QJEGH

Research article

Quarterly Journal of Engineering Geology and Hydrogeology

Published online January 25, 2019

https://doi.org/10.1144/qjegh2018-140 | Vol. 52 | 2019 | pp. 336–345

Engineering characteristics of soils prone to rainfall-induced slope failure in Viti Levu, Fiji

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Abstract: Fiji's infrastructure is regularly affected by rainfall-induced slope failures, but the engineering properties of failed soils are rarely described. We report mineralogical, geotechnical and index properties of soils from headscarp exposures of 18 slope failures from tropical residual soils of differing parent rocks in Viti Levu, Fiji. Scanning electron microscopy and X-ray diffraction revealed that kaolinite and smectite are the dominant clay minerals in the soils. Index properties included *in situ* moisture content (28–114%), dry bulk density (0.7–1.5 g cm^{-3}), Atterberg limits (25–56% plastic limit; 38–79% liquid limit), effective particle size (0.4–12.6 µm) and clay fraction (0.6–19%). Geotechnical measurements included field compressive strength (127–461 kPa), hydraulic conductivity (*c.* 10^{-7} m s^{-1}), shear vane (16–128 kPa), ring shear (9.3–17.4°) and Emerson dispersion. Collectively, results indicated that most of the soils were cohesive, stiff, sensitive and in a plastic state in the field. Soils plotted below the A-line on the plasticity chart as fine silts of intermediate to high plasticity, and can theoretically sustain >50° slopes. Failure of these soils following high rainfall events is influenced by low permeability and the presence of expanding clays (e.g. smectite), causing temporary porewater pressure increases. No explicit relationships between soil properties and parent lithology were evident.

Received 26 September 2018; **revised** 18 October 2018; **accepted** 2 November 2018

Tropical soils include a wide variety of pedogenic materials, of which the engineering behaviour and material properties can vary significantly (Fookes 1997). In particular, the high amount of rainfall combined with the deeply weathered nature of tropical soils of Viti Levu makes the largest volcanic island of the Fiji Group highly susceptible to rainfall-induced slope failures (e.g. Cochrane 1969; Crozier *et al.* 1981; Nunn 1990; Terry 2007; Stephens *et al.* 2018). Many of these are shallow failures (typically 1–5 m deep) and are usually confined to the wet season. Collectively, the landslides significantly affect the country's infrastructure and economy (see Lawson & Dau 1992; Greenbaum *et al.* 1995). Single storm events are also highly efficient landslide-generators; for example, Tropical Cyclone Winston in 2016 was the strongest cyclone on record in Fiji and caused widespread flooding and slope failures. Winston-related infrastructure losses were at least FJ$246.8 million (US$121.7 million), half within the transport sector alone (Esler 2016). Although previous studies in Fiji have related slope failure occurrence to rainfall thresholds (e.g. Lawson & Dau 1992; Terry 2007) and environmental factors (e.g. Cochrane 1969; Crozier *et al.* 1981; Stephens *et al.* 2018), few studies have explored the role that engineering characteristics of soils play in slope failure in Viti Levu. This is despite Lovegrove & Fookes (1972) highlighting that a key geotechnical issue is the stability of highway cuttings in residual soil and weathered rock in SE Viti Levu. An important characteristic of residual soils (those formed by high degrees of deep weathering of bedrock) is the low strength owing to the destruction of bedrock coherence and cementation during the weathering process (Fookes 1997). Under dry conditions, residual soils appear to have high shear strength, but as they become saturated, their shear strength reduces markedly, toward very low effective cohesion (Wesley 1990). Residual soils also tend to have higher permeability and porosity compared with the underlying parent rock, often leading to shallow failures and stripping of soil layers from bedrock contacts in high rainfall events (Wesley 2010). Residual soils can, however, have highly variable properties, depending on the bedrock geology, slope, vegetation and other factors (Fookes 1997), so that universal assessments of slope stability are problematic in areas of marked lithological or soil heterogeneity.

Most previous studies of the residual soils in Viti Levu, Fiji (e.g. Lovegrove & Fookes 1972; Knight 1986; Bronders 1994) have emphasized different aspects of their engineering characteristics. These studies have not explicitly examined relationships between parent rock type and engineering characteristics of residual soils or focused on areas of slope failures. The aim of this paper is to present the results of an investigation of residual soils at 18 slope failures across different lithological settings along three roads in Viti Levu: Kings Road (KR), Namosi Road (NR) and Lololo Road (LR). These sites are susceptible to rainfall-induced landslides and are immediately adjacent to highways of national strategic significance to Fiji. KR is one of the two major routes used by Viti Levu road commuters and tourists to travel around the eastern half of the island, LR is located within a major pine forest area and NR services the area of a large-scale copper mining lease. The objectives are to (1) characterize the mineralogical, index and geotechnical properties of weathered residual soils prone to rainfall-induced slope failures in Viti Levu, Fiji, and (2) probe relationships between residual soil properties and parent rock lithology. This will help determine priorities in slope-failure mitigation strategies in the study area from a geotechnical standpoint.

Study area

Fiji is in the Pacific Ocean, *c.* 3000 km east of Australia and 2000 km NE of New Zealand. The archipelago totals *c.* 18 300 km^2 in land area spread over an area of 194 000 km^2, comprising 332 predominantly volcanic islands of which 110 are inhabited and 222 are uninhabited, and 522 additional islets. Viti Levu, the focus of this study, is the largest Fijian island at 10 300 km^2, and is where the majority of Fiji's population of about 900 000 reside. Fiji's geological history includes a period of subduction forming an island arc, with later uplift, rotation and deformation as a result of back-arc extension and shear deformation (Begg & Gray 2002). Fiji currently sits on a prominent offset of the convergent boundary between the Pacific and Australian tectonic plates. The geology of Viti Levu is mapped within six groups (Fig. 1; Hathway 1993; Rodda 1994). The oldest rocks, the Yavuna Group, formed in the Late Eocene to Early Oligocene. They occur in southwestern Viti Levu and consist of basaltic lavas and intrusive rocks with minor epiclastic conglomerates and limestones. The overlying Wainimala Group, formed in the Early Oligocene to Middle Miocene, mainly comprises volcaniclastic rudites, lavas including reef limestones and thinly bedded marine sediments. The Wainimala Group covers most of southern Viti Levu and forms a broad, ENE–WSW-trending anticline, the core of which was intruded by stocks of the Colo Plutonic Suite from the Middle to Late Miocene. Rocks of the Colo Orogeny form the third group, and are mainly low-potassium tholeiitic gabbros, tonalites and trondjhemites. Erosion of the emergent landmass in the Middle to Late Miocene formed sediments of the Wainimala Group. Intermediate and basic high-K lavas of the shoshonite association erupted in the Late Miocene and Early Pliocene, initially in NW Viti Levu, forming rocks of the Koroimavua Volcanic Group. Later, calc-alkaline lavas (termed the Ba Volcanic Group) erupted across the northern half of the island, forming the sixth and youngest volcanic group of rocks (Rodda 1994).

Located close to the Tropic of Capricorn, Fiji experiences a tropical maritime climate with narrow temperature extremes (Fiji Meteorological Service 2006), a dry season from May to October and a wet season from November to April. The NE–SW orientation of mountains in central Viti Levu produces an orographic effect on prevailing SE trade winds, producing dry leeward and wet windward conditions (Terry 2007). Annual rainfall ranges from 2000 to 6000 mm a^{-1}, and temperatures range from 22 to 27°C, for the dry and wet seasons, respectively (Leslie 1997). The wetter southeastern and central parts of Viti Levu promote a growth of thick rainforest cover, whereas the west and north is under sugar cane and other plantation crops or covered by *talasiga* grassland and scrub. This study focuses on residual soils along KR, LR and NR, across eastern, western and southern Viti Levu, respectively, with parent rocks belonging to Ba Volcanic Group, Wainimala Group, Medrausucu Group, and Ra and Verata Sedimentary Groups (Fig. 1). Whereas KR falls in the intermediate rainfall zone of Viti Levu, NR is in the wet zone and LR in the dry zone. Rock is typically moderately to strongly weathered, and residual soils are formed more than several metres deep in many places. Previous investigations during road (e.g. Lovegrove & Fookes 1972), bridge (e.g. Amir-Ansari 2013) and dam (e.g. Knight 1986) construction in Viti Levu revealed that high tropical rainfall amounts, combined with hot and humid conditions, cause deep bedrock weathering, but to varying degrees depending on lithology. A six-stage weathering profile classification scheme was developed by Lovegrove & Fookes (1972) for southern Viti Levu, and this is adopted for this study (Fig. 2).

Methods

Soils were sampled using cores from the upper zone of residual soil profiles (Fig. 2) exposed within the headscarps of 18 slope failures located on different parent rock types along the three roads. Additional soil samples were collected for X-ray diffraction (XRD) and scanning electron microscopy (SEM). Each slope failure was located using a Trimble Juno 3B GPS (global positioning system), which has an accuracy of 1–4 m. Field description of soils was undertaken using the New Zealand Geotechnical Society Guidelines (NZGS 2005), and the vegetation and topography around the sampling sites were also noted (Table 1). A Geonor H60 hand-held shear vane tester and Eijkelkamp pocket penetrometer were used to obtain *in situ* soil strength values. The field saturated hydraulic conductivity on headscarps of selected soil failures was measured using procedures outlined by Hatt & Le Coustumer (2008). For moisture content and dry bulk density, core samples were oven-dried to 105°C. Dry samples were crushed and sub-sampled for particle-size distribution analysis using a Malvern Mastersizer 2000. The Atterberg limits were obtained on the <0.425 µm fraction of soil samples using the procedure outlined in BS 1377-2 (BSI 1998). Residual friction angle was investigated for selected soil samples using a Bromhead ring shear apparatus (Bromhead 1979), whereby samples were remoulded close to their

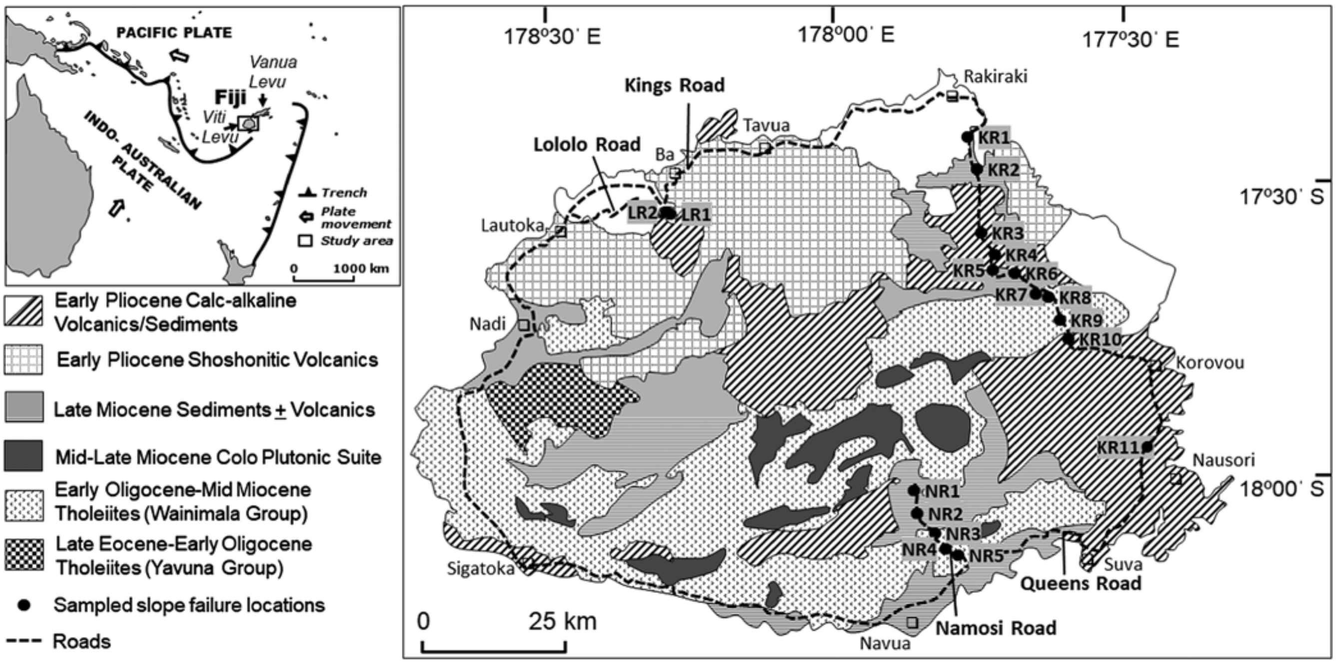

Fig. 1. Generalized geological map of Viti Levu, Fiji showing locations of sampled slope failures along KR, NR and LR. Inset map shows regional geological setting of Fiji (adapted from Begg & Gray 2002).

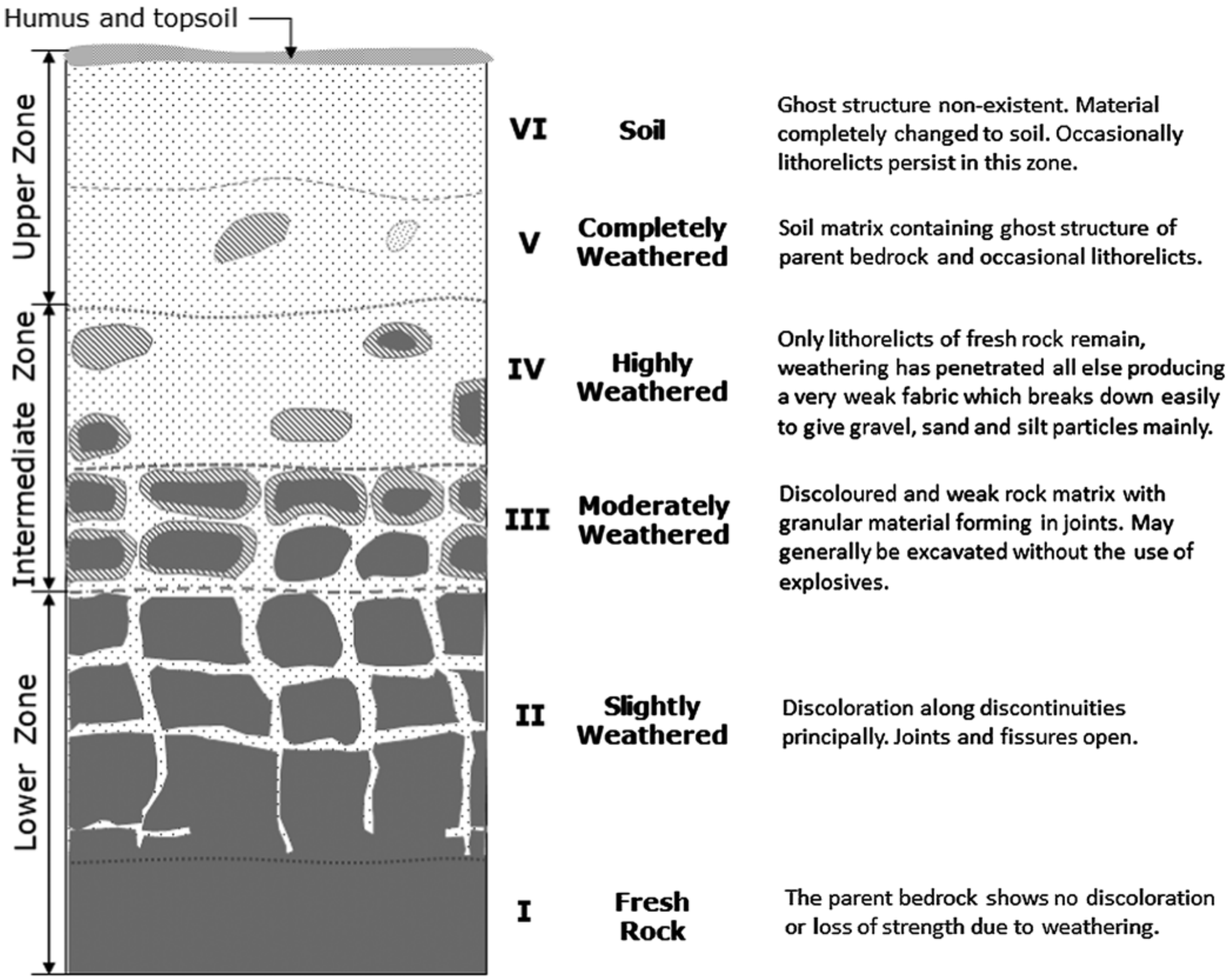

Fig. 2. Typical weathering profile of residual soils in Fiji (modified from Lovegrove & Fookes 1972).

plastic limit. Soil dispersion potential was investigated using the Emerson class number, following the procedure outlined in AS 1289.3.8.1 (Standards Australia 2006). Recognizing that the behaviour of soft and expansive soils is largely dominated by the amount and type of clay minerals present (Mitchell & Soga 2005), a PANalytical Empyrean X-ray diffractometer was used to obtain XRD diffractograms for clay mineral identification. Additional analysis of clay minerals was carried out on air-dried soil samples using an FEI Quanta 200 field emission environmental SEM (ESEM) to image the soil microfabric and characteristic clay mineral shapes.

Results

Descriptions of the soil characteristics and environmental setting of the 18 sites are reported in Table 1 and Figure 3. Sites ranged in elevations from 34 to 357 m above sea-level. The KR sites were mostly under mixed vegetation whereas the LR and NR sites were within pine forest and rainforest, respectively. Although none of the residual soils at the sampling sites exposed the full weathering profile to bedrock, the visible zones were typical of V and VI as outlined by Lovegrove & Fookes (1972; Fig. 2) with a diffuse boundary between the two zones (Fig. 3). Soil samples were obtained from zone VI, although some could have been taken from the uppermost portion of V. A summary of the minerals found in the clay fraction of the soil samples from XRD and ESEM and their relative abundances are reported in Table 2, with example XRD patterns for untreated, glycolated and heated clay soil from the NR1 site reported in Figure 4a. Kaolinite was the most common clay mineral in almost all samples, followed by smectite. Residual feldspar and quartz were also present in significant amounts in half of the samples analysed (Table 2). Interlayered clay minerals such as kaolinite–illite and smectite–chlorite occurred in high amounts in LR1 and NR2, respectively. Illite was identified in significant quantities in two samples, KR7 and NR1 (Fig. 4a). Vermiculite occurred in trace amounts in KR8, and sample KR5 contained trace amounts of calcite. Imaging of the soil samples under ESEM confirmed the presence of these minerals as well as identifying an additional mineral, erionite (a type of zeolite) within the KR2 soil sample (Fig. 4b).

Table 3 summarizes the soil index properties of the samples. The *in situ* moisture content of the samples ranged from 28 to 114%, the plastic limit (PL) from 25 to 56% and the liquid limit (LL) from 38 to 79%. Approximately half of the samples had field moisture contents close to the LL and based on plasticity index (PI) have medium to high plasticity, with the exception of the low-plasticity sample KR2. The samples have dry bulk density values ranging from 0.7 to 1.5 g cm^{-3} and effective particle size (D_{10}) ranged from 0.4 to 12.6 µm. The particle-size distribution graph shows that for all the samples their percentage fine fraction (<60 µm) is close to or greater than 35%, thus the soils are cohesive (Fig. 5). The amount of clay in the samples varied from 0.6 to 19% (Table 3), and all

Table 1. *Location, underlying lithology and topographic description of sampled slope failures in the study area*

Site	Latitude (S)	Longitude (E)	Elevation (m)	NZGS field description	Topography and vegetation
KR1	17°26′7.59"	178°13′42.30"	34	Silty CLAY, some sand; light brown. Firm, moist, low plasticity (VG)	Flatland with sparse vegetation
KR2	17°29′59.10"	178°14′27.90"	34	Sandy SILT, some clay; yellowish brown, mottled black and white. Very soft, moist, low plasticity (SD)	Hillslope with grassland
KR3	17°35′17.90"	178°14′45.20"	56	Silty CLAY, minor sand; reddish brown, mottled black. Stiff, dry, low plasticity (BS)	Adjacent to terrace with mixed vegetation
KR4	17°37′47.40"	178°15′28.30"	47	Silty CLAY, some sand, trace organic matter; reddish brown, mottled black. Firm, moist, medium plasticity (RB)	Adjacent to terrace with grassland
KR5	17°39′22.00"	178°16′41.90"	40	Clayey SILT, some sand, minor gravel; light greyish brown. Firm, moist, low plasticity (WC)	Hillslope near river terrace, mixed vegetation
KR6	17°39′28.26"	178°16′48.66"	38	Silty CLAY, minor sand, trace gravel; orangish brown. Firm, moist, low plasticity (WC)	Hillslope near river terrace with grassland
KR7	17°39′37.10"	178°17′3.00"	60	Silty CLAY, some sand; reddish brown, mottled orange, white and black. Firm, moist, low plasticity (WC)	Gentle hillslope with grassland
KR8	17°40′26.90"	178°20′02.70"	48	Sandy CLAY, some silt; reddish brown. Soft, moist, high plasticity (LS)	Steep hillslope with disturbed forest
KR9	17°44′14.94"	178°23′24.48"	34	Silty CLAY, trace gravel; brownish orange. Firm, moist, high plasticity (WT)	Adjacent to river terrace with scrubland
KR10	17°46′52.88"	178°26′23.52"	145	Silty CLAY, some sand; light brownish orange. Soft, moist, high plasticity (NS)	Flatland with grassland
KR11	17°58′07.80"	178°31′40.00"	58	Silty CLAY, some sand; greyish orange. Soft, moist, medium plasticity (WS)	Hillslope near floodplain with mixed vegetation
LR1	17°34′55.27"	177°40′8.81"	123	Silty CLAY, minor sand; light brownish orange, mottled white. Firm, moist, low plasticity (UB)	Gentle hillslope with disturbed pine forest
LR2	17°34′56.11"	177°40′5.25"	132	Silty CLAY, minor sand; light brownish orange, mottled white. Firm, moist, low plasticity (UB)	Gentle hillslope within disturbed pine forest
NR1	18°2′52.71"	178°9′14.32"	295	Silty CLAY, minor sand; light grey, mottled yellow and white. Firm, moist, high plasticity (NA)	Hillslope within forest
NR2	18°3′29.48"	178°9′28.71"	357	Clayey SILT, minor organic matter; yellowish brown, mottled white. Soft, moist, low plasticity (NA)	Hillslope within forest
NR3	18°6′37.15"	178°10′58.31"	275	Silty CLAY, some sand, trace organic matter; reddish brown, black on fracture surface. Firm, moist, low plasticity (TT)	Hillslope within forest
NR4	18°6′51.81"	178°11′15.86"	277	Sandy SILT, some clay; light pinkish brown, mottled white. Firm, moist, low plasticity (TT)	Hillslope within forest
NR5	18°7′48.85"	178°12′6.92"	70	Silty CLAY, trace organic matter; reddish brown, black on fracture surface. Firm, moist, low plasticity (TT)	Hillslope within forest

VG, Early Pliocene Vatukoro Greywacke (Ba Basaltic Group); SD, recent surficial deposits; BS, Mio-Pliocene Barotu Sandstone (Ra Sedimentary Group); RB, Early Pleistocene Rokavukavu Basalt (Ba Basaltic Group); WC, Late Miocene Wailoa Conglomerate (Ra Sedimentary Group); LS, Mid-Miocene Lawalevu Sandstone (Wainimala Group); WT, Early Miocene Wainimbuka Trachyte (Wainimala Group); NS, Early Pliocene Nacua Sandstone (Verata Sedimentary Group); WS, Mio-Pliocene Waidina Sandstone (Medrausucu Group); UB, Early Pliocene undifferentiated basaltic and derived flows (Ba Volcanic Group); NA, Mio-Pliocene Namosi Andesite (Medrausucu Group); TT, Mid-Oligocene Tawavatu Tuff (Wainimala Group).

samples plot well below the A-line in the plasticity chart either as medium- to very-high-plasticity fine silts (Fig. 6). The percentage clay fraction and the PI were plotted together according to Skempton's (1953) activity index (AI), defined as the ratio of the plasticity index to the percentage clay-sized fraction (Fig. 7). According to Skempton (1953), inactive clays have an AI of <0.75, normal clays an AI of 0.75–1.25 and active clays an AI of >1.25. All the samples classify as active to highly active with AI values of ≥1.25 (Fig. 7). Liquidity index (LI) values varied from −0.4 to 2.4, indicating that some soils are over-consolidated and have a natural moisture content less than the plastic limit (LI < 0), whereas other samples have a natural water content generally larger than the LL (LI > 1.0). Consistency index values (CI) varied from −1.4 to 1.4, indicating varied soil properties from a stiff, semi-solid state (CI > 1), to soils where the natural water content is greater than the liquid limit, with fluid-like behaviour (CI < 0).

A summary of geotechnical properties is given in Table 4. The field unconfined compressive strength (UCS) of soils as obtained from the pocket penetrometer ranged from 127 to 461 kPa. The undisturbed (S_u) shear vane test gave values of 16–128 kPa and the disturbed testing (S_d) 9 to 37 kPa. The former values corresponded to stiff to very stiff consistencies for almost all soils except LR1 and NR2, which exhibited soft and firm consistencies, respectively. Thus, the sensitivity index (SI) of soils ranged from 1.3 to 8.2, with most soils being moderately sensitive to sensitive (Skempton & Northey 1952). Saturated hydraulic conductivity (K_{fs}) was measured on eight selected headscarp exposures, and varied from zero to 8.51^{-7} m s^{-1}, typical for silty and clayey soils. The residual friction angle (ϕ'_r) values from ring shear tests on four samples produced angles ranging from 9.3 to 17.4° (example in Fig. 8). These are typical of tropical residual soils composed of platy clay minerals such as kaolinite and smectite (Rigo *et al.* 2006). Finally, Emerson class numbers generally indicated reactive properties, such as minor dispersion (Class 2 and 3) or flocculation characteristics (Class 6).

Discussion

All the 18 slope failures across the three study areas were from cut slopes adjacent to roads, reiterating the continued problems of designing cut slopes in Fiji, as initially described by Lovegrove & Fookes (1972). Observations concur in part with the Lovegrove & Fookes (1972) Fiji residual soil model, in that the road cuttings penetrate several different sub-zones of residual soils, with differences in soil textures and appearances only subtly detectable visually. The different depth-related variability in internal soil strength characteristics tends to mask other variability induced by different parent rock material. All the sites involved failure of cohesive soils, with almost all being kaolinite and/or smectite

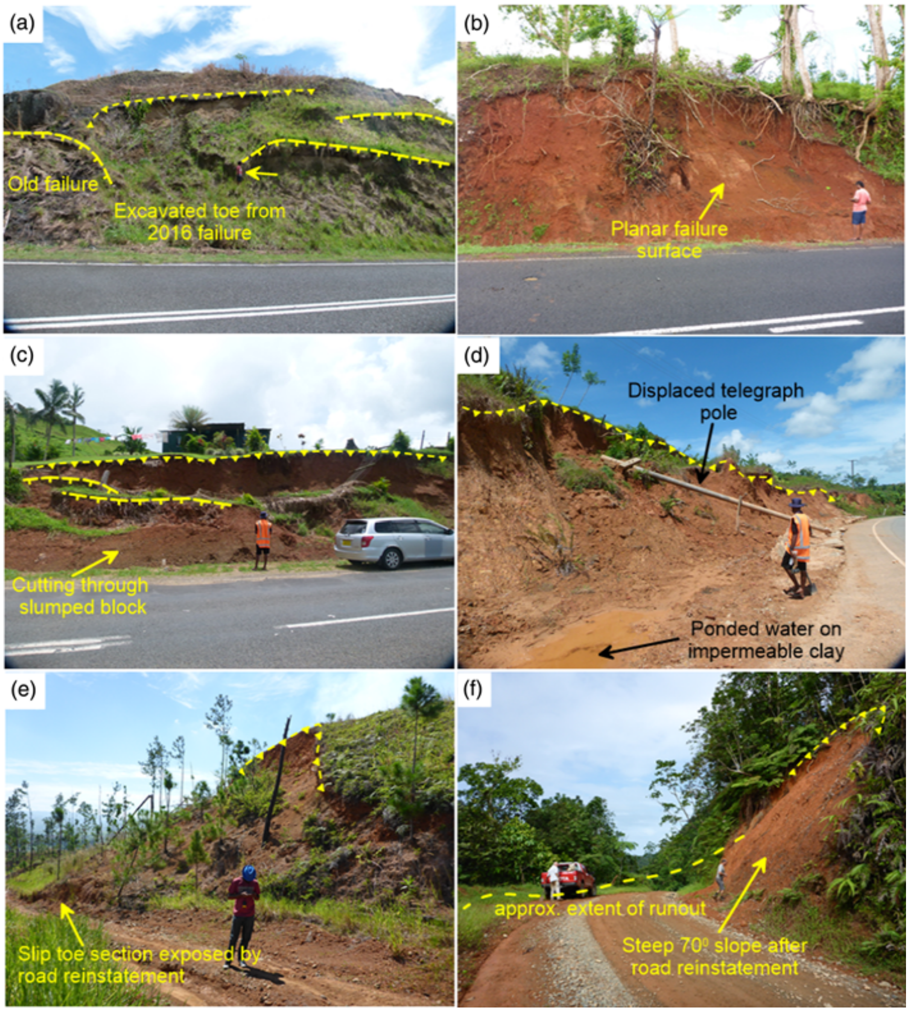

Fig. 3. Selected 2016 slope failures sampled, showing typical terrain and vegetation encountered. (**a**) Slumped blocks adjacent to pre-2016 slope failure along site KR2. Arrowed person indicates scale. (**b**) Steep (60°) headscarp with planar failure surface exposed along reinstated site KR3. (**c**) Slumped blocks adjacent to settlement along reinstated section of site KR6. (**d**) Earthflow headscarp with water emerging at toe (site KR9). (**e**) Shallow translational slip under thin pine forest along site LR1. (**f**) Steep headscarp next to the reinstated site NR5.

dominant. Kaolinite, essentially dominated by silica and alumina, is often the residue following prolonged or severe chemical weathering (Nesbitt & Young 1989). Its predominance in the samples indicates that soils at most sites are intensely weathered with little difference noted between geological age and location. Further, there is no explicit relationship between clay minerals and the underlying lithology. A 2:1 structured clay mineral such as smectite has weak interlayer bonding, which means it shrinks in dry periods and swells to several times its original volume when saturated, and is extremely sensitive (Wesley 2010). Although smectite and illite were not measured in all the soil samples, they are likely to be present in other horizons in these highly weathered residual soils. The presence of

Table 2. *Summary of minerals present in the clay fraction of soil samples and their relative abundance*

Site	Kaolinite	Kaolinite–illite	Smectite	Smectite–chlorite	Illite	Vermiculite	Quartz	Feldspar	Calcite
KR1			+ + +				+		
KR2			+ + +						
KR3	+ + +								
KR4	+ + +								
KR5	+ + +		+ + +					+	+
KR6	+ +							+	
KR7	+ + +		+ +		+ +		+	+ +	
KR8	+ + +					+			
KR9	+ + +							+	
KR10	+ + +						+	+ +	
KR11	+ + +		+ + +						
LR1		+ + +						+ +	
LR2	+ + +							+ +	
NR1	+ +		+ +		+ + +		+ + +	+ +	
NR2				+ + +					
NR3	+ + +						+		
NR4			+ + +				+		
NR5	+ + +						+ +		

Mineral abundance key (qualitative): + + +, abundant; + +, minor; +, trace.

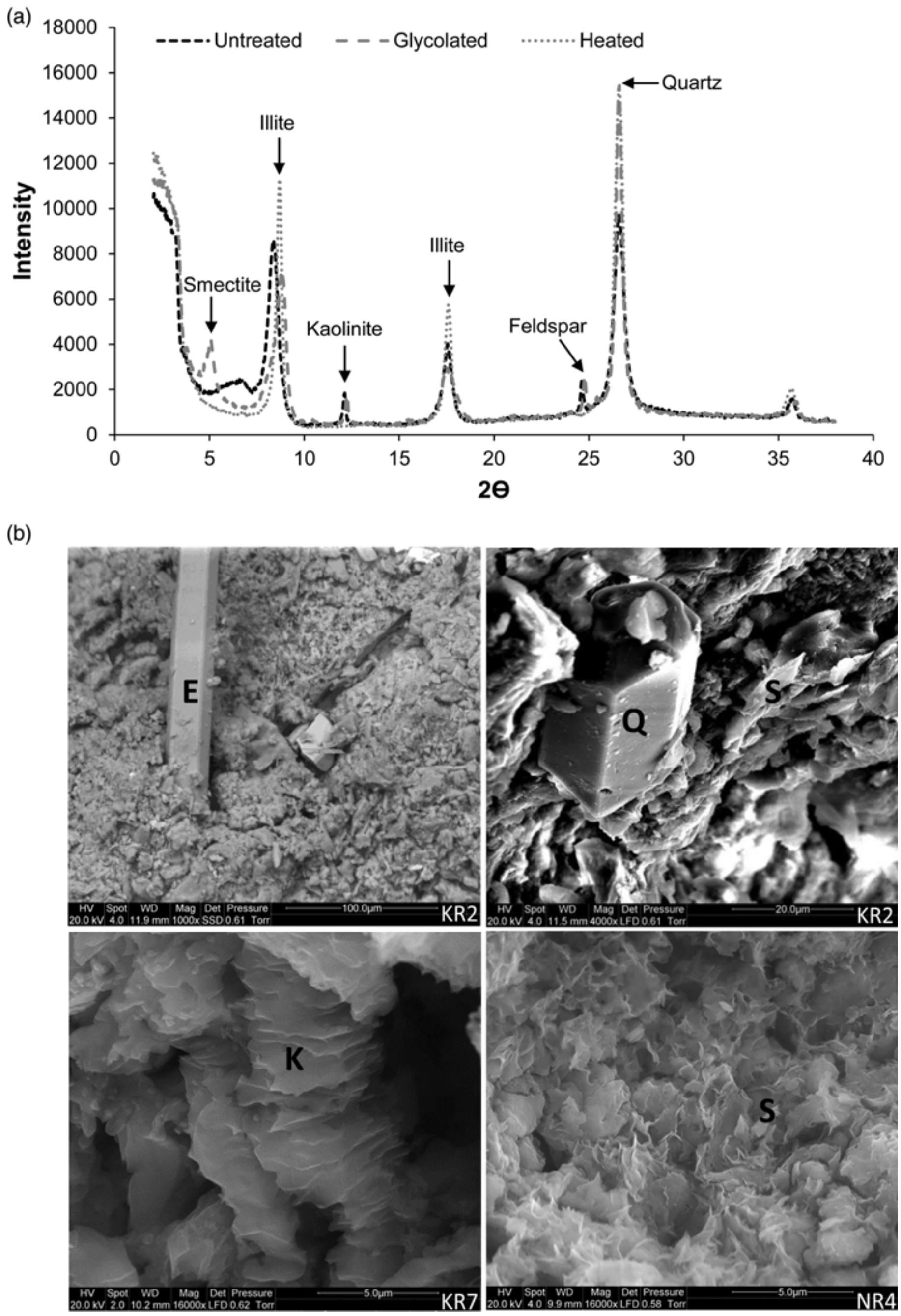

Fig. 4. (**a**) Clay minerals identified in NR1 soil samples using XRD pattern generated from CuKα radiation; (**b**) SEM photomicrographs of KR2, KR7 and NR4 soil samples showing various minerals identified. E, erionite; K, kaolinite; S, smectite; Q, quartz.

swelling clays in most sites studied is consistent with their very high *in situ* moisture contents and the active to highly active nature of the clay fraction (see Skempton 1953). Although smectite was not detected at sites with very high *in situ* moisture contents (e.g. KR4 and KR10), a large amount of short-range order minerals, mainly Fe and Al oxides and hydroxides (e.g. gibbsite and ferrihydrite), are also present in the clay fraction, leading to high effective soil surface area and thus high water-holding capacity (see Fookes 1997).

Moreover, the high mobility and runout of many of the landslides studied is also associated with highly sensitive clay minerals. Sensitivity represents a loss of strength upon remoulding and is quantified as the ratio of undisturbed (S_u) to disturbed (S_d) undrained strength (sensitivity index, SI), determined at the same moisture content. Soils with values of <2 are insensitive, those with values of 4–8 are sensitive, those with values of 8–16 are extra-sensitive and those with values >16 are considered ‘quick’, following Skempton & Northey (1952). Most of the samples measured here are within the bounds of the sensitive to extra-sensitive categories (Table 3).

Previous work in Fiji (Knight 1986) reported halloysite as a common clay mineral in the soils of Viti Levu. However, although Knight (1986) concluded that the halloysite soil’s high LL, PL and natural moisture content implied problematic behaviour, the soils were benign from a geotechnical standpoint. In contrast, Moon (2016) have implicated the presence of halloysite as a susceptibility factor for several slope failures in the Tauranga region of New Zealand, where sensitivity indices range from 5 to 20, with the highest values and most landslides triggered under rainfall-induced elevated porewater pressures.

The index properties accord with previous results described by Lovegrove & Fookes (1972). They reported LL values of 67–82% for residual soils formed on tuff bedrock (our values are 62–79% for the Tawavatu Tuff; NR3, 4 and 5). Along Queen’s Highway in southern Viti Levu, Lawson (1993) found that residual soils that were formed on conglomerate, sandstone and tuff developed highly to very plastic silts. Whereas the reported clay content (12–26%) and moisture content (53–84%) are very similar to those found in

Table 3. *Summary of soil index properties*

Site	*W* (%)	D_{10} (μm)	Clay (%)	DD (g cm^{-3})	LL (%)	PL (%)	PI (%)	LI	CI
KR1	47.7	12.6	0.6	1.3	47.6	30.9	16.6	1.0	0.0
KR2	28.4	7.4	1.0	1.4	39.1	31.3	7.9	−0.4	1.4
KR3	71.4	0.4	15.4	1.0	79.1	56.3	22.7	0.7	0.3
KR4	102.8	2.2	9.7	0.7	73.5	52.0	21.4	2.4	−1.4
KR5	49.3	4.6	2.5	1.2	45.9	32.1	13.8	1.2	−0.2
KR6	59.8	1.6	12.1	1.2	54.0	42.3	11.7	1.5	−0.5
KR7	77.5	6.8	1.5	1.0	61.1	44.6	16.5	2.0	−1.0
KR8	56.8	2.0	9.9	1.1	62.3	42.8	19.6	0.7	0.3
KR9	50.7	1.9	10.7	1.3	50.0	36.5	13.6	1.0	0.0
KR10	114.3	6.3	1.8	0.8	78.7	52.1	26.6	2.3	−1.3
KR11	70.9	7.2	1.9	1.0	71.4	47.9	23.5	1.0	0.0
LR1	61.2	0.4	19.2	1.0	71.7	47.7	24.0	0.6	0.4
LR2	57.7	3.1	7.1	1.0	76.0	53.5	22.5	0.2	0.8
NR1	34.8	2.4	5.9	1.5	49.1	30.9	18.2	0.2	0.8
NR2	36.8	6.6	1.7	1.4	38.3	25.6	12.7	0.9	0.1
NR3	67.7	12.1	0.9	1.0	60.4	43.7	16.7	1.4	−0.4
NR4	64.4	8.9	1.4	1.1	53.8	37.9	15.9	1.7	−0.7
NR5	63.8	2.3	9.1	1.2	60.9	43.4	17.5	1.2	−0.2

W, *in situ* moisture content (%); D_{10}, effective particle size (μm); DD, dry density (g cm^{-3}); LL, liquid limit (%); PL, plastic limit (%); PI, plasticity index; LI, liquidity index; CI, consistency index.

our study, both LL (68–118%) and PI (23–57%) values were much higher. In addition, Knight (1986) reported a range of index values (*W* (*in situ* moisture content) 83%; PL 59%; LL 107%; PI 48; LI 0.35) for very wet halloysite clay in the extreme precipitation (5000 mm a^{-1}) highlands of central Viti Levu. Likewise, Lupini *et al.* (1981) reported similarly high index properties (40% clay fraction; LL 90%; PI 37%) from kaolinite soil in Viti Levu. All the index values mainly overlap with the extreme upper end of the index property ranges reported here.

Unfortunately, a paucity of soil strength results exists for direct comparisons with previous work. Knight's (1986) residual friction angle values (ϕ'_r, 14–28°) accord with the 9.3–17.4° values from the present study. In addition, UCS values of 35–48 kPa were reported by Knight (1986) from the same wet, halloysite-rich soils, but these are much lower than the stiffer values reported here. The shear strength values reported by Knight (1986) of S_u = 43.2–140 kPa, S_d = 15.7–35 kPa (SI = 2.75–4.11) closely correspond to the shear vane undisturbed and disturbed strength values identified here. Stephens *et al.* (2018) reported a mean shear vane value of 28.0 kPa from headscarps above debris flows close to the LR1 and LR2 sites, although this appears low, and it is uncertain whether this was from undisturbed material. A final interesting comparison relates to the field-based hydraulic conductivity values, which are very similar to the data (10^{-6} m s^{-1}) reported by Bronders (1994), from auger-hole tests in sandy silt soils in SE Viti Levu. This equates to 86.4 mm day^{-1}, well below the maximum rainfall intensities reported in the literature for Fiji (e.g. Crozier *et al.* 1981; Lawson & Dau 1992; Stephens *et al.* 2018; >100 mm day^{-1}). The corollary is that during intense storms, the soils rapidly reach a saturated condition, leading to excess porewater pressure and slope failure.

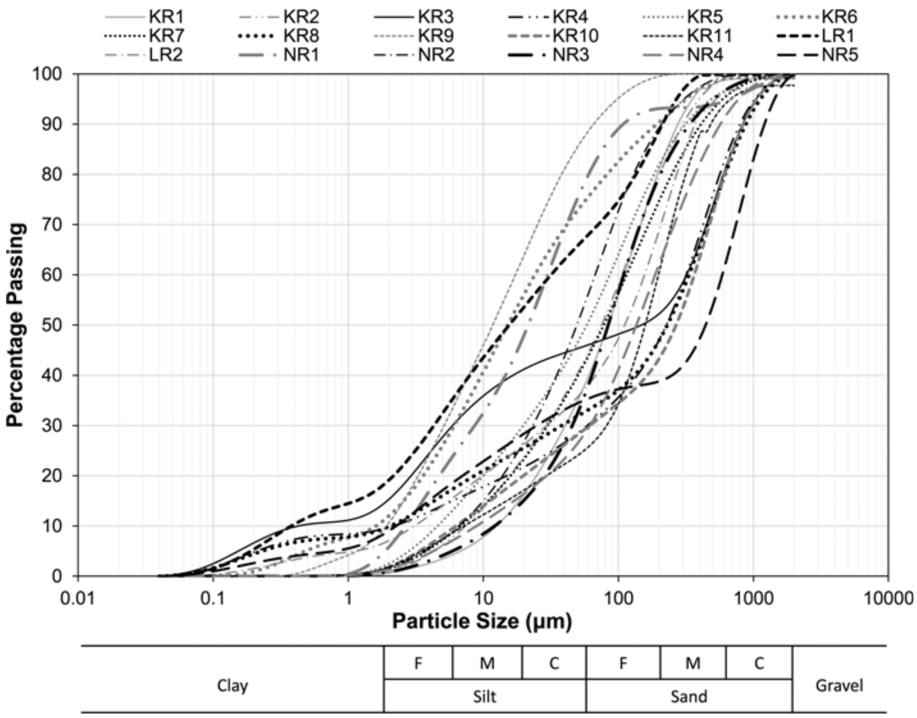

Fig. 5. Particle-size distribution graph of soil samples from the study area.

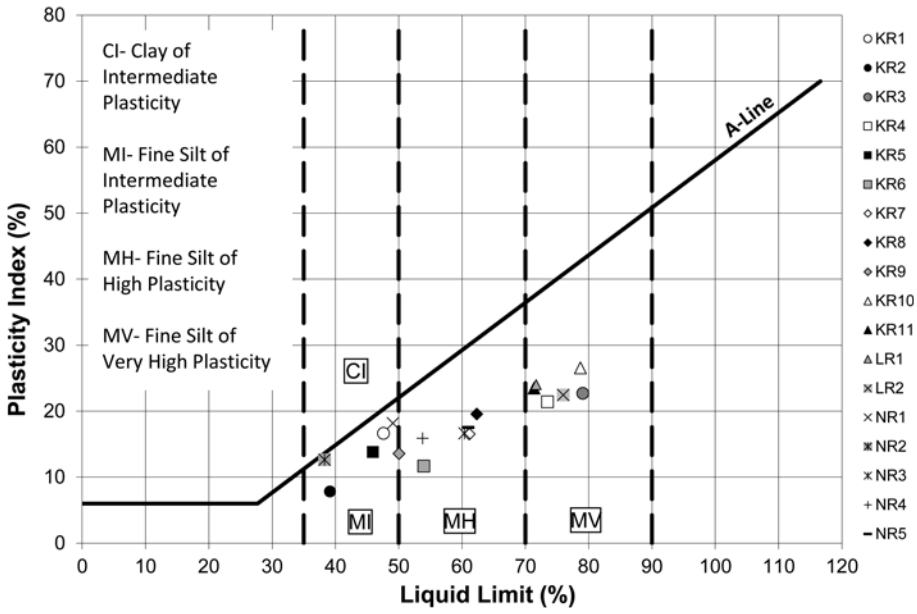

Fig. 6. Casagrande plasticity chart of soil samples from the study area. The A-line is based on NZGS (2005). Vertical dashed lines represent boundaries between plasticity zones.

Unlike coarse-grained materials where engineering properties are closely related to particle size, the properties of fine-grained soils are governed by both the size and composition of the particles (Wesley 2010). As highlighted elsewhere (e.g. Fookes 1997), because the soils in the present study contain a large coarse fraction, Atterberg limits (from the fine fraction) are a limited indicator of soil behaviour, even though a correction factor was applied. Nevertheless, comparing the soils encountered here with Wesley's (2009) review, the soils plot below the A-line and within Wesley's (2009) 'Tropical red clays' boundary on the plasticity chart, thus behaving as silts. Because of their widely varying nature and properties, it has proved difficult to devise an adequate classification system for residual soils (Wesley 2009). In addition, index property tests were developed for primarily temperate soils and are usually sufficient for that purpose (Fookes 1997). Notwithstanding this, Brink & Hörtkorn (2016) cautioned against applying conventional testing procedures to tropical soils, with laboratory drying methods having important impacts on index results. For soils in southern Viti Levu, Lovegrove & Fookes (1972) observed that the LL of residual soils varied with mixing time and moisture condition before testing. A small increase in LL was noted after working for 30 min and air-drying of the samples. Knight (1986) also observed that air-drying of soils yields higher LL values compared with samples not allowed to air dry before testing. Thus, attempting to relate residual soils and their properties to accepted classification systems (e.g. BS 5903, BSI 2015) based on LL or PL may be problematic, especially if the drying procedures vary (e.g. Mutaya & Huat 1993).

A particular issue observed at the sites is the short-term stability of the road cuttings. Some of the slopes (e.g. Fig. 3) are currently sustaining angles of >45°, much steeper than might be expected in sedimentary soils. The failures are relatively shallow, but follow a near-planar failure surface, concurring with the observations of Wesley (2009). Lovegrove & Fookes (1972) also observed that short-term stability of road cuttings is governed to a major extent

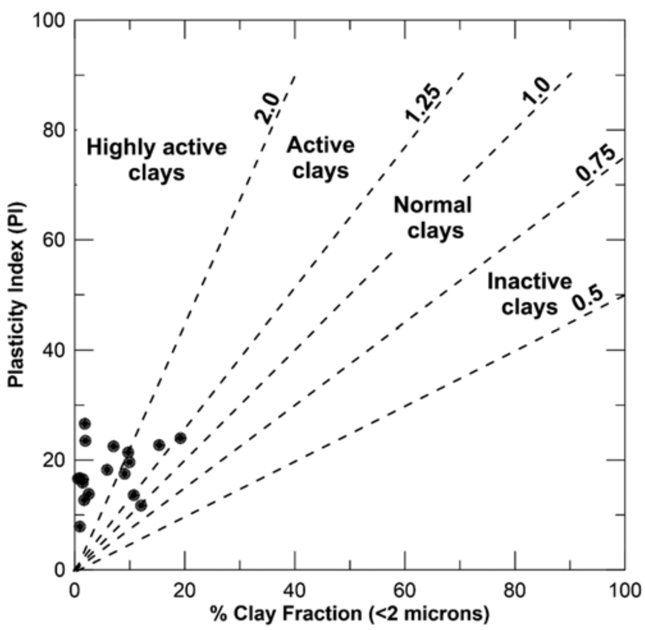

Fig. 7. Activity plot of the relationship between PI and clay fraction for all samples (modified from Skempton 1953).

Table 4. *Summary of soil geotechnical properties*

Site	UCS (kPa)	ϕ'_r (degrees)	S_u (kPa)	S_d (kPa)	SI	ECN	K_{fs} (m s^{-1})
KR1	255	–	74.3	25.7	2.8	2	–
KR2	304	–	53.0	9.7	7.7	2	8.51^{-7}
KR3	461	–	77.2	20.6	3.8	3	0
KR4	323	–	71.8	15.5	5.2	3	5.67^{-7}
KR5	245	–	93.3	17.3	6.5	5	0
KR6	362	12.0	128.0	28.5	4.5	2	–
KR7	156	–	53.0	8.8	8.2	3	5.7^{-8}
KR8	255	–	110.0	21.3	5.2	3	2.84^{-7}
KR9	255	–	54.3	21.5	2.5	6	–
KR10	127	–	60.0	20.0	3.0	3	–
KR11	215	9.3	101.7	23.3	4.6	3	–
LR1	372	–	16.0	5.5	3.2	6	1.84^{-7}
LR2	392	14.6	93.3	34.7	2.8	6	1.13^{-7}
NR1	362	–	80.8	12.0	7.3	6	–
NR2	225	17.4	42.5	37.5	1.3	3	–
NR3	255	–	67.5	10.5	6.4	3	–
NR4	274	–	52.5	10.0	5.3	3	–
NR5	402	–	65.0	9.5	7.1	8	–

UCS, unconfined compressive strength (kPa); ϕ'_r, residual friction angle (degrees); S_u, undisturbed shear vane (kPa); S_d, disturbed shear vane (kPa); SI, sensitivity index; ECN, Emerson class number; K_{fs}, field-saturated hydraulic conductivity (m s^{-1}).

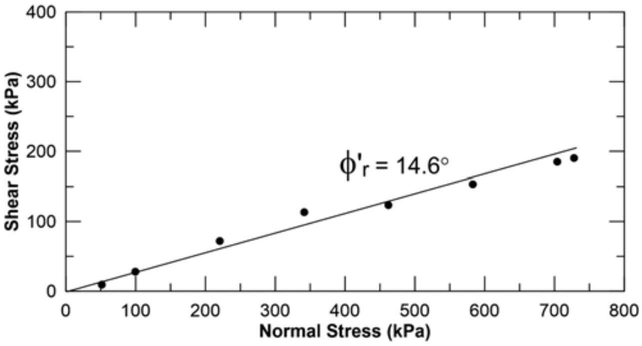

Fig. 8. Example Mohr–Coulomb failure envelope of LR2 soil sample obtained from ring shear testing.

by discontinuities in weathering zone IV. Thus, the relevance of residual friction angles reported here for any stability analyses can be questioned, as the four samples exhibit low strengths when remoulded. Stability analyses of residual slopes along highways require reliable shear strength estimates (Hayden *et al.* 2018). However, correlations between residual strength and soil index properties and grading cannot be generalized as the residual strength of clays is largely determined by type of clay minerals and porewater chemistry (Lupini *et al.* 1981). Although Moore (1991) found that the residual shear strength of pure montmorillonite clays was 5.3° lower than the residual friction angle of pure kaolinite, slips and landslides in residual soils in Fiji and elsewhere generally occur during periods of heavy rainfall, owing to temporary increases in the porewater pressure in the slope. Thus, following Wesley (2009), cohesion and the rapid changes in porewater pressure that occur within residual soils mean that slope stability analysis and material strength must be considered in terms of effective stresses during and after rainfall conditions.

Although residual soils from the same parent rock (Wailoa Conglomerate, Basalt (Ba Volcanic Group), Namosi Andesite and Tawavatu Tuff) displayed similar index (e.g. *W*, LL, PL, PI and CI) and geotechnical (UCS and SI) properties, the small sample size is probably not fully representative of soils across the broad range of rock types that crop out across Viti Levu. In addition, not all soils have properties exclusively controlled by their parent rock, as the weathering environment can significantly influence soil properties (see Wesley 2009). In this study, field-estimated UCS displays significant moderate negative correlation with D_{10} ($r = -0.57$, $P < 0.05$) and a significant moderate positive correlation with per cent clay ($r = 0.68$, $P < 0.001$), highlighting how stiffness of the Fiji soils increases with increasing clay fraction. Finally, it is apparent that the results highlight the incongruence of qualitative field-based soil behaviour descriptions and strength measurements, compared with quantitative laboratory-based soil analyses, and this is consistent with previous studies (e.g. Hind 2017). For example, soils that plot below the A-line on the plasticity chart (as 'silts') are generally regarded to be good engineering materials as they tend to have low compressibility, high shear strength and do not display shrink–swell behaviour (Wesley 2009). However, descriptions and testing of the soils indicated that they were clay-rich (up to 19%). This has emerged as a particular issue for fine-grained soils, whereby the same material is assigned to entirely different soil groups owing to taxonomical differences between field-based guidelines (e.g. NZGS 2005) and laboratory testing procedures (e.g. Hind 2017).

Conclusion

This study characterizes the mineralogical, index and geotechnical properties of weathered residual soils prone to rainfall-induced slope failures in Viti Levu, Fiji, and explores relationships with parent lithology. Eighteen slope failures belonging to various sedimentary and volcanic lithologies in three study areas, KR, LR and NR, were sampled. Tropical residual soils sampled from headscarp exposures within slope failures in Viti Levu show distinct engineering characteristics, which may be markedly different from those observed in soils developed from sedimentary materials in temperate environments. Overall, the residual soils are very highly weathered with crystalline clays dominated by kaolinite and smectite. From conventional laboratory-based testing methods, the soils are characterized as being reasonably stable in that they are able to sustain steep slopes under dry conditions. However, these methods were developed for temperate conditions and should only be applied with caution to tropical environments such as Fiji where soils are deeply weathered and are subjected to high rainfall. Residual soil slopes in Fiji upon wetting are easily prone to failure, despite their high water-holding capacity, high plasticity and low density. No clear contrasts exist between parent rock lithology and soil index properties and behaviour across the study sites here, but this may reflect the similar overall age of much of the Fiji bedrock from a soil-development perspective. The soils typically plotted well below the A-line on a plasticity chart, which is indicative of good engineering properties. However, the presence of expanding and high-activity clay minerals (e.g. smectite) makes the soils sensitive and susceptible to slope failure. Such failures typically occur during high rainfall events, as a result of temporary increases in the porewater pressure in the slope. The presence of planar discontinuities within the residual soils is also an influence on slope stability at the road cuttings observed. Although there is now a reasonable understanding of the strength and plasticity of the materials, the processes and mechanisms of initial slope failure remain poorly understood. Finally, when evaluating the engineering properties of residual soils, our findings indicate that careful field observations of soil behaviour should be made prior to laboratory-based testing programmes. Monitoring of rainfall and porewater pressure along road cuttings over several years could be used to determine variations over time, to help understand the role of porewater pressure as a driving mechanism of failure in Fiji soils.

Acknowledgements We thank the New Zealand (NZ) Ministry of Foreign Affairs and Trade for providing a NZ Pacific Scholarship (NZPS) for A.R.R.'s doctoral study at The University of Auckland. The assistance provided in Fiji by S. McCone, Opus-Fiji Labs, as well as E. de Vries and W. Cadle of Fulton–Hogan Highways Joint Venture-Fiji is much appreciated. We also thank G. Morris of Namosi Joint Venture-Fiji and N. Chand for their kind assistance in the field. Technical staff at The University of Auckland are acknowledged for their support, and P. White of Panda Geoscience is thanked for undertaking XRD analysis on some samples.

Funding This study was conducted as part of the PhD research of A.R.R., funded by NZPS and The University of Auckland, with School of Environment internal funding support to M.S.B. and S.J. C.

Scientific editing by Cherith Moses; James Griffiths

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