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Weathering and weathering processes

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Abstract

Definitions of weathering are examined and a definition of weathering for geotechnical purposes is proposed. Weathering is achieved by weathering processes, which depend upon the nature of the new environment to which the geological materials are introduced. Weathering processes are reviewed with particular reference to examples from engineering practice. The weathering product, the modified geological material and mass, is a consequence of the interaction of the weathering processes and the geological materials and mass on which the weathering processes act. Modes of weathering of particular rock types are reviewed. The paper concludes with a discussion of classification policy, recommending simplification.

Introduction

All engineering works are conducted on the Earth's surface or at a relatively shallow depth below it, and are commonly constructed from materials won from the Earth. The shallow domain of engineering in the Earth's crust happens to be that zone in which the processes of weathering, erosion, transportation and deposition are conspicuously active. Weathering modifies the mineralogy and texture of the geological materials within this zone and thus the phenomenon of weathering may be considered to be one of the greatest sources of potential difficulties in geotechnical engineering. This is because weathering may:

- considerably modify material and mass engineering properties
- result in a distribution of these modifications in a way which is very difficult to forecast
- produce variations in the distribution of mass properties which cannot be readily dealt with by calculation techniques
- modify material and mass engineering properties after the engineering work has been completed.

Weathering is defined in a number of ways depending on the standpoint of the definer. Those most commonly concerned with weathering, outside of engineering geology, are geomorphologists and soils scientists. Thus Reiche (1950) defined weathering as '... the response of materials which were in equilibrium within the lithosphere to conditions at or near to its contact with the atmosphere, the hydrosphere, and perhaps more importantly, the biosphere'. Ollier (1991) wrote: 'Weathering is the alteration and breakdown of rocks near the earth's surface, mainly by reaction with water and air, to form clay, iron oxides and other weathering products', while Selby (1993) described weathering as '...the process of alteration and breakdown of soil and rock materials at and near the Earth's surface by physical, chemical and biotic processes'.

The author suggests a possible definition for application in geotechnology could be:

'Weathering is the irreversible response of soil and rock materials and masses to their natural or artificial exposure to the near surface geomorphological or engineering environment'.

Weathering is achieved by weathering processes, which depend upon the nature of the new environment to which the geological materials are introduced. The weathering product, the modified geological material and mass, is a consequence of the interaction of the weathering processes and the geological materials and mass on which the weathering processes act. If weathering processes have continued and will continue without interruption, the weathered condition of any particular geological material or mass may be seen as but a stage in the progress of weathering towards its ultimate product, usually a residual soil. However, weathering as response to the natural environment seems to proceed very slowly and, in the course of weathering, environmental changes may modify the nature of the weathering process. In nature, over the last 20 000 years, the climatic environment in Britain has changed from glacial to temperate. Engineering may expose geological materials rapidly to a new environment. Rocks, previously dry and cool underground, may be exposed to the moist, warm conditions of a tunnel. Quarried fragmental material may be placed in the new environment of concrete, breakwaters, embankments or exposed as cladding for buildings.

Weathering processes act in the continuing or new environment. The principal processes are usually considered to be those bringing about mechanical disintegration and chemical decomposition; the former 'physical weathering' breaking up rock and mineral particles to smaller grain sizes without change in the nature of the minerals, the latter 'chemical weathering' changing the nature of the component minerals. Most weathering is compounded of both processes but physical weathering occurs quite close to the surface, while chemical weathering may extend to depths of the order of tens or hundreds of metres below surface (Chorley 1969). Which process is most active at any particular location will depend upon climate.

Both processes depend upon access to the rock mass to be effective. On the small scale access is given by porosity, on the larger scale by jointing. All rocks are jointed, joints being formed at some stage in their genesis and later under tectonic stresses, and it would not be unreasonable to argue that the first stage in weathering is the formation of joints, for such mechanical discontinuities allow access of fluids to the rock mass and determine the surface area of rock blocks.

However, near surface discontinuities may be opened or brought about by destressing or rebound of the soil or rock mass when naturally or artificially exposed. This is possibly the first weathering process that begins to act upon the virgin rock mass in its progress towards decay and may thus form the first topic for discussion.

Rebound

Rocks underground have become lithified under stress and, if stresses are reduced by surface erosion, may be exposed containing locked-in strain energy (Nichols & Abel 1975). The release of this energy may cause the development of fractures generally somewhat parallel to the erosion surface, but quite often aligned with regard to the orientation of an existing integral discontinuity (for example, a bedding plane in sedimentary rocks) or mechanical discontinuity (for example, a joint in igneous rocks). Such rebound fractures have been observed in almost all geological materials, ranging from soft clays to granites. Their development appears to be time dependent. Nichols (1980) has pointed out that rebound features are most pronounced as a consequence of the rapid excavations associated with engineering works.

What actually happens as a consequence of stress relief depends upon the nature of the rock, the rock mass and the stress field operating before excavation. Most engineering geologists have at some time observed excavated slopes displaying opened steep joints and small overhangs of shallowly dipping joints indicating movement into the excavation. Deep boreholes into strong uniform rock may give cores which, after some time, disc into smaller core lengths, a phenomenon often interpreted as an indication of the existence of high stresses underground and their relief. Many natural rock cliffs can be seen to show sets of joints which, as the top of the slope is approached, maintain their orientation but become more closely spaced. If the rocks are bedded, integral bedding plane discontinuities may become mechanical close to the surface.

The opening or formation of mechanical discontinuities allows ingress of percolating waters, thus promoting weathering. Since all rocks exposed near surface have once been under higher stresses than they now carry, it would seem correct to assume that the development of rebound fractures is an important stage in the general development of weathering.

Physical weathering

If rebound induces fractures, the fracture and/or joint bounded blocks may still contain strain energy. Further physical action on such blocks may cause yet more fracturing. Such physical action may occur as a result of thermal expansion and contraction, although the extent of the role of thermal changes in rock disintegration may be questioned. It is known that in early times rock to be excavated in mines was broken by heating and dowsing, but such rock may have been in any case quite highly stressed. Exposed rocks in deserts will heat up or cool with greater or lesser rapidity depending on their colour and their thermal conductivity. High surface temperatures will build up on dark rocks, such as basalt, but to a lesser degree on white rocks, such as chalks. Where large blocks of rock are piled one upon the other, such as in some outcrops of dolerite, spalling from the block may be related to release of internal residual stresses as well as to external factors.

Ice and crystal growth

Water penetrating into cracks and pore spaces may freeze and by expansion (about 9% at 0°C) exert force across existing fractures or initiate cracks from ice-filled pore spaces. Salts may be carried by percolating water into pore spaces and there, by crystal growth and thermal expansion or hydration of already existing crystals, exert pressure and form cracks. Porous weak rocks are more susceptible to this form of disintegration than non-porous strong rocks.

Wetting and drying

Most engineering geologists have observed that cores of mudrocks, if stored outside in leaky core boxes may, as a consequence of some weeks of wetting and drying, disintegrate. The same may be observed on new cuts and in natural exposures in mudrocks. The cause of this 'slaking' may be volume expansion of clay minerals or be associated with moisture movements in the rock mass.

FIG. 1. Tombstones at Wymondham Abbey, Norfolk.

Plant growth

Plant roots may penetrate into cracks and joints and, by growth, exert pressure to widen them, thereby fostering mass disintegration and facilitating fluid access for chemical weathering. This phenomenon may be viewed in many old man-made or natural slopes but is seldom considered as a long-term engineering hazard. The engineering lifetime of the majority of structures may be considered to be of the order of 50 to 100 years; within this timespan many trees and plants will achieve full maturity both above and below ground and cause significant damage by root wedging.

Aspect

The degree of physical weathering experienced by exposed rock is closely associated with local climatic conditions. The intensity of weathering may depend upon whether or not a location is sheltered from the prevailing wind, how many hours of sunshine it receives and other factors (see Emerick 1995). Studies of tombstone weathering are an almost traditional method of establishing relative rates of weathering of various rock types. Three tombstones in the graveyard of Wymondham Abbey, Norfolk are shown in Fig. 1. Those on the left- and right-hand sides are of reddish sandstone, while the centre is a grey calcareous sandstone. They date from between 1870 and 1880. Following the scale of tombstone weathering established by Rahn and reported in Fookes *et al.* (1988) the left- and right-hand stones would be 'very badly or extremely weathered' while the centre stone would be only 'slightly weathered', the difference presumably reflecting relative rock durability. However, elsewhere in the churchyard, a grey sandstone tombstone, dated 1883, is 'slightly weathered' on the west facing side (Fig. 2a), but the east facing side (Fig. 2b), which shows scaling, is 'extremely weathered'. Other tombstones in the same churchyard show different grades of weathering between front and back, although not always the same difference. Clearly the aspect of the weathering surface is of importance.

Chemical weathering

Chemical weathering below surface takes place via water movement through mass and materials. Movement through the mass is via joints and other discontinuities

FIG. 2. (a) West-facing side and (b) east-facing side of a tombstone at Wymondham Abbey.

and the distribution of mass weathering may reflect both minor and major joint set spacing and orientation and the presence of faults (Currey 1977). Taylor (1988), writing on Coal Measures mudrocks, considered physical disintegration to be the control on chemical weathering, and identified sedimentary structures, slaking and expandable mixed layer clay content as features and mechanisms which would open the rock mass to the passage of percolating waters. Surface chemical weathering is often assisted by atmospheric pollution and the source chemicals may be deposited by rain, dew or mist.

Chemical weathering usually includes solution, the degree of which will depend principally upon the quantity of water passing over the surface of solution, the solubility of the solid being dissolved, and the pH of the water. Solubility of elements varies: an often cited order of solubility for common mineral forming elements is:

$$Ca > Na > Mg > K > Si > Al > Fe.$$

However, the degree of solubility may vary depending on pH value. Thus Fe is about 100 000 times more soluble at pH6 than pH8.5.

The most commonly encountered solution phenomena are found in limestones or rocks bound by calcareous cement. Examples of the occurrence of cavities in limestones as a consequence of calcite solution are too numerous to quote. Solution of cement or grains in geological material is a more subtle source of decay. The decalcification of rocks and soils is not uncommon; Hawkins & McDonald (1992), for example, have reported on the influence of decalcification on the residual shear strength of Fuller's Earth mudstone clay. Solution of other minerals may also be significant in some materials; according to Torrance (1974), the reduction, by leaching, of pore water salinity below a certain level has a significant effect on the properties of Norwegian marine clays.

Further chemical weathering involves such chemical processes as hydration, hydrolysis, oxidation, reduction and chelation as a consequence of which secondary minerals (often clay minerals) are formed from the primary minerals. It is recognized that some minerals are more resistant to solution and chemical weathering than others. An often quoted sequence of increasing stability (Selby 1993) is:

↓	Olivene		Ca Feldspar
	Augite		↓
	Hornblende		
Increasing	Biotite		Na Feldspar
stability		K Feldspar	
↓		Muscovite	
		Quartz	

The development of secondary minerals may involve volume change, introducing internal pressures leading to material fragmentation. This offers more surface area on which chemical weathering can act. Sometimes the weathering of one particular mineral is sufficient to bring about the decay of the whole rock. Raymahashay & Sharma (1993) observed that the decay of almandine to kaolinite and goethite in khondalite (a quartz–garnet metamorphic rock) increased porosity and weakened the rock, thereby damaging the Konark Sun Temple.

Biological agencies, such as bacteria, may produce complex mineral–organic chemical substances, and are often particularly active in waterlogged environments. Surface organisms, such as lichen, fungi, moss and algae, may, by chemical and perhaps mechanical actions, detach rock slivers and grains from exposed rock surfaces.

Chemical transfer

Chemical compounds taken up into solution may be precipitated elsewhere. Thus calcium carbonate dissolved from limestone may be precipitated in 'dripstone' formations underground or discontinuity infills in other rock formations. Formations below iron bearing rocks may be heavily ironstained.

If precipitation takes place between pore spaces granular materials may become cemented to form duricrusts (Fookes 1978). The cementing material may be derived from an underlying weathered (and thus depleted) zone by upward leaching or by downward percolation from overlying materials. Duricrusts are usually of the order of a few metres thick, and cementation may be very irregular. Popular nomenclature incorporates the cement type with '-crete' to give a type name. Thus 'calcrete', 'ferricrete', 'silcrete', 'gypcrete', 'salcrete' and 'alcrete' are examples. Laterite and bauxite are associated with a form of duricrust development, but terminology is vague and connected to economic factors. The term laterite covers rock-like material but also includes materials having the properties of engineering soils. The actual engineering properties of such materials depend much upon the nature of the source rock (Tuncer & Lohnes 1977; Ogunsanwo 1988). Residual soils in tropical environments may pose many engineering difficulties; appropriate description is a prerequisite to working with them and has been the subject of an Engineering Group Working Party Report (Anon 1990).

Weathering underwater

Weathering of geological materials presumably takes place underwater as well as on surface and is described as 'halmyrolysis'. Little seems to be known regarding presently active underwater weathering, but it is well to remember that sea level falls in the Pleistocene exposed what is now the sea bed to surface weathering and denudation appropriate to the climate. The complexity of weathering that is now to be observed on the surface may be the clue to understanding features encountered in marine boreholes and geophysics.

Modes of weathering of typical rock types

Certain modes of weathering are associated with particular rock types. However, before taking these as being the rule it is well to remember that weathering may take place on 'fresh' geological masses or on rocks that have already suffered weathering when previously exposed to the surface. Every older rock surface in a temporal unconformity was once the surface of the land or sea floor. Thus fossil karst may be found affecting old limestone land surfaces now buried under younger rocks (Bless *et al.* 1990; Poty 1980) and fossil soils may be present between successive lava flows or pyroclastic deposits. Such weathering may have taken place under climatic conditions very different to those at that place today. More recent weathering may have acted and present weathering is acting on yet older materials already weathered under a different climatic regime.

Weathering depends upon the external environmental agents acting to promote weathering (climate, plant growth etc.), which will vary from place to place and through time, and upon the properties of the rock material and rock mass. For the rock material the properties that determine sensitivity (or resistance) to weathering are:

- mineralogy (solubility and resistance to chemical weathering)
- grain size
- porosity and permeability

In the rock mass the spacing, nature, persistence and aperture of discontinuities together with the conditions of stress would appear to have a major influence on weathering.

Within any particular environment any one of these rock material/mass factors may be dominant and determine weathering style. Thus when the presence of soluble minerals is the dominant factor, some form of karstic weathering may occur, as in limestones, dolomites and gypsum rocks. What that form may be will depend upon other factors, hence the well known differences in expression of solution weathering between the porous chalks and the crystalline limestones of Britain. However, 'karstic' weathering is not limited to the most obviously soluble rocks; such weathering is also known in quartz sandstones and quartzites in the Guiana Highlands and in Australia (Selby 1981).

Within one particular style of weathering, weathering intensity may vary between strata apparently composed of more-or-less the same rock. Thus, in crystalline limestones one or more layers in a thick sequence may show a greater intensity of karst caverns. This may be due to some minor change in solubility of the rock, differences in the intensity of discontinuities in the layers, the presence of minor layers of non-soluble rocks (such as shales) which have influenced groundwater flow, or variations in environmental factors.

In igneous rocks differences in grain size and mineralogy produce varying resistance to weathering. In granites coarser grained rocks tend to weather more readily than any 'aplitic' intrusions contained within the plutons. In basic igneous rocks finer grained varieties also resist weathering more than the coarser grained types. However, fine grain is not necessarily indicative of high resistance to weathering. For example, Higgs (1976) has described 'slaking' basalts from the United States, in which the slaking mode of collapse is attributed to the presence of montmorillonite which is itself a product of weathering of minerals such as olivene.

Both acid and basic coarser grained intrusive rocks tend to produce the well known 'corestone' weathering, in which weathering can clearly be seen to be progressing into rock blocks from their surrounding joints, leaving corestones surrounded by a compact sandy weathering product containing ghost joints. Such weathering does not necessarily uniformly decrease with depth, and intensity may vary relative to minor mineralogical changes or as a response to past environments.

Considerable attention has been given to describing the weathering of coarse grained igneous rocks, mostly granites, presumably because these rocks are often quite well exposed and, before weathering, relatively uniform. Irfan & Dearman (1978) described the engineering petrography of granite weathering, while Krank & Watters (1983) have recorded the changes in engineering properties associated with granodiorite weathering. Weathering profiles in granite have been described by Raj (1985). Attempts have been made by many researchers to establish weathering indices based on some physical or chemical change in the rock type. In the case of granite Malomo (1980) noted that the abrasive pH of pulverised feldspars changes with the weathered condition of the rock in relation to porosity and density, thereby offering a potential for use as an index of change in engineering properties. The most significant weathering boundary is that in which the weathered material can be considered to be changing from material with the properties of rock to material with the properties of soil; this problem, in granites, has been examined by Howat (1985), who paid particular attention to the use of the Standard Penetration Test in the weathered granites of Hong Kong. Problems associated with weathered coarse grained basic igneous rocks are less conspicuous in the literature but are much the same as for granitic rocks. Dobie (1987) has reported stability problems in norite slopes associated with changes in permeability as a consequence of weathering. The author's own experience with Scottish and Tasmanian dolerites confirms weathering as a major source of slope instability in these rocks.

Metamorphic rocks are usually both mineralogically, texturally and, in the mass, structurally more complex than other rocks. For example, schistose and gneissose rocks tend to contain concentrated accumulations of minerals such as biotite, muscovite and hornblende, in foliated layers. Chemical weathering in such layers may tend to be more concentrated than in adjacent quartz and feldspar rich bands. Dobereiner *et al.* (1993) noted that anisotropy in engineering properties in the fresh gneisses became more pronounced as weathering increased. They also remarked that stress release may have been the cause of the development of microfissuring which contributed to changes in engineering properties. Papadopolous & Marinos (1992) observed that, for Athenian schist, the anisotropy index increased from fresh rock to slightly weathered rock but then decreased as the rock became more decomposed.

Weathering is probably least complex in the coarser grained clastic sedimentary rocks. Most sandstones are composed of cemented quartz grains. The grain packing and quantity of cement will influence the porosity of the rock. Weathering below surface may take place by the solution of carbonate or ferrous cements.

It is probably true to say that, of all the rocks on which engineering may be performed, probably the greatest attention has been paid to mudrocks. Mudrocks (mudstones, shales, pelites, etc.) are composed of clay and silt sized particles, are commonly laminated and, in the mass, closely jointed. Surface weathering includes stress release cracks (more readily displayed than in most rocks because of the greater frequency of integral discontinuities), as well as cracks produced by cyclic wetting and drying, while the final weathering product is a soil usually of clayey character. Clay minerals present may include those which change volume with moisture content. Swelling following water absorption is a common problem that is particularly pronounced in dry areas if the rock comes into contact with water. Orhan Erol & Dhowian (1990) have described the particular swelling problems in Saudi Arabia associated with exposure of desiccated shales to utility water. The role of successive desiccation and wetting in the weathering of pelitic rocks has been examined by Lempp (1981). Wetzel & Einsele (1991) have described the wetting/drying sequence leading to the shrinkage/swelling mechanism of disintegration by weathering as 'pelitoclastesis'.

Many mudrocks contain minerals susceptible to weathering. Pyrite is not uncommon and on exposure to a new environment, as in an embankment (Pye & Miller 1990), may oxidize, leading to the generation of acid waters which then react with the other minerals present (Steward & Cripps, 1983). If such rocks are used in cement stabilized fills the weathering products of pyrite may attack the cement itself (Thomas *et al.* 1989). Heave affecting structures built on pyritic shale has been often reported; Wilson (1987), for example, attributed heave to the conversion of pyrite to gypsum.

Not only mudrocks but also clayey soils display weathering. Thus variations in strength of Lias clay have been ascribed to weathering by Chandler (1974) and the effects of weathering on London Clay have been reported by Chandler & Apted (1988). Weathering in clays is usually detected by colour changes, commonly from grey to brown, which are attributed to oxidation. Common experience indicates that such weathering will usually cause deterioration in engineering properties. While most literature deals with overconsolidated clays, the effects of weathering have also been noted in much weaker clays. Balasubramaniam & Waheed-Uddin (1977), writing on deformation characteristics of the usually soft normally consolidated Bangkok Clay reported that samples from the weathered zone displayed consolidation characteristics appropriate to an overconsolidated clay when tested at low consolidation pressures.

Differential weathering in the mass

The geological mass is composed of a range of geological materials arranged in a geological structure ramified by discontinuities. In such an anisotropic mass the weathering front extending downwards from surface is unlikely, on the large scale, to be other than irregular in spacial distribution. Thus, in relation to depth below surface, relatively unweathered rocks may well overlie rocks displaying a greater degree of weathering. Higginbottom & Fookes (1971) reported selective decomposition as a consequence of decalcification within a steeply dipping series of shales underlying Pembroke Power Station in South Wales.

Rates of weathering

Some studies on rates of natural weathering on rock surfaces have been accomplished by the examination of artifacts (gravestones, monuments and the like) as reported by, for example, Livingston & Baer (1988) and Dragovich (1988). Measurable changes take place within a timescale of hundreds of years. The author's own observations of chisel and saw cut scars on the walls of the underground calcarenite mines of Belgium and The Netherlands indicate that scar profile softening takes place only after exposure of the order of 300 to 400 years. Little seems to be known with regard to weathering rates in rocks deep below surface.

In the engineering context the modification of material and mass properties by weathering is a factor to be considered in all work involving all geological materials and masses. Establishing the nature and influence of any past modifications is an important aspect of site investigation. Furthermore, since the engineering works have to perform satisfactorily throughout their engineering lifetime it is important to consider whether or not weathering processes, acting during this time period, will impair the security of the completed work.

Reactions of the ground to changes in stress, which may initiate weathering, are assessed by engineering calculation. Both slope destressing in surface excavations and opening convergence in underground excavations induce fractures to form and open existing discontinuities which provide new paths for the ingress of fluids and thus encourage material change. Freeze/thaw and wetting/drying cyclic processes will act on exposed surfaces. The effects on engineering properties may occur rapidly. For example, Shakoor *et al.* (1982) report the freeze/thaw resistance of argillaceous carbonates, used as asphalt and concrete aggregate in Indiana, to be so low that roads surfaces had to be resurfaced after less than one year of use.

TABLE 1. *Relative solubility of soluble minerals (from James & Kirkpatrick, 1980)*

Material	Solubility in pure water c_s (kg/m^3) at 10° C
Gypsum	2.5
Halite	360.0
Limestone	0.015
Anhydrite	2.0
Quartz	0.01

Solution is an important weathering process in geological time but its significance in engineering time will depend upon the mineral being dissolved. There is ample evidence, from dam and tunnel construction for the solution of gypsum, anhydrite and halite within engineering time (James & Lupton 1978; James & Kirkpatrick 1980). The solubility of calcite is much less (Table 1). While there are many examples of engineering problems associated with karstic limestone there is little evidence to associate clearly these problems with limestone solution initiated by the engineering work. With regard to most dams on crystalline limestone, for example, the general opinion seems to be that the grouting used to seal off seepages will provide adequate protection against future solution (James & Kirkpatrick 1980).

Chemical change from one mineral to another within engineering time has been most commonly observed in mudrocks, particularly those containing pyrite. The oxidation of pyrite and the associated development of acids in mudrocks used as fills may lead to decalcification of the rock. According to Taylor (1988) chemical weathering of fine disseminated pyrite in fresh mudrocks may start within days of exposure to the atmosphere. Such rapidity of chemical weathering is seldom observed in rocks chosen for construction purposes other than for fill, presumably because the first selection criteria of strength and resistance to wetting and drying remove most mudrocks from consideration. On those rocks selected, mostly the stronger sedimentary, metamorphic and igneous rocks, the agents of physical and chemical weathering will act, together with such additional mechanisms of degradation as are associated with the particular engineering use, such as impact, abrasion and cyclic stressing. However, most reports of problems (Fookes *et al.* 1988) and general experience associate the already weathered condition of the construction rocks with the problems encountered. The presence of secondary minerals, alteration products and microcracking as sources of problems recommend petrographic analysis as a first stage in establishing the suitability of a rock to perform within a new engineering environment.

Durability

Considerable attention has been paid to assessing the durability of rock in a new engineering environment. For example, Bell (1992) has reviewed the durability of sandstone when used as a building stone, Dibb *et al.* (1983) have examined durability in the marine environment, while Latham (1991) has produced a rating system, incorporating rock properties, engineering design and environmental factors, to build up a rock degradation model for armourstone.

Various tests have been devised to simulate the weathering process to which the materials will be subjected. Well known tests such as the slake-durability test, swelling test, and the resistance to abrasion test have been standardized by various bodies such as British Standards or the American Society for Testing Materials. Many of these tests are reviewed in Smith & Collis (1993) and by Fookes (1991). Attempts have been made to modify tests to render them more effective. Richardson & Long (1987), for example, examined modifications of the slake-durability test in an attempt to make the test more sensitive.

Construction materials for new works usually use rock which is as fresh as possible and there is a need to assess its durability. However, assessments of the effects of increasing climatic pollution and of further exposure to weathering in time, coupled with a desire to preserve items of cultural heritage often require an examination of the future durability of rocks which have been used to construct ancient monuments and which are already weathered. An assessment of the damage done to engineering properties by weathering (Christaras 1991) is required before making proposals for remedial works.

Discussion

This paper is based upon a lecture given on the occasion of the presentation of the draft Engineering Group Working Party Report on 'The description and classification of weathered rocks for engineering purposes' and it was presented in Leeds in April 1994. The importance of weathering to engineering work is clear, as is the need for a systematic approach to its description. Weathering is a response to environmental change and engineering brings about environmental change. Thus every engineering work sets in train a new phase of weathering on the materials or mass affected by the work. There are thus two main systems to be developed in dealing with weathering. The first is a means of describing the existing weathered condition of mass and materials, the second a means of forecasting the weathering which may be brought about as a consequence of the application of the engineering processes.

With regard to the former the weathered condition which has been achieved in the mass depends upon the weathering processes and the materials and mass to which they were applied. Once the mass or material has been destressed the weathering processes acting are chiefly influenced by climate, which is the basic control for groundwater movement, plant growth, freeze–thaw cycles, wetting and drying and other significant processes of weathering. Which weathering process is dominant at a particular location will depend the susceptibility of the rock mass and material to that process. The weathering processes themselves may change. Climatic change has occurred quite rapidly in recent times and the contemporary increase in air and moisture borne pollutants has introduced a new weathering process into the geological environment.

Since the weathered condition of a rock mass depends upon process, material and mass weathering stage boundaries will depend upon different boundary recognition signals for each rock mass type. Thus, while still using the basic weathering scale framework as proposed in the British Standards Institution Code of Practice for Site Investigations (Anon 1981), researchers have seen the need for modification with regard to particular rock types. Thus Hawkins & Pinches (1992) have proposed a modified weathering scale for mudrocks while Lee & de Freitas (1989) have done this for granites. Fookes & Hawkins (1988) have produced an engineering classification for crystalline limestone terrain which is related to the degree of solution weathering. In view of the existence of a large range of rock types and masses and weathering processes there are many possibilities for future classifications of particular rock masses weathered in particular environments. While those that have been developed can be justified, too many special case modifications employing limited terminology would lead to confusion. Perhaps the emphasis of any future classification for engineering purposes should lie in simplification rather than elaboration, paying particular regard to establishing the boundary between that part of the weathered mass which will behave as an engineering soil and that which will behave as an engineering rock.

Most investigations are conducted using boreholes and assessments of mass weathering depend upon interpretation of borehole samples and correlation between boreholes. It would be useful to devote some research to building up a database of typical weathering styles associated with mass lithologies, for this would aid the interpretation of borehole data. In the description of mass weathering for engineering purposes, the uniformity or regularity and style of weathering is a key issue. The author suggests that, to aid recognition of the engineering difficulties mass weathering may present, mass weathering could be described in terms of uniformity and style, using terms such as:

- *uniform(ly) weathered*, implying a gradual decrease in weathering intensity with depth, as might be encountered in thick strata of homogeneous lithology.
- *complex(ly) weathered*, an irregular weathering profile as might be found in layered strata which have different susceptibilities to weathering. If they are dipping it could imply that less weathered strata lie under more weathered strata.
- *corestone weathered*, indicating, usually in coarse grained igneous rock, the weathering style in which rounded 'corestones' of almost fresh rock may be surrounded by very decomposed highly friable material, similar to a compact sand.
- *solution weathered*, signalling, in soluble rocks, that joints and bedding planes could be open and underground caverns may have developed.

Forecasting the nature, degree and rapidity of future weathering depends upon assessing the environment to which material or mass will be exposed while also estimating the reaction to that environment. In the case of geomaterials much work on material testing and assessing durability has already been done. For future mass weathering reliance must be placed on material behaviour and well documented experience.

References

ANON 1981. *Code of Practice for Site Investigations* (BS5930). British Standards Institution, London.

——— 1990. Geological Society Engineering Group Working Party Report: Tropical Residual Soils. *Quarterly Journal of Engineering Geology*, **23**, 1–101.

BALASUBRAMANIAM, A. S. & WAHEED-UDDIN. 1977. Deformation characteristics of weathered Bangkok Clay in triaxial extension. *Géotechnique*, **27**, 75–92

BELL, F. G. 1992. The durability of sandstone as building stone, especially in urban environments. *Bulletin of the Association of Engineering Geologists*, **29**, 49–60.

BLESS, M. J. M., BOUCKAERT, J., & PAPROTH, E. 1980. Environmental aspects of some Pre-Permian deposits in NW Europe. *Mededelingen Rijks Geologische Dienst*, **32**, 1/14, 3–13.

CHANDLER, R. J. 1974. Lias clay: the long term stability of cutting slopes. *Géotechnique*, **24**, 21–38

——— & APTED, J. P. 1988. The effect of weathering on the strength of London Clay. *Quarterly Journal of Engineering Geology*, **21**, 59–68.

CHORLEY, R. J. 1969. The role of water in rock disintegration. *Introduction to Fluvial Processes*, Methuen, 53–73.

CHRISTARAS, C. 1991. Durability of building stones and weathering of antiquities in Creta/Greece. *Bulletin of the International Association of Engineering Geology*, **44**, 17–25.

CURREY, D. T. 1977. Deeply weathered rock at Victorian damsites. *Engineering Geology*, **11**, 341–363.

DIBB, T. E., HUGHES, D. W., POOLE, A. B. 1983. The identification of critical factors affecting rock durability in marine environments. *Quarterly Journal of Engineering Geology*. **16**, 149–161.

DOBIE, M. J. D. 1987. Slope instability in a profile of weathered norite. *Quarterly Journal of Engineering Geology*, **20**, 279–286.

DOBEREINER, L., DURVILLE, J. L., & RESTITUITO, J. 1993. Weathering of the Massiac gneiss Massif Central, France). *Bulletin of the International Association of Engineering Geology*, **47**, 79–96.

DRAGOVICH, D. 1988. Weathering of sandstone tombstones in a coastal environment, Sydney (Australia). *In:* MARINOS, P. & KOUKIS (eds) *Engineering Geology of Ancient Works, Monuments and Historical Sites*, Balkema, Rotterdam, **2**, 853–858.

EMERICK, K. 1995. The survey and recording of historic monuments. *Quarterly Journal of Engineering Geology*, **28**, 201–206.

FOOKES, P. G. 1978. Middle East — inherent ground problems. *Quarterly Journal of Engineering Geology*, **11**, 33–49.

——— 1991. Geomaterials. *Quarterly Journal of Engineering Geology*, **24**, 3–16.

——, GOURLEY, C. S. & OKIHERE, C. 1988. Rock weathering in engineering time. *Quarterly Journal of Engineering Geology*, **21**, 33–58.

—— & HAWKINS, A. B. 1988. Limestone weathering: its engineering significance and a proposed classification scheme. *Quarterly Journal of Engineering Geology*, **21**, 7–32.

HAWKINS, A. B. & MCDONALD, C. 1992. Decalcification and residual shear strength reduction in Fuller's Earth Clay. *Géotechnique*, **42**, 453–464

—— & PINCHES, G. M. 1992. Engineering description of mudrocks. *Quarterly Journal of Engineering Geology*, **25**, 17–30.

HIGGINBOTTOM, I. E. & FOOKES, P. G. 1971 (for 1970). Engineering aspects of periglacial features in Britain. *Quarterly Journal of Engineering Geology*, **3**, 85–117.

HIGGS, N. B. 1976. Slaking basalts. *Bulletin of the Association of Engineering Geologists*. **13**, 151–161.

HOWAT, M. D. 1985. Completely weathered granite - soil or rock? *Quarterly Journal of Engineering Geology*, **18**, 199–206.

IRFAN, T. Y. & DEARMAN, W. R. 1978. The engineering petrography of a weathered granite in Cornwall, England. *Quarterly Journal of Engineering Geology*, **11**, 233–244.

JAMES, A. N. & KIRKPATRICK, I. M. 1980. Design of foundations of dams containing soluble rocks and soils. *Quarterly Journal of Engineering Geology*, **13**, 189–198.

—— & LUPTON, A. R. R. 1978. Gypsum and anhydrite in foundations of hydraulic structures. *Géotechnique*, **28**, 249–272.

KRANK, K. D. & WATTERS, R. J. 1983. Geotechnical properties of weathered Sierra Nevada granodiorite. *Bulletin of the Association of Engineering Geologists*, **20**, 173–184.

LATHAM, J-P. 1991. Degradation model for rock armour in coastal engineering. *Quarterly Journal of Engineering Geology*, **24**, 101–118.

LEE, S. G. & DE FREITAS, M. H. 1989. A revision of the description and classification of weathered granite and its application to granites in Korea. *Quarterly Journal of Engineering Geology*, **22**, 31–48.

LEMPP, Ch. 1981. Weatherability of overconsolidated pelitic rocks of the Keuper and Jurassic in southwestern Germany. *Bulletin of the International Association of Engineering Geology*, **23**, 101–108.

LIVINGSTON, R. A. & BAER, N. S. 1988. The use of tombstones in the investigation of the deterioration of stone monuments. *In:* MARINOS, P. & KOUKIS (eds) *Engineering Geology of Ancient Works, Monuments and Historical Sites*. Balkema, Rotterdam, **2**, 859–867.

MALOMO, S. 1980. Abrasive Ph of feldspars as an engineering index for weathered granite *Bulletin of the International Association of Engineering Geology*, **22**, 207–211.

NICHOLS, T. C. 1980. Rebound, its nature and effect on engineering works. *Quarterly Journal of Engineering Geology*, **13**, 133–152.

—— ABEL, J. F. 1975. Mobilised residual energy - a factor in rock deformation *Bulletin of the Association of Engineering Geologists*. **12**, 213–225.

OGUNSANWO, O. 1988. Basic geotechnical properties, chemistry and mineralogy of some laterite soils from S.W, Nigeria. *Bulletin of the International Association of Engineering Geology*, **37**, 131–136.

OLLIER, C. 1991. *Ancient Landforms*. Belhaven Press.

ORHAN EROL, A. & DHOWIAN, A. 1990. Swell behaviour of arid climate shales from Saudi Arabia. *Quarterly Journal of Engineering Geology*, **23**, 243–254.

PAPADOPOULOS, Z. & MARINOS, P. 1992. On the anisotropy of the Athenian Schist and its relation to weathering. *Bulletin of the International Association of Engineering Geology*, **45**, 111–116.

POTY, E. 1980. Evolution and drowning of palaeokarst in Frasnian carbonates at Vise, Belgium. *Mededelingen Rijks Geologische Dienst*, **32 - 1/14**, 53–55.

PYE, K. & MILLER, J. A. 1990. Chemical and biochemical weathering of pyritic mudrocks in a shale embankment. *Quarterly Journal of Engineering Geology*, **23**, 365–381.

RAJ, J. K. 1985. Characterisation of the weathering profile developed over a porphyritic biotite granite in peninsula Malaysia. *Bulletin of the International Association of Engineering Geology*, **32**, 121–130.

RAYMAHASHAY, B. C. & SHARMA, S. 1993. Decay of building stones: a mineralogical model for Konark Sun Temple, India. *Quarterly Journal of Engineering Geology*, **26**, 155–157.

REICHE, P. 1950. A survey of weathering processes and products. *University of New Mexico Publications in Geology*, **3**, University of New Mexico Press.

RICHARDSON, D. N. & LONG, J. D. 1987. The sieved slake durability test. *Bulletin of the Association of Engineering Geologists*, **24**, 247–258.

SELBY, M. J. 1993. Hillslope Materials and Processes. Oxford University Press.

SHAKOOR, A., WEST, T. R. & SCHOLER, C. F. 1982. Physical characteristics of some Indiana argillaceous carbonates regarding their freeze–thaw resistance in concrete. *Bulletin of the Association of Engineering Geologists*, **19**, 371–384.

SMITH, L. R. & COLLIS, L. (eds) 1993. *Aggregates: Sand, Gravel and Crushed Rock Aggregates for Construction Purposes* Geological Society, London, Engineering Geology Special Publication, **9**.

STEWARD, H. E. & CRIPPS, J. C. 1983. Some engineering implications of chemical weathering of pyritic shale. *Quarterly Journal of Engineering Geology*, **16**, 281–289.

TAYLOR, R. K. 1988. Coal Measures mudrocks: composition, classification and weathering processes. *Quarterly Journal of Engineering Geology*, **21**, 85–100.

THOMAS, M. D. A., KETTLE, R. J. & MORTON, J. A. 1989. The oxidation of pyrite in cement stabilised colliery shale. *Quarterly Journal of Engineering Geology*, **22**, 207–218.

TORRANCE, J. K. 1974. A laboratory investigation of the effect of leaching on the compressibility and shear strength of Norwegian marine clays. *Géotechnique*, **24**, 155–173

TUNCER, E. R. & LOHNES, R. A. 1977. An engineering classification for certain basalt-derived lateritic soils. *Engineering Geology*, **11**, 319–339.

WETZEL, A. & EINSELE, G. 1991. On the physical weathering of various mudrocks. *Bulletin of the International Association of Engineering Geology*, **44**, 89–100.

WILSON, E. J. 1987. Pyritic shale heave in the Lower Lias at Barry, Glamorgan. *Quarterly Journal of Engineering Geology*, **20**, 251–253.

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