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A review of igneous and metamorphic saprolites

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ABSTRACT

Major difficulties in ground engineering works in areas of humid climates arise from the internally heterogeneous and erratically varying zones of weathering profiles developed over igneous and metamorphic rocks as a result of dominantly chemical weathering processes. This paper provides a critical review of recent efforts on improving the description and classification of weathering grades, and discusses current conceptual and practical issues and proposed methods for the engineering geological characterisation of igneous and metamorphic saprolites. Analysis of these issues reveals that lack of comprehensive (geochemical, mineralogical, microfabric, and engineering geological) characterisation studies within well-defined geological frameworks is the underlying reason for failure to define, characterise, and model saprolites as complex engineering geological units and to devise specific site investigation methodologies to explore these complexities.

INTRODUCTION

Major difficulties in ground engineering works in areas of humid climates arise from the internally heterogeneous and erratically varying zones of weathering profiles developed over igneous and metamorphic rocks as a result of dominantly chemical weathering processes. This paper provides a critical review of recent efforts on improving the description and classification of weathering grades, and discusses current conceptual and practical issues and proposed methods for the engineering geological characterisation of igneous and metamorphic saprolites. Attempts to relate weathering-induced changes in engineering properties and behaviour to weathering grades are re-examined from the viewpoint of site investigation objectives and the progressive nature of weathering. Hierarchical structure of uncertainty in engineering geological site models is emphasised with reference to the characterisation of weathering profiles. The value of site-specific evaluation in reducing such uncertainties is highlighted, particularly when based on a sound understanding of the local geological environment as a whole. This study introduces the initial phase of a comprehensive research programme with the purpose of integrating a large number of radically different approaches and methods of weathering studies to improve our understanding and prediction of ground performance in saprolites.

Definition

In this paper, the term saprolite refers to that part of the weathering profile where the soil largely preserves its original rock fabric and volume. In humid climates, saprolites often reach depths of tens of metres and generally have unusually heterogeneous internal structures and spatially variable boundaries. The uppermost section (generally less than 2 m) of the soil over saprolites is considered as true or mature residual (lateritic) soils (Sowers 1963; Deere and Patton 1971; Gidigasu 1974). The mature and saprolitic soils together are often referred to as (tropical) residual soils.

As a mappable (generally irregular) body of weathered rock, saprolite consists of materials dominantly decomposed to Grades IV and V (according to the six-fold weathering classification system; IAEG 1981). The choice of Grade IV as the lower boundary for the dominant material in the saprolite mixture is arbitrary (Sowers 1963; De Mello 1972). This choice is based on the perception that Grades I to III represent rock, Grades IV and V engineering (young) soil, and Grade VI mature soil. However, the transition from rock to soil behaviour (at material-scale) takes place gradually through Grades III and IV, which together represent weak-rock behaviour.

Typical igneous and metamorphic weathering profiles

Comparative studies of the weathered profiles developed over igneous and metamorphic rocks (Fig. 1) include those of Moye (1955), Sowers (1963), and Deere and Patton (1971). Parent rock lithology and structure appear to control the morphological characteristics of weathered profiles, including the nature of the transition from saprolite to rock and the development of corestones during weathering. Weathering profiles developed over widely fractured, coarse-grained granites exhibit abundant corestones and a sharp transition (Ruxton and Berry 1957) while those over closely fractured granites are generally free of corestones and display a gradual transition (Newbery 1970). The pervasive nature of foliation planes in schists and phyllites leads to the formation of saprolites with rare occurrence of corestones and a gradual transition to the underlying rock (Komoo and Yaakub 1990; Fookes 1997). On the other hand, saprolites over gneiss often display a sharp transition to rock although gradational in itself (Barroso et al. 1993; Dobereiner and Porto 1993; Fookes 1997).

Barroso et al. (1993) concluded in a study of gneiss saprolite profile that fractures (especially relief joints) have a stronger influence on the profile formation than foliation. Dobereiner and Porto 1993 indicated that the influence of schistosity on the weathering of gneiss profiles is remarkable; rock masses with vertical schistosity planes show deeper (double) weathering and much more regular rock head profiles than those with horizontal ones. Costa Filho et al. (1989) reported the results of geochemical, index, and engineering tests that reveal multilevel (at scales of samples and on the order of a few m) heterogeneity, denying any relationship with depth in a 15 m deep gneiss profile.

Lithological and structural controls are compounded with local climatic, hydrogeological, geomorphological and pedogenic factors, which make profile correlations between and within rock types difficult (Deere and Patton 1971). Dobereiner et al. (1993) and Gulla and Matano (1997) presented examples of complex zonal boundaries within profiles of weathered gneiss in temperate regions, where irregular boundaries despite intense fracturing clearly suggest an overriding influence of climate. On the other hand, site-scale characterisation of typical profiles can be a useful design guide if they are defined within "uniform" geological sub-domains.

Profile characterisation and zoning systems

Existing weathering classification schemes are based on classification (Little 1969), a modified version of the original classifications by Moye (1955) and Ruxton and Berry (1957), both developed for granitic rocks. Little's classification is generalised to all rock types by Dearman (1976), which forms the basis for the schemes suggested by ISRM (1978), IAEG

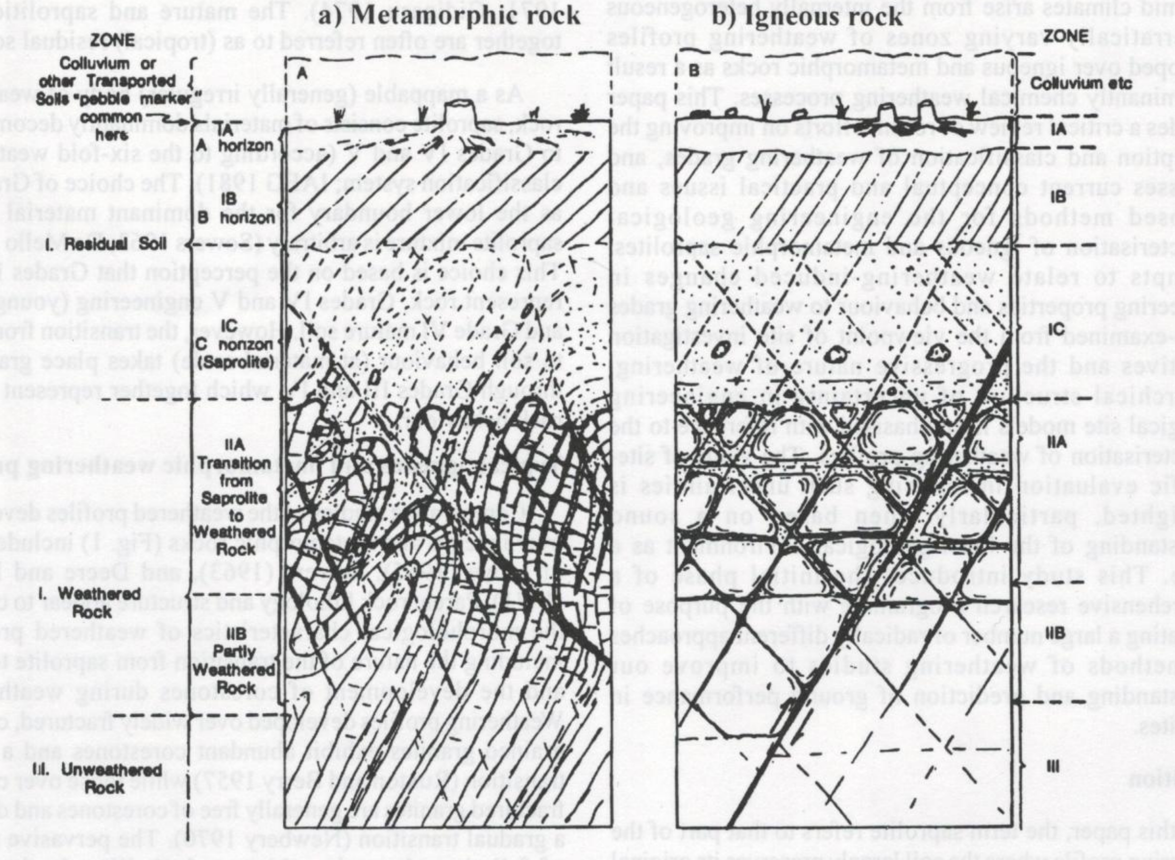

Fig. 1: Typical weathering profiles for (a) metamorphic and (b) igneous rocks (Deere and Patton 1971)

(1981), and BSI (1981). Lee and de Freitas (1989) and GSL (1995) provide a comparative summary of the features and evolution of the current systems.

The intent of classification (Moye 1955) is to standardise description and to provide an indication of engineering properties of the materials, using available experience. Lee and de Freitas (1989) define the description of a rock as a record of what is present and the classification of a rock as an assessment of the rock's character in a form which permits a comparison to be made with other rocks of similar character. These comply with the definition of taxonomic classification based on degrees of relatedness among the described features. As a result of this approach, a large number of weathering classification schemes for engineering purposes in-use today are based on different criteria emphasising different applications, and they significantly overlap in delineating grade or zone boundaries. Search for a universal set of criteria or system, even for a specified rock type, has been unsuccessful. Therefore, studies on the characterisation of weathering profiles for engineering purposes should recall that the ultimate aim is to delimit, on a site-specific basis, "uniform" sub-domains for which purpose-specific performance rating systems or empirical design criteria can be developed to predict the engineering behaviour.

Profile characterisation should include description of geometry (thickness and boundaries) and structure (microfabric, discontinuities, corestones, mineralogical changes, etc.) of the zones and determination of indices (chemical, petrographical, and physical) reflecting weathering-induced changes in each zone. For the delineation of zonal boundaries within a weathered rock mass, the zone as a mapping unit should have a relatively (with respect to project dimensions) small representative volume of similar grade mixtures (encompassing rock/soil ratio). Weathering state and distribution of relict joints, macrofabric created by the presence of corestones and other heterogeneities should be reported as part of a general description of each zone. Because this definition satisfies the concept of uniformity and the scale over which the representative volume is determined is known, design parameters for such zones could be determined more confidently and less conservatively.

Current schemes for the characterisation of weathered rock masses are essentially based on the determination of the corestone ratio or the coarse volume (Lee and de Freitas 1989; GSL 1995), because the field strength and deformability is greatly influenced by the volumetric percentage of the coarse fraction. Criteria for the delineation of the lower boundary of saprolites on the basis of corestone percentage include those <10% for convenience of locating a boundary (Ruxton and Berry 1957; Deere and Patton 1971), <30% for slope stability purposes (Hencher and Martin 1982) and <50% for excavatibility (Little 1969; Dearman 1974). However, such prescribed and specific boundary definitions may be misleading in design and construction as they reflect average values with no reference to distribution parameters. Assigning a volumetric percentage to the coarse fraction, it must be noted that the size and shape of the resistant part of blocks depend on the decomposition penetration depth. Better means to detect corestones and bimodal (gap-graded) nature within the weathered profiles should be devised; the potential of geochemical (including element mobility, sesquioxide,and clay mineral distribution) and hydrogeological (including tracers and chemical variations in water chemistry) methods should be fully investigated.

QUANTIFICATION EFFORTS

As a multi-factorial system, rock mass weathering system can be studied effectively using the Interaction Matrix concept of Rock Engineering Systems (RES) methodology to assess significant factors in this system (Hill and Rosenbaum 1994, 1998). Influential factors are selected to define the system and are assigned semi-quantitative interaction activity factors, FA. Based on assumed or established conceptual relationships, functions are derived to express relative (normalised) contribution of various states of a given factor to the weathering process. These membership functions (of the Fuzzy Set Theory) are then used together with FAs to calculate an index of weathering, WI, at any given site as:

$$WI=FV_1 \cdot FA_1+....+FV_n \cdot FA_n$$

where FV_1, for instance, is the contribution of the first factor, ranging from 0 to 1. If system factors are selected to reflect local variations in intensity of weathering, this attempt may prove useful in quantification and prediction of site-scale heterogeneities in saprolites and particularly in delineation of susceptible zones. However since the membership functions are determined subjectively, a comprehensive database and expert consensus should be developed to put this approach into practice.

Price (1993) proposes a rating system for the classification of rock mass weathering. The purpose of this system is to zone weathered rock exposures by contouring the ratings assigned to unit areas or quantifying the visually identified zones. Such a rating system is no doubt useful (when developed and used for local purposes) in standardising field recognition of saprolitic horizons. Another attempt by Hack and Price (1997) is the proposal of a Slope Stability Probability Classification System for the quantification of weathering influences on slope stability. With this method, weathering-induced reduction in any given rock mass parameter is quantified by normalising its weathered value with respect to the value in fresh(er) state.

To quantify a spatially distributed complex system of saprolites, graphical overlay, data storage, and processing capabilities of the Geographic Information Systems (GIS) should be explored in volume characterisation using multiple sources of data. Overlay analysis allows zoning in both visual

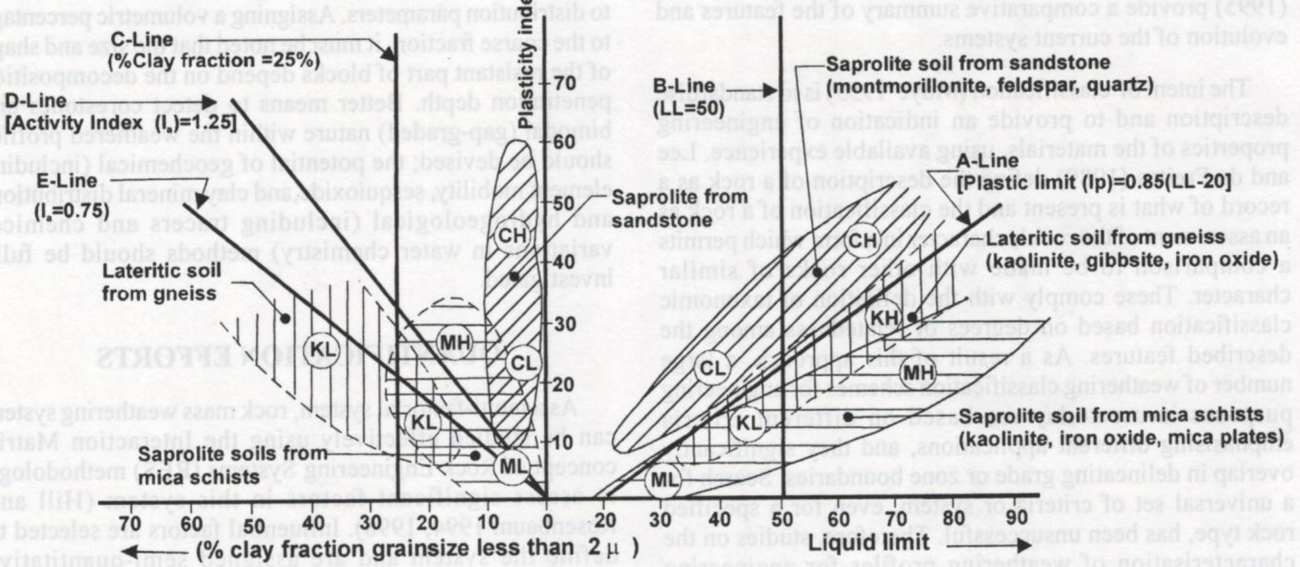

Fig. 2: Combined use of plasticity and activity charts (Vargas 1988)

and matrix forms using different combination of semi-quantitative or quantitative variables. The individual variable matrices can be superimposed using various interaction functions and weightings. As a visual method of sensitivity analysis, the influence of the choice of description parameters (or classification scheme adapted) and possible interactions can be studied effectively. The overlay method of zonation also allows spatial combination of data from linear sampling of rock masses or areal mapping of exposures orientated and distributed variably in space, and interpolation of data between the control points within the rock mass volume.

Zoning a body of a given mixture of weathering intensity is meaningful only if it can be extrapolated to the volume unexplored. This can be best performed on a sound basis established through micro-terrain and sub-domain analyses of the site and its vicinity. The framework is provided by delineation of domains of homogeneous structural, lithological, geomorphological, and hydrogeological regimes and properties. This leads to understanding mechanisms operating within each system domain and the interaction of these mechanisms to form dynamic changes in the overall geological environment. Overlay and matrix analyses should prove very useful to study such interactions.

MATERIAL CHARACTERISATION: NATURE OR STATE

Vargas (1988) indicates that any classification system of natural materials should consider their nature and not the eventual state. He defines the index property of a certain material as a property that is only related to the material's nature, and is necessary and sufficient to classify the material. This view advocates the application of Casagrande's transported soil classification system with its index properties. The main handicap is that the soil constituents in residual soils participate not in their unit conditions but as clusters (De Mello 1972). Therefore, only if grain clusters (silt-size particles of clay aggregations cemented by iron oxide) can be completely disaggregated, the grain-size, and Atterberg limits can be used as an equally valid basis for identification and classification of residual soils (Vargas 1988). The mineralogy of clay fraction can be approximately estimated from Skempton's activity index. Hence a combined use of Casagrande's plasticity and Skempton's activity charts (Fig. 2) enables identification of fine-grained residual soils (Vargas 1988; Yudhbir and Sahu 1988).

The applicability of this approach in saprolitic soils lies in overcoming the difficulty of obtaining reproducible results (from clay fraction and plasticity determinations) using proper sample treatment and testing procedures and understanding how treatment methods influence the grain-size distribution, plasticity and activity of the soil (Gidigasu 1988). The influence of air and oven drying on reducing the plasticity index (possibly due to aggregation and reduction in clay content particularly in soils with considerable free iron oxide content) is well known. In the less weathered (lower) parts of the saprolitic profiles, clay content in samples with partially decomposed feldspars cannot be accurately determined unless broken mechanically (Massey et al. 1988). Hence the possibility of obtaining a reliable particle size distribution in saprolites is also limited because of the presence of clay (particularly books of kaolinites) as pseudomorphic replacement within partially decomposed and relict feldspars, and relict (primary) and secondary (iron oxide) bonding.

In transported soils, initial porosity (determined by grain size distribution controlled by the depositional processes) and subsequent stress history determine the degree of packing and density, and hence their engineering behaviour. In saprolitic soils, all fabric elements are inherited from the parent rock and have progressively evolved to their present state through weathering processes. The result is a material with a wide range of voids and grain mixtures (both in origin, size/shape and mode of distribution). The behaviour of this material is not a function of grain size or stress history, but highly dependent on its present state characteristics, particularly relict and secondary bonding (Fig. 3). This bonded structure of the material contributes to its strength and stiffness, which is independent of effective stress and porosity. The patterns of observed engineering behaviour in residual soils therefore cannot be directly related to the limits and percentage of clay particles.

Rock as an engineering material cannot be reconstituted from a given set of index properties and can only be characterised at its present state. Therefore, what rock classification tests accomplish is to delimit, for a certain physical or engineering property, a range of values valid for a given state of rock characterised by its microfabric description. However this limitation does not seem to have received much attention. The engineering geology literature includes numerous attempts proposing general relationships for a given rock type with little reference to the state of the material tested. In treating the saprolitic material using rock-testing methodology, more pronounced microfabric heterogeneity makes it crucial that microfabric characterisation accompany test results.

The difficulties involved in identification, description, classification, and zonal delineation have resulted in a large number of radically different approaches and methods proposed to characterise saprolites. These methods, based on microscopic, chemical and physical studies, involve a wide range of semi-quantitative and quantitative indices devised to capture weathering-induced changes in relevant aspects of rock materials. Useful discussions of these indices can be found in Baynes and Dearman (1978), Rocha Filho et al. (1985), Martin (1986), and Lee and de Freitas (1989). Integrated use of the indices for profile characterisation purposes provides an insight into the degree and scales of heterogeneity.

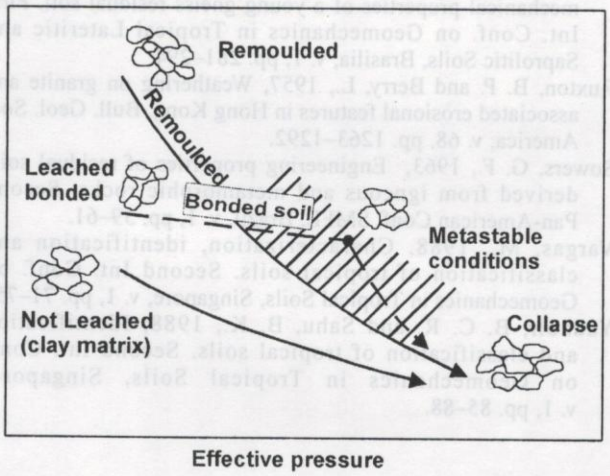

Fig. 3: Behaviour of saprolitic soils under increasing effective pressure (Fookes 1997). Note the open framework fabric of leached-bonded soils and the well-defined yield point at a critical pressure.

CONCLUSIONS

Analysis of current issues in characterisation of igneous and metamorphic saprolites reveals that the lack of comprehensive (geochemical, mineralogical, microfabric, and engineering geological) characterisation studies within well-defined geological frameworks is the underlying reason for the failure:

- to define, characterise and model saprolites as complex engineering geological units; and
- to devise specific site investigation methodologies to explore these complexities.

To improve our understanding of the consequences of weathering, it is highly necessary to integrate data from multiple sources at both regional and site scales. In order to arrive at firm, traceable, and comparable process models and characterisation schemes, the investigation methodology should include:

- the construction of a sound geological framework from lithological, structural, hydrogeological, and geomorphological microterrain analyses to:
  - appreciate important factors and their interactions in weathering processes;
  - characterise domains of "uniform" terrain characteristics;
  - provide a base to predict site-scale variations; and
  - integrate data of varying source and nature.
- the integration of geochemical analyses of rock, soil and groundwater compositions to establish weathering-induced changes within these domains and establish the level of process heterogeneity (and not only simple determination of chemical indices);
- the establishment of a distribution pattern and the type of clay minerals and range of microfabric configurations within the domains (and not only simple determination petrographical indices); and
- the calibration of variations in physical indices in terms of changes in chemical composition, mineralogy, and microfabric configurations (and not simply in terms of grades).

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