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The effects of weathering on the physical and mechanical properties of igneous and metamorphic saprolites

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ABSTRACT

The present paper presents three extensive datasets of laboratory testing on weathered geomaterials, which are emblematic of soil types widely found worldwide. The overall dataset includes soils originating from igneous and metamorphic rocks, either coarse or fine grained and having either felsic or mafic minerals. In particular, the data are interpreted to highlight the effects that weathering has on the physical and mechanical properties of these natural geomaterials comparing them with published data with the aim to provide a general framework of interpretation that takes into account this geological process and links soil mechanics to engineering geology. Generally, weathering induces a reduction in the grain size, both due to physical actions (e.g. opening of grain contacts) and to the chemical decomposition of minerals resulting in the formation of clay minerals. As weathering proceeds and the soil becomes finer, the in situ specific volume and the location of the normal compression and critical state lines move upwards in the volumetric plane. On the other hand, the clay minerals cause its angle of shearing resistance to reduce. When analysing the behaviour of the intact soil, in all cases positive effects of structure, albeit small compared to some sedimentary soils, were observed and these reduced as a consequence of weathering.

1. Introduction

Although weathering is an inherent process undergone by any material, in the geotechnical community, this geological process tends to be associated particularly with certain climates. This is true to the extent that for long “tropical soil” has been used as a synonym of residual soil and indeed the geomaterials presented here are from tropical areas. However, as explained by Hall et al. (2012), climate merely influences the rate at which weathering occurs, while the specific processes involved are dictated by the parent rock characteristics, such as porosity and permeability, pre-existing joints and bedding planes, mineralogy and mineral properties.

Extensive research exists that has investigated changes of physical properties and mineralogy along weathered profiles. However, as pointed out by Moon and Jayawardane (2004) it is often difficult to measure meaningful mechanical parameters across the whole weathering profiles as the material investigated can span from a hard rock to a soft soil. For this reason the present paper focuses on the “soil end” of the weathering spectrum, i.e. saprolites and residual soils, where the fundamental concepts of soil mechanics can be applied.

Vaughan et al. (1988) were perhaps the first to investigate the effects of structure on the mechanics of natural residual soils within a critical state framework. This work was further extended to other natural soils and rocks by Leroueil and Vaughan (1990), who recognised the importance of natural structure irrespective of its geological origin, while previous work had concentrated almost solely on its effects for sedimentary “sensitive” clays (e.g. Skempton, 1970). After these pioneering studies, more recently Futai et al. (2004) investigated in detail the mechanical behaviour of an intact saprolite comparing it to that of the recompacted soil at different depths along a weathered profile. However, a well-established framework of behaviour like that proposed by Cotecchia and Chandler (2000) for natural sedimentary clays that includes the effects of structure is still lacking for geomaterials originated from weathering.

The current paper aims at establishing the basis for such a general framework of interpretation and improving the understanding of the weathering effects on the geotechnical behaviour, linking the latter to the geological processes that have occurred. The effects of weathering

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Table 1
Summary of the soils properties, tests and effects of weathering for the weathered soils studied. Note: U stands for unknown, R for reconstituted, I for intact, Incr for increasing, Decr for decreasing and n.d. for not determined.

Soil	1	2	3	4[a]	5[b]	6[c]
Parent material	Granite	Gneiss	Basalt	Dolerite	Gneiss	Volcanic ash
Depth (m)	6–40	2–14	8–30	2–9	1–7	1–10
Physical properties						
Dmax (mm)	6–20	2–9	5	2–5	U	U
D_{50} (mm)	1–11	0.002–0.040	0.06–0.26	0.04–0.73	0.03–0.25	U
c_u	5–32	27–141	47–52	29–89	6–30	n.a.
Clay fraction (%)	0–13	5–66	0–2	2–10	4–46	45–87
PI (%)	n.a.	n.a.	5	14–18	16–29	13–65
w_n (%)	5–23	12–21	40–76	31–42	26–46	47–67
Test type						
1D compression	R and I	I	R	R and I	–	R and I
Isotropic compression	R and I	I	I	–	I	–
Tiaxial shear	R and I	I	I	–	I	–
Reference line	CSL	CSL	CSL	1D–NCL	CSL	1D–NCL
v_0	1.4–2.0	1.71–2.20	2.30–2.56	2.23–2.74	1.88–2.34	2.61–4.54
N and Γ	2.30–2.75 and 2.27–2.58	n.d. and 2.33–3.64	n.d. and 2.74	2.77–3.49 and n.d.	2.90–3.20	8.56 and n.d.
λ	0.10–0.15	0.10–0.29	0.27	0.14–0.21	0.21–0.23	0.76
M	1.28–1.53	1.54–1.57	1.42–1.75	n.d.	1.15	n.d.
Weathering effects						
e_0	Incr	Incr	Incr	Incr	Incr	Incr
N, Γ and λ	Incr and decr	Incr	None	Incr	Incr	n.d.
M	Decr	None	Decr	n.d.	None	n.d.
Structure	+ ve	+ ve	+ ve	+ ve	+ ve	+ ve
	Decr	Decr	Decr	Decr	Decr	Decr

[a] Data from Maccarini et al. (1989).
[b] Data from Futai et al. (2004).
[c] Data from Wesley (1973, 1990).

on the physical and mechanical properties of a granitic saprolite from Hong Kong, a gneissic saprolite from Brazil and a basaltic saprolite from Mauritius are discussed. In particular, profiles of significant depth and having a variety of weathering degrees are considered. These data are compared with published data regarding weathered geomaterials, which were reanalysed applying the critical state and sensitivity frameworks. Finally, the trends of behaviour were contrasted with the influence of weathering on a sedimentary clay.

2. Materials and testing procedures

Three types of soil were considered in detail, making comparisons and contrasts with examples from the literature that were of broadly similar materials. Table 1 summarises the soil properties, the test data available and the main findings for each case. This information is also presented in Figs. 1–3, plotted against depth. Because both physical and mechanical properties are included to aid a global understanding at a glance, this will require reference to these figures in different sections of this paper. Fig. 1 compares a granitic saprolite from Hong Kong to a diabase saprolite from Santa Catarina (Brazil), as both parent rocks have an igneous intrusive origin, but differ in mineralogy and partly in grain size. Fig. 2 compares two gneissic saprolites from Brazil (Rio de Janeiro and the State of Minas Gerais, respectively), which share the same geological origin and approximately the same grain size and mineralogy, although it is not clear whether the geological formation considered is indeed the same one. Fig. 3 compares a basaltic saprolite from Mauritius to a volcanic ash residual soil from Java (Indonesia), as both parent rocks are extrusive igneous rocks, but they differ in mineralogical composition.

As mentioned above, the first soil considered (Fig. 1) is a granitic saprolite from Hong Kong. According to the guidelines of the Geological Society Working Party (1990), the soil has grades IV (highly weathered) and V (completely weathered). The parent rock (Sha Tin Granite) is an intrusive coarse to fine grained felsic igneous rock, having crystal sizes between 1 and 4 mm with plagioclase, feldspars, quartz, and to a lesser extent biotite as the main mineral components. The soil was sampled from two boreholes (BHA and BHB) located at a close distance, covering depths up to 27 m. A variety of different weathering degrees were encountered, which are detailed in Table 2, based on Rocchi and Coop (2015). However, for simplicity in Fig. 1, distinction is made only between the two decomposition grades, i.e. CDG and HDG that stand for Completely Decomposed Granite and Highly Decomposed Granite, respectively. Furthermore, the tests presented will focus on the shallow extremely weak CDG (sh ewCDG) and HDG, which represent the extremes encountered.

For the granitic saprolite several one-dimensional compression and triaxial tests were carried out, both on intact and reconstituted samples, using the techniques described in detail by Rocchi and Coop (2015). The soil gradings in Fig. 1a (and similarly in Figs. 2a and 3a) are presented by dividing the particle size distribution curves into their main components, i.e. gravel, sand and fines (silt and clay). As several grading curves were available at similar depths, the values were averaged over 0.5–1 m intervals. The soil ranges from sandy gravel to gravelly sand (D_{max} = 6–20 mm and D_{50} = 1–11 mm) so that the soil grains mostly include clusters of different minerals. Generally, the shallower and more weathered the soil, the finer and better graded. However, below 12 m a larger data scatter in the relative amounts of gravel and sand can be observed. This rather regular alternation between more and less weathered strata could be an indication of the joint spacing. In addition, at approximately 20 m depth a more weathered stratum was encountered, as shown by the increased amount of fines. Rocchi and Coop (2015) described this granitic saprolite mineralogy as consisting mainly of quartz and feldspars in similar amounts, and to a lesser extent of mica, clay minerals (kaolinite and illite) and some amorphous minerals. Compared to the parent rock, amorphous and clay minerals have replaced the biotite and to a lesser extent the feldspars due to weathering. This is reflected in the specific gravity (G_s), which is 2.65 for the HDG and on average 2.63 for the CDG.

The gradings of a diabase saprolite from Santa Catarina (Brazil) studied by Maccarini et al. (1989) are included in Fig. 1a for comparison as it differs from the granitic saprolite in mineralogy and partly in grain size. This saprolite was from a shallow intrusive medium grained