure 3C) which range from common short, stubby forms (< 0.4 μm) to less common long tubes up to 2 μm, plates (up to 2 μm) that have coalesced into books as large as 50 μm long (Figure 3D), and spheres of approximately 0.2 – 0.7 μm (Figure 3F).

The microstructure sees few grain-to-grain interactions, with most being mediated by clays (Figure 3B). Interactions between matrix clay minerals create a flocculated structure, but not in the normal way of a card house, in this case the tubes etc interact by edge contacts alone as there are no platy surfaces (Figure 3E). Interaction of clays in this way results in a highly porous structure (porosity 62 – 77 %), but the pore space is hugely dominated by ultrapores (< 0.1 μm) and micropores (< 5 μm) with dominant pore sizes being < 1 μm (Figure 3F). Whilst these micropores impart high porosity, we infer that they are poor at transmitting water, hence the low measured coefficients of permeability.

4. CONE PENETROMETER

A cone penetrometer test (CPT) was undertaken at a site immediately behind the scarp of the Bramley Drive landslide at Omokoroa in February 2012. The instrument used (GOST) is an offshore CPT instrument developed at Bremen University (MARUM – Center for Marine Environmental Sciences) in Germany. GOST incorporates a small (5 cm^2) piezocone, and thus gives high-resolution traces. The traces of tip resistance and pore water pressure are shown alongside a graphic log of the scarp face in Figure 2.

Table 1. Measured geomechanical data for sensitive materials from the Tauranga region. [1] Data for halloysite and allophane from Indonesia from Wesley (1973, 1977), [2] Allophane data from Wesley (2010).

	location (NZTM)	peak vane strength (kN m^{-2})	remoulded vane strength (kN m^{-2})	sensitivity	dry bulk density (kg m^{-3})	porosity (%)	natural moisture content (%)	void ratio	saturation (%)	PL	LL	PI	LI	c' (kN m^{-2})	phi' (°)	permeability (*10^{-9} m s^{-1})
OMOK1	5831082.0N 1868958.5E	92 ± 6	8 ± 6	11 ± 0.6	834 ± 14	66 ± 3	84 ± 4	1.9 ± 0.1	107 ± 8	46	72	27	1.44	8.0	37.0	-
OMOK2	5831082.0N 1868958.5E	74 ± 4	5 ± 0.6	15 ± 2	779 ± 14	68 ± 3	89 ± 1	2.1 ± 0.1	103 ± 8	51	74	22	1.71	16.0	28.0	-
TEPU1	5827011.0N 1872145.4E	122 ± 6	12 ± 1	11 ± 2	688 ± 6	69 ±1	109 ± 7	2.2 ± 0.1	109 ± 9	46	89	44	1.45	16.0	41.0	-
PAHO1	5831343.7N 1865826.9E	69 ± 2	6 ± 0.3	11 ± 0.5	975 ± 2	62 ± 3	68 ± 2	1.6 ± 0.1	108 ± 7	34	53	19	1.79	15.0	32.0	-
PAHO2	5831269.8N 1865368.7E	67 ± 2	8 ± 0.3	9 ± 0.4	952 ± 8	63 + 3	70 ± 2	1.7 ± 0.1	106 ± 7	36	54	18	1.91	10.0	36.0	-
TAUR1	5817385.4N 1872985.1E	58 ± 3	6 ± 3	9 ± 1	656 ± 41	74 ± 5	115 ± 1	2.9 ± 0.3	103 ± 12	57	81	24	2.39	11.8	27.3	0.5
TAUR2	5817385.4N 1872985.1E	45 ± 3	2 ± 3	20 ± 2	589 ± 13	77 ± 3	109 ± 1	3.3 ± 0.2	83 ± 8	47	73	26	2.41	-	-	-
TAUR3	5817385.4N 1872985.1E	151 ± 3	34 ± 3	5 ± 1	966 ± 10	62 ± 3	64 ± 1	1.6 ± 0.1	100 ± 8	39	52	13	1.88	24.0	31.1	6.2 ± 4.7
OTUM1	5824797.3N 1877275.8E	101 ± 6	13 ± 4	8 ± 1	656 ± 8	75 ± 3	104 ± 3	3.0 ± 0.2	91 ± 8	47	90	43	1.33	34.5	25.7	160 ± 130
OTUM2	5824797.3N 1877275.8E	125 ± 7	15 ± 3	10 ± 1	893 ± 51	66 ± 4	69 ± 4	2.0 ± 0.2	94 ± 12	32	57	25	1.46	4.7	38.5	130 ± 120
OTUM3	5824797.3N 1877275.8E	> 227	36 ± 3	> 6	920 ± 15	65 ± 3	66 ± 3	1.9 ± 0.1	93 ± 8	54	96	42	0.27	8.3	35.4	22 ± 17
OTUM4	5824797.3N 1877275.8E	72 ± 8	5 ± 3	14 ± 0.5	743 ± 9	72 ± 3	86 ± 3	2.6 ± 0.1	88 ± 8	37	73	36	1.35	13.7	28.5	130 ± 40
ranges		**45- >227**	**2 - 36**	**5 - 20**	**656-975**	**62-77**	**64 - 109**	**1.6-3.3**	**83 - 100**	**32 - 57**	**52 - 96**	**13-44**	**0.3-2.4**	**5-35**	**27-41**	**0.5 - 160**
halloysite[1] Indonesia				not sensitive			31-51		100	55-75	70-110	20-45		14	37	1 - 13
allophane[1] Indonesia				not sensitive			68-180		100	65-150	85-190	20-50		14	37	10.8 - 27
allophane[2]				5 – 55			50 - 300	1.5 - 8	90 - 100				0 - >1	20	40	

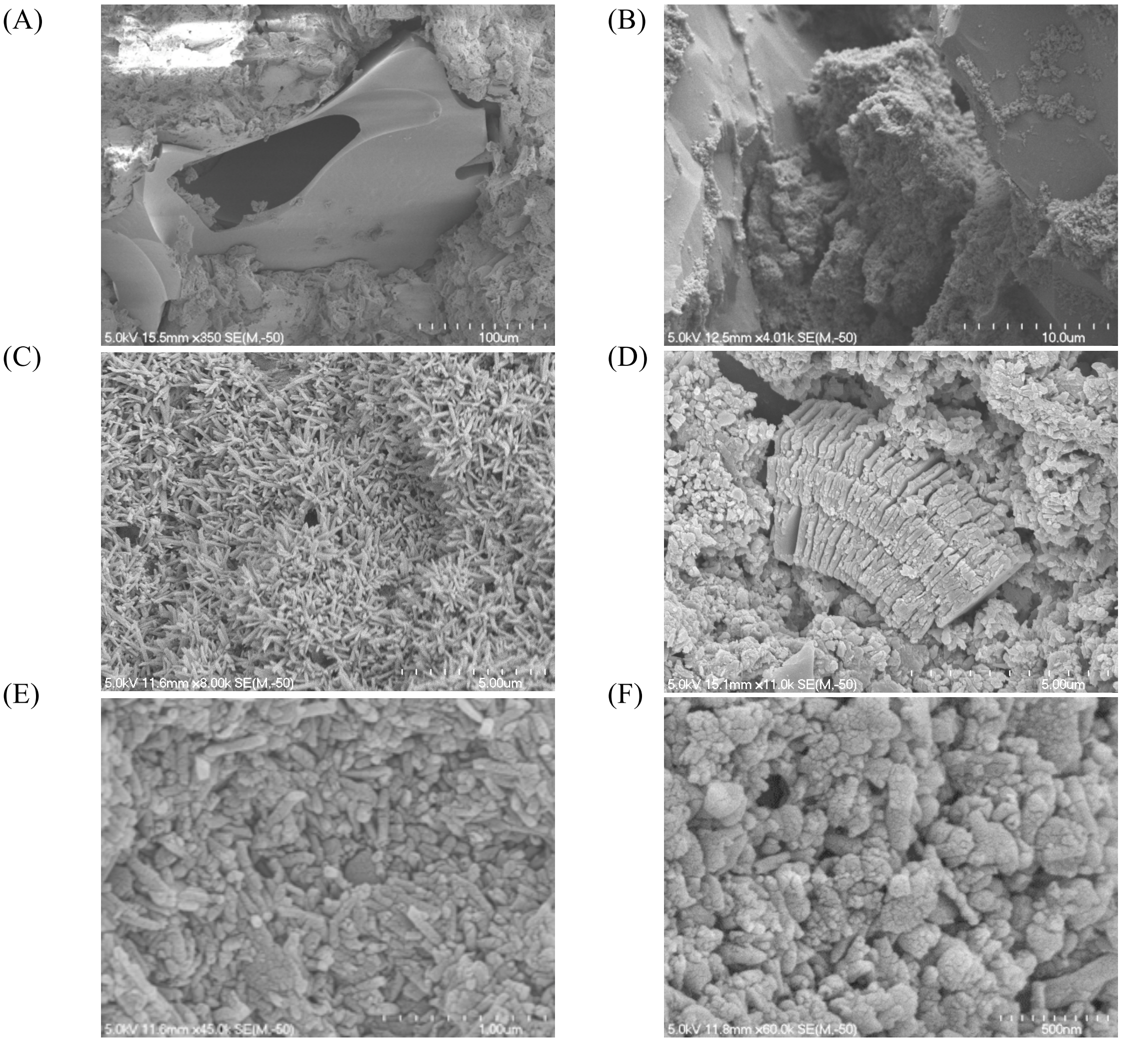

Figure 3: (A) Glass fragment from Tauriko showing vesicular pyroclastic texture. (B) Accumulated clay minerals forming bridge between two glass shards. (C) Typical tubular halloysite forms. (D) Platy halloysite joined to form books. (E) Edge to edge contacts between tubular clay minerals form an open, porous structure. (F) Spherical clay mineral grains form ultrapores. Photos H. Turner.

In the CPTu profile, the tip resistance is responsive to effects of soil formation, with increased tip resistance near the present ground surface, and spikes in the measured resistance at each of the identified paleosols. Between these spikes, the tip resistance of the materials is generally low (< 1.5 MPa). However, just below the exposed sequence (about 28 m), the tip resistance increases, and generally stays high until the maximum depth of 38 m was reached; this represents the ignimbrite underlying the Pahoia Tephra sequence.

The pore water pressure shows a water table depth of approximately 1.5 m, followed by a steady rise in induced water pressures to a depth of 24 m. It then falls sharply at this point, corresponding with a spike in the tip resistance (a coarser layer) and then rises to a further peak at approximately 28 m, after which the induced pore water pressures fall in the ignimbrite, though still remain above hydrostatic. A zone from about 17 – 24 m depth shows particularly high induced pore water pressures, indicating low permeability in these materials. This location is believed to be the approximate position of the initial failure zone for the 1979 failure at Bramley Drive (Gulliver and Houghton, 1980), where it was assumed to lie near the contact of the ignimbrite and overlying materials.

From this we infer that there is essentially a single aquifer overlying the ignimbrite near the base. There seems to be little leakage through any more permeable zones, and even the paleosols, which have a well-developed soil structure that in other traces in the region allow partial water transmission (Jorat *et al*., in press), are of low permeability. The only "leak" is in the zone just below 24 m, above the top of the ignimbrite, but within the volcaniclastic sequence.

5. DISCUSSION

In summary, the results presented here show these halloysite-dominated soils to have high porosity, high Atterberg limits, but with non-plastic characteristics, and high shear strength, all in keeping with previously published data for halloysite. The materials are saturated under field conditions, and with high porosities they have liquidity indexes typically greater than one. These conditions make for highly sensitive materials with low remoulded strength.

Initial estimates of the permeability from laboratory testing suggest low permeabilities. These values are supported by the CPTu testing that indicates that the profile at Bramley Drive consists largely of a single aquifer with very high induced pore water pressures developed in poorly-drained materials. The microstructure of these materials shows a variety of morphologies of the halloysite minerals, but most importantly, the clay sizes are small, and their arrangements mean that the high porosity occurs almost entirely within very small pore spaces. Thus, the materials can hold very large amounts of water, but that water cannot move readily within the soils (low permeability).

Wesley (1973, 2010) suggests that allophane is transformed to halloysite as a later stage in the weathering sequence. However, more recent work indicates that allophane and halloysite form directly from dissolution of primary minerals via different pathways. Halloysite formation is favoured by a Si-rich environment (Joussein et al, 2005) and a wet, even "stagnant", moisture regime (Churchman et al., 2010). Allophane, conversely, forms preferentially in soils where Si is low in solution, allowing development of Al-rich allophane. This occurs with better drainage where Si is removed from the profile, and in andesitic materials where the original Si content is lower. Thus, halloysite forms preferentially in the Tauranga region where the overlying rhyolitic Hamilton Ashes provide a ready source of Si that is leached into the Pahoia Tephras; the high porosity yet low permeability of these units results in consistently high natural moisture contents with limited water transport.

The materials at the top of the profile are highly permeable, allowing rapid infiltration of surface water. Deeper layers have lower permeability, meaning that transport from the profile is low, and water tables remain high year-round, creating consistently high saturation levels. Consequently, pore water pressures can rise quickly and easily, triggering failure; the very high porosity and high liquidity indexes result in sensitive soils that generate extensive debris flows.

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