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PRACTICAL ASSESSMENT OF GRADE IN A WEATHERED GRANITE

EVALUATION PRATIQUE DU DEGRÉ D'ALTÉRATION D'UN GRANITE

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Summary:

The variability of the engineering character of a chemically weathered granite from South-west England has been assessed in the context of quarrying to produce roadstone and concrete aggregates. Present grading schemes are reviewed with regard to their practical application, and have been developed into methods of grading capable of characterizing both the relevant engineering properties and the distribution of weathering grades in the weathering profile. The data obtained have been used to deduce a geological model for the prediction of rock conditions from an engineering geological plan of the quarry.

The economic implications of the distribution of weathering grades are considered from the aspects of practical quarrying grades related to the criteria of material quality and ease of excavation.

Résumé:

La variabilité des propriétés techniques d'un granite du sud-ouest de l'Angleterre, chimiquement altéré, a été estimée dans le cadre de l'exploitation de carrières productrices de matériaux d'empierrement et de granulats pour le béton. On passe en revue les systèmes de séparation actuels, en ayant en vue leur application pratique, et on en tire des méthodes de séparation pouvant caractériser à la fois les propriétés techniques correspondantes et la répartition des degrés d'altération dans un profil d'altération. Les résultats obtenus furent utilisés pour en déduire un modèle géologique pour la prévision de la qualité des roches par l'examen d'un plan géotechnique de la carrière.

Les conséquences économiques de la répartition des degrés d'altération sont examinées au double point de vue de la facilité de l'excavation et de la détermination pratique d'un zonage de la carrière correspondant à la qualité du matériau.

Introduction

Rock mass characterization for engineering purposes involves the description of the geological nature of the rock mass, including the petrographic properties and details of discontinuities and structure, coupled with an assessment of the engineering properties of the rock material. Various workers, including Moye (1955), Kiersch & Treasher (1955) and Newbery (1970), have shown that, in single rock types in particular, weathering grade classification is an extremely useful tool for rock description. Consequently, assessment of weathering grade has become an important aspect of rock mass description for engineering purposes (Anon. 1970, 1972; Dearman 1974a, 1976). Moreover, the distribution of grades in a weathering profile plays an important part in the recognition and assessment of uniformity of foundation conditions (Knill & Jones 1965), and in other civil engineering applications (Deere & Patton 1971). However, ground conditions at engineering sites are usually available for study for a limited period: excavations for foundations are obscured once construction begins, tunnels are lined during driving if weathered rock is encountered, and cuttings in weathered rock are covered with soil and grassed. The one civil engineering setting in which **fresh** exposures of weathered rock are availalbe for analysis for any length of time is in quarries opened for the supply of concrete and road aggregates. In this, as in any other engineering setting, the distribution of rock grades suitable or unsuitable for a specific purpose is of paramount importance.

A working quarry with a possibly complete, distinct weathering profile therefore provides an ideal environment in which to assess critically the practical application of the British methods proposed for the characterization of weathered rock masses (Anon. 1972). There are a number of quarries in the south-west of England which fulfill this requirement, and Dearman & Fookes (1972) have discussed in general terms the influence of weathering profiles on the layout of quarries in the region.

The rock types available for study include basic igneous rocks, granite and limestone. Limestone weathers mainly by solution (Dearman 1974b) and presents its own atypical type of weathering profile (Deere & Patton 1971, fig. 9). The distribution of weathering products in dolerites and other basic igneous rocks in South-west England is dictated by variations in joint spacing and to a very great extent by the influence of major discontinuities (Baynes & Dearman, in press). Weathering in granites is also influenced by the pattern and nature of discontinuities, but in the rock material is mainly determined by the behaviour of a single group of minerals, the feldspars; the weathering stages are easy to determine and the resultant weathering profiles are relatively uncomplicated. A working granite quarry, with in places a well-developed complete weathering profile, was therefore chosen to study the problems associated with the assessment of engineering **grade**, including weathering grade, in a rock mass.

Each distinct weathering grade comprises a single, homogeneous engineering geological type (Anon. 1976a) which may be used as the basic unit for large-scale engineering geological or geotechnical mapping. The resultant plan provides the basis for a practical assessment of the proposed methods of characterization of rock masses for engineering purposes.

The geological setting

The mapping and sampling of a weathering profile were carried out in a working granite quarry at Hingston Down in the South-west of England. Opened initially as a local source of roadstone and brick-shaped sets (Reid, Barrow, Sherlock, MacAlister & Dewey 1911), the quarry remained relatively small until the post-war expansion of demand for roadstone and concrete aggregates led to the present output of about 300 000 tons a year.

The Gunnislake granite, situated to the west of Dartmoor (Fig. 1), is a small cupola intruded into Devonian slates. The granite outcrop is known from mining records to be faulted at its eastern end by the Great Cross Course across which there is a dextral offset of over 200 m (Dines 1956), while elsewhere along the granite contact the outcrop pattern suggests that other NNW trending wrench-faults may be present. East to west trending quartz-tourmaline veins, mineral lodes and aplite dykes also cut the granite. The fresh granite is a uniform grey colour, of medium grain size, with scattered porphyritic feldspar crystals (Reid et al. 1911); however, some isolated flow structures are present. Other variations in the granite include a sporadic coarse-grained variety. Slight hydrothermal alteration associated with mineral lodes has proably been the cause of some isolated kaolinised areas within the granite outcrop which were at one time exploited for brick manufacture (ibid.).

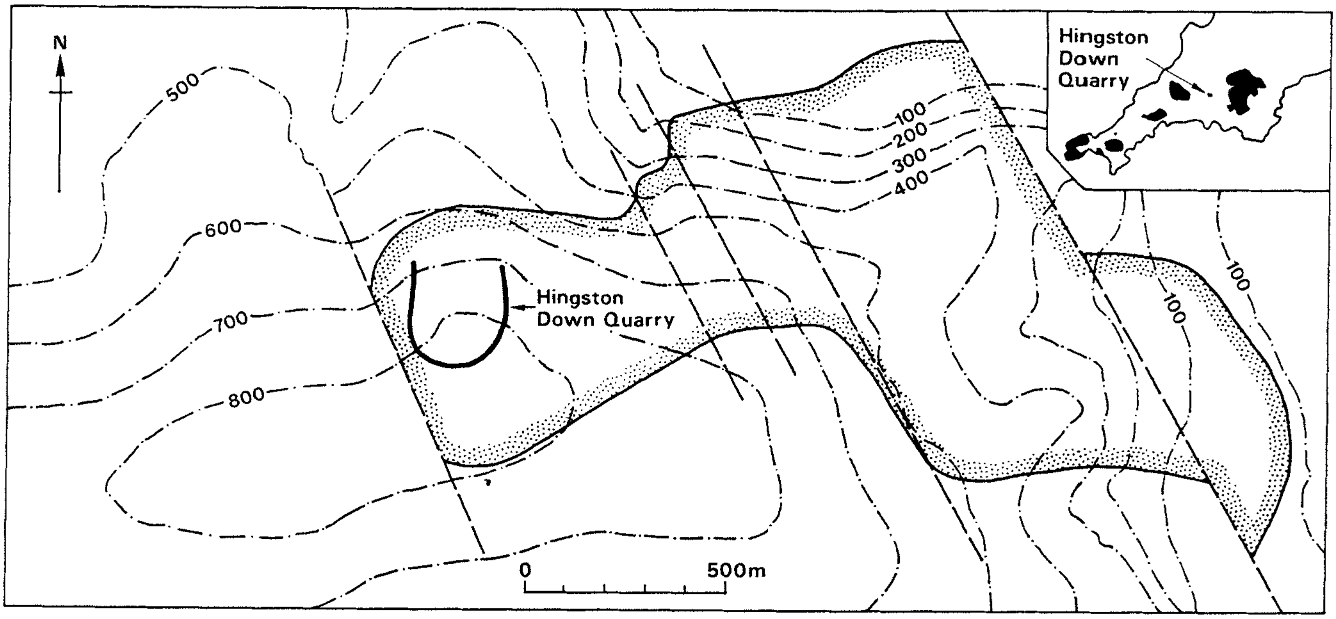

Fig. 1: The location of Hingston Down quarry in the Gunnislake granite, with inset the position of the granite in S.W. England. The north-westerly trending broken lines are wrench-faults; the most easterly is the Great Cross Course, the others are presumed to be faults on the basis of the outcrop pattern. Topographic contours are in feet A.O.D.

The ridge in which the quarry has been opened is thought to be a remnant of an ancient planation surface (Orme 1964) on which parts of a early Tertiary weathering profile have been preserved (Brunsden 1964). Preservation of the weathering mantle here, as in other parts of South-west England, is probably due to the fact that the area was not glaciated during the Pleistocene, although the profile has undoubtedly been modified and locally stripped away by periglacial solifluction processes (Waters 1964).

The weathering profile

The quarry was opend at a low topographic level in fresh granite on the northern slope of the ridge (Fig. 1), and has been extended south on three levels towards the crest of the ridge. At these levels, quarrying is limited to the east and west by deeply weathered areas, and even the main face at the highest level is not entirely in fresh granite. Consequently, weathering profiles are available for study through a maximum height range of about 55 m.

Stages of weathering

In the quarry faces the effects of weathering can be seen to increase in intensity upwards towards the present ground surface in the eight stages shown in Table 1. All these changes may be recognised visually with the exception of the change from stage 4 to 5 which is reflected only in a marked change in strength, a property that nevertheless is easily determinable in the field by the point load strength test (Broch & Franklin 1972) which can also be assessed more crudely by a hammer below.

The observed distribution of the weathering stages tends to confirm that the decomposition of the granite is due to chemical weathering acting downwards from the land surface, rather than hydrothermal alteration that is brought about by internal processes. In order to characterize the resultant weathering profile it is necessary to devise a suitable weathering grade classification based on the combinations of weathering stages of the rock material that can be seen to have developed progressively in the profile. The weathering profile may thus be defined in terms of a sequence of weathering grades above fresh, unweathered rock; a profile may be simple where there is a progressive increase in weathering towards the ground surface, or complex where there are out-of-sequence intercalations of weathering grades within the basic simple sequence.

FRESH GRANITE

(1) Some iron-staining on the joint surfaces.

(2) Deep brown discoloration penetrating into the rock* as a selvedge to discoloured joints.

(3) Slight yellow staining throughout the interior of joint-bounded blocks accompanying the deep brown selvedge.

(4) Complete light brown discoloration of the granite without any appreciable weakening of the rock.

(5) Complete light brown discoloration of the granite with appreciable weakening of the rock.

(6) Granular disintegration developing along joint planes giving rise to corestones of discoloured weakened rock in soil*.

(7) Complete granular disintegration of the rock, but the structure and texture are preserved.

(8) Loss of granitic texture due to disruption of granular weathering products by solifluction.

GRANITIC SOIL

*The terms rock and soil are used in the engineering sense (Anon. 1972).

Table 1: Stages of the weathering of granite at Hingston Down Quarry.

Weathering grade classifications

Early attempts to devise weathering grade classifications for engineering purposes, such as those of Moye (1955) and Kiersch & Treasher (1955), were based on weathering profiles developed in specific geological settings, the former in a granitic and gneissic terrain, the latter in a quartz-diorite. As such they are particularly relevant to the present study, but suffer from certain disadvantages. Both have a rock material basis, in which the identification of any particular weathering grade is based on examination of a hand specimen, usually in the form of a piece of drill core. Criteria for the grades relate almost exclusively to the strength or petrographic characteristics, or both, of the rock material in question. As the authors admit, however, at any particular level in the profile weathering tends to have produced mixtures of rock materials weathered to differing degrees; a rock mass weathering grade classification should allow for this.

Although not developed for geotechnical purposes, Ruxton & Berry (1957) presented a more satisfactory classification using percentage discoloration and proportions of rock and soil as the bases for a series of rock mass grades for the different parts of the weathering profile in the granite of Hong Kong. Little (1969) modified Moye's classification by introducing rock: soil ratios into a series of grades numbered from one for fresh rock to six for the residual weathered soil. Newbery (1970) also adapted the Moye scheme to the granites of the Cameron Highlands of Malaysia where microfracturing, affecting the granite to varying degrees, had inhibited the formation of spheroidal corestones during the chemical decomposition of the rock mass.

Fookes & Horswill (1970) also adopted the Ruxton & Berry (1957) approach by using both material and mass characteristics as diagnostic feature of distinctive mass weathering grades. The classification, published by Fookes, Dearman & Franklin (1971) with the addition of an indication of the engineering properties of each grade based on Little (1969) was later recommended for mapping purposes (Anon. 1972), with each distinct grade, defining an engineering geological type (Anon. 1976a), to be used as a basic mapping unit. A broadly similar classification for core logging (Anon. 1970) had also been produced.

Dearman (1976) analysed the two Working Party classifications (Anon. 1970, 1972), and pointed out that some aspects of rock description, for example the nature of the discontinuities and the rock material strength, were adequately accounted for without additional inclusion as diagnostic features of weathering grades. It was therefore suggested that recognition of distinct weathering grades in the rock mass should be based only on the degree of discoloration, the rock: soil ratio, and the presence or absence of the original rock texture. Consideration of rock: soil ratio alone gives rise to three possible grades: all rock, rock-and-soil, and all soil. Each of these grades may be divided: "all rock" on the basis of discoloration; "rock-and-soil" on the basis of percentage of soil present with 50 per cent as the dividing line; and "all soil" on the basis of texture (Dearman 1974a, fig. 4). However, as is indicated in Table 1, an intermediate stage between rock and soil, "complete light brown discoloration of the granite with appreciable weakening of the rock" consistently occurred at Hingston Down and it was therefore necessary to adapt the system to allow for this. The distinct mass weathering grades finally adopted in the present study are shown in Fig. 2.

Mapping weathering grades

When the distribution of the different types of weathering rock material is being considered, whether as areas on a rock face or as lengths of drill core, the limiting factor is the scale at which the record is being made. The different material types are readily distinguishable whatever their dimensions.

On the other hand, distribution of weathering stages in the rock mass is determined by structures such as joints and other discontinuities. As the resultant mass weathering grades are proportions of different materials (Fig. 2), it thus becomes necessary to decide the minimum mappable area of any one grade. Discontinuity spacing, and hence block size, determines the minimum mappable unit for any one grade from I to V. But in practice not every discontinuity in a rock mass is weathered, and, for example, penetration of discoloration into adjacent joint-bounded blocks may not be uniform. Assessment of mass weathering grade is thus an averaging process applied to the number of joint-bounded blocks included. A different aspect of scale is thus introduced into the assessment.

An additional factor is the presence of major discontinuities such as faults (Anon. 1972) that may have an important influence on the local development, for instance, of soil in the weathering profile. Is such a thin seam of soil to be mapped as grade V (Fig. 2) within grade II, or is the whole of the surrounding rock mass mapped as a mixture of soil-and-rock, and if so what dimensions should the resultant grade IV or III volume of weathered rock have?

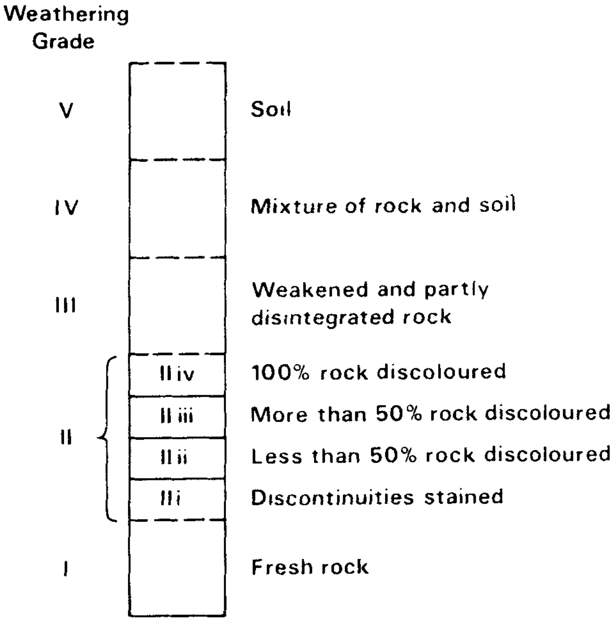

Fig. 2: The sequence of mass weathering grades used in mapping the quarry.

The averaging process was applied to mapping the quarry by assessing mass weathering grade in square areas with a side-length equal to one-third of the height of the face in the different quarry levels, i.e. in 5 to 7 m squares. A distinctive 2 m thick continuous soil layer in a thick zone of discoloured granite (mass grade II) was mapped separately.

Polaroid photographs of the quarry faces were used for field mapping using the criteria described. Grade boundaries were then transferred to plans and elevations of the quarry levels. By constructing generalized structure-contours of the surfaces marking the boundaries between grades I and II and between grades III and IV it was possible to assess the gross distribution of the weathering profile.

The distribution of weathering grades

The results of mapping the weathering grades presented in Figs. 3, 4 as an engineering geological plan and sections respectively, show that in general the profile is spatially unrelated to present-day topography. The form of the grade I/II boundary, the recognisable base of the weathering profile, is an elongate dome aligned north to south. Consequently, grade boundaries in the weathering profile dip steeply east and west on either side of the quarry. In fact it is only in the east and west faces of the quarry that a complete weathering profile is preserved; at the top of the central part of the most southerly working face, grade II material crops out and fresh rock is close to the surface.

If it is assumed that a complete weathering profile was formerly present over the entire area then weathered material must have been removed from the top of the hill. The removal of this material from a weathered convex hill (Fig. 5) of the form proposed by Ruxton & Berry (1957) could well have been achieved during the Pleistocene by the solifluction processes active in the periglacial environment of the area at that time (Dearman, Baynes & Irfan 1976).

This supposition is reinforced by the presence, above the grade V material on both the east and west flanks of the quarry, of slightly to completely discoloured subangular boulders lying in the solifluction head deposits. Such slightly weathered material can only have been derived from further up the hill where it is assumed to have been stripped from near these base of a former complete weathering profile. The resultant distribution is shown in Fig. 4.

The thin soil zone within grade II, which follows the general form of the structure contours of the weathering profile on the eastern flank of the quarry, has been disregarded in assessing mass grades IIi-IIiv but is included in Figs. 3 and 4. It is thereby implied that the weathering profile is of the complex variety, with an intercalation of mass grade V within grade II.

Economic implications of weathering grade distribution

In terms of quarry development, the results of the mapping, related to the proposed model for the distribution of grades in the weathering

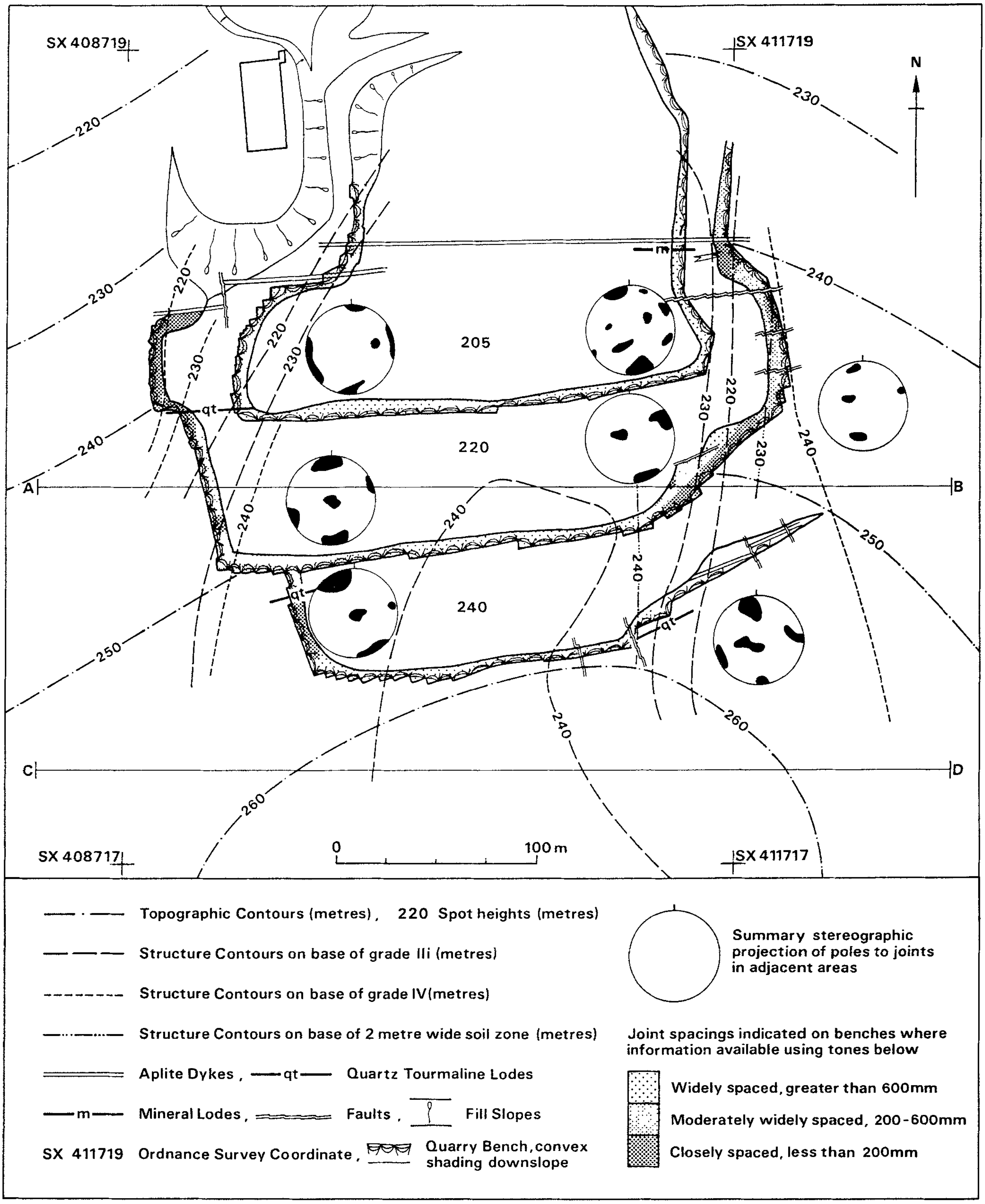

Fig. 3: Engineering geological plan of the quarry, drawn originally at a scale of 1 : 1250.

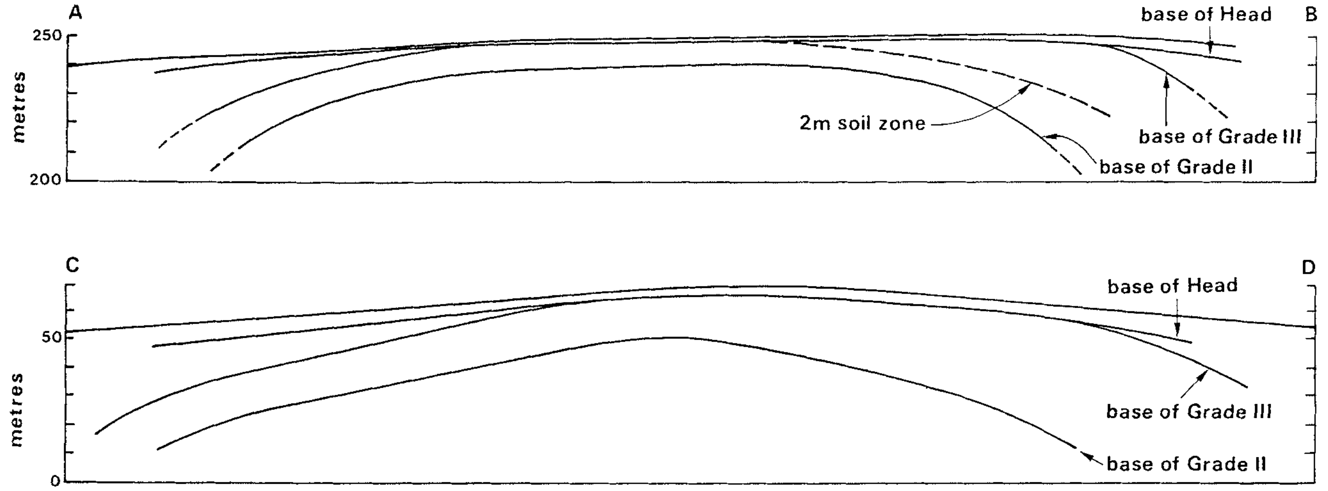

Fig. 4: Cross-section through the quarry, along lines A-B and C-D marked on Fig. 3, showing the distribution of weathering grades and the 2 m soil zone within grade II.

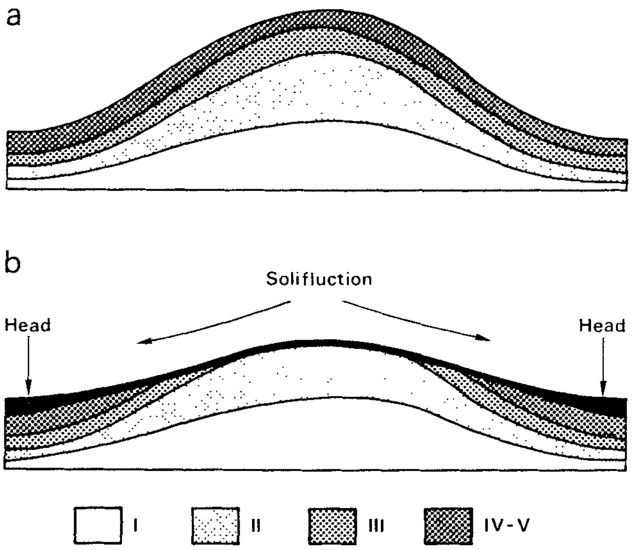

Fig. 5: A model for (a) the presumed Tertiary topography and distribution of weathering grades at Hingston Down, and (b) the Pleistocene modification produced by periglacial solifluction.

profile, imply that economic quarrying can only be undertaken in the ground due south of the present quarry (Fig. 3). Quarrying in the east and west flanks would encounter increasing depths of unsuitable weathered granite which would make extraction of the unweathered rock below uneconomic.

Practical quarrying grades

When the distribution of mass weathering grades is considered in the practical context of quarrying, the first distinction to be made is between overburden which can be excavated by face shovel or ripped and scraped and the quarryable stone beneath. Overburden comprises the solifluction head deposits and mass weathering grades V, IV, with the grade IV-III boundary marking the practical limit for easy ripping. This defines the first practical quarrying grade boundary in terms of general weathering grade, but obviously the size of joint-bounded blocks presents a serious constraint to ripping, and hence to the definition of a practical quarrying grade.

In appraising the underlying material, in this particular quarry the practical mapping units involve square areas of the face with side length of 5 to 7 m, roughly one-third of the height of individual quarry benches. Smaller units would have been irrelevant from the point of view of the practical aspects of economic selection of suitable material. When sections of whole faces are to be blasted as a unit, selectively drop-balled in the heap, loaded, hauled and crushed, the material in the resultant heap of broken rock may fall into one of three categories: all suitable for purpose; some admixture of unsuitable with suitable material; all unsuitable. Because some selection is possible as the heap is being loaded, the second category may be subdivided at a predetermined sorting level beyond which all the material must be regarded as unsuitable. Thus, there are only two practical categories: suitable, but requiring varying degrees of sorting; and unsuitable. It is now necessary to consider first the controls on material quality as a means of subdividing the rock mass below the overburden.

The criterion of material quality

Crushed Hingston Down granite is used as roadstone and concrete aggregate, and although methods are prescribed for determining such material properties as strength, water absorption, density and particle shape (British Standard 812: 1975), the practical requirements are not laid down in standard specifications. For general guidance, relative densities below 2.6 or water absorption above 3 per cent may be regarded as beyond the normal working limits for concrete aggregates (Higginbottom in Anon. 1976b). If an aggregate meets these requirements, it is unlikely to be deficient in strength. For a particular rock type, strength can readily be estimated from bulk density or some index of porosity such as the quick absorption test (Irfan & Dearman in press, a).

Recommended strength tests are the 10 per cent fines aggregate crushing test and aggregate impact test, and specifications are laid down for acceptable limits for aggregates from natural sources for concrete (British Standard 882: 1973). Specifications for crushed stone aggregates for bituminous surfacings and bases (British Standard 594: 1973; 4987: 1973) are essentially the same as those for concrete aggregates, with the additional requirement that in wearing surfaces certain values may be prescribed for the polished stone value (PSV) and the aggregate abrasion value (AAV). Acceptable values for both concrete and roadstone aggregates are collated in Table 2.

In the examination of aggregate produced from variously weathered granite, the polished stone value and the 10 % fines value have not been determined, but an extensive range of other index tests have been performed (Table 3). From these it is possible to relate material weathering stages to acceptability for purpose, and hence to attempt to define those mass weathering grades (Fig. 2) which are either wholly suitable or wholly unsuitable as an aggregate source (Table 4).

A marked change in most rock properties occurs between partially stained granite of weathering grade IIiii and completely stained granite of mass weathering grade IIiv. This change occurs before the boundary between acceptable and unacceptable test values given in Table 2 or heralds it except in the case of saturated bulk density for which the acceptance value is 2.6 (Higginbottom 1976). Material for the production of high quality aggregate would thus be that retaining some vestige of unstained granite. As percentage discoloration is easily determined in the field, provided that the joint-bounded blocks are fractured through, rock mass grades based on the presence or absence of discoloration, equivalent to an acceptance limit, would provide meaningful **engineering grade boundaries** for quarrying purposes.

USE	TEST	TEST VALUE	AUTHORITY
C.R.	Bulk density	> 2.6 g/cm^3	Higginbottom *in* Anon. 1976
C.R.	Water absorption	$< 3\%$	Higginbottom *in* Anon. 1976
C.	Unconfined compressive strength	> 34.5 MN/m^2	Reynolds 1950
C.R.	Aggregate impact value	$\not> 45\%$ $\not> 30\%^+$	British Standard 882: 1973 British Standard 882: 1973
R.	Modified aggregate impact value	40% maximum*	Hosking & Tubey 1969
R.	Aggregate abrasion value	10% max. for difficult conditions	Anon. 1976c
		12% max. for average conditions	Anon. 1976c
R.C.	10% fines aggregate crushing value	50 kN min. $\not<$ 100 kN for wearing surfaces	Hosking & Tubey 1969 British Standard 882: 1973

C. concrete aggregates. R. road aggregates
* used in the assessment of low-grade aggregates
\+ for wearing surfaces

Table 2: British Standard and other acceptance values for test results on roadstone and concrete aggregates.

Description	Mass weathering grade		Uniaxial compressive strength saturated MN/m^2	Bulk density saturated g/cm^3	Saturation moisture content %	Aggregate impact value %	Aggregate impact value modified %	Aggregate abraision value %	Soundness magnesium sulphate %
FRESH GRANITE	I	Fresh	262	2.61	0.11	6	7	3.5	0.05
PARTIALLY STAINED GRANITE	IIi-iii	Stained rim of IIii block	232	2.62	0.35	8	10	4.7	0.08
				* * *					
		Whole sample, IIiii 90% stained	163	2.58	1.09				
PRACTICAL ACCEPTANCE LIMIT FOR GOOD QUALITY AGGREGATES									
COMPLETELY STAINED GRANITE	IIiv	Completely stained IIiv block	105	2.56	1.52	14	16	8.0	0.23
							* * *	* * *	
WEAKENED GRANITE	III-IV	Rock core of III block	46	2.55	1.97	24	49	17.1	33.4
			* * *		* * *				
		Rock core of IV block	26	2.43	4.13				
						* * *			
GRANITIC SOIL	V	Weakly cemented soil, coreable	5	2.24	10.0	nd	nd	nd	nd

nd: not determinable

* * * boundary between acceptable and unacceptable values from Table 2.

Table 3: Index properties for selected weathering stages of Hingston Down granite. Data from Irfan & Dearman 1978a, b.

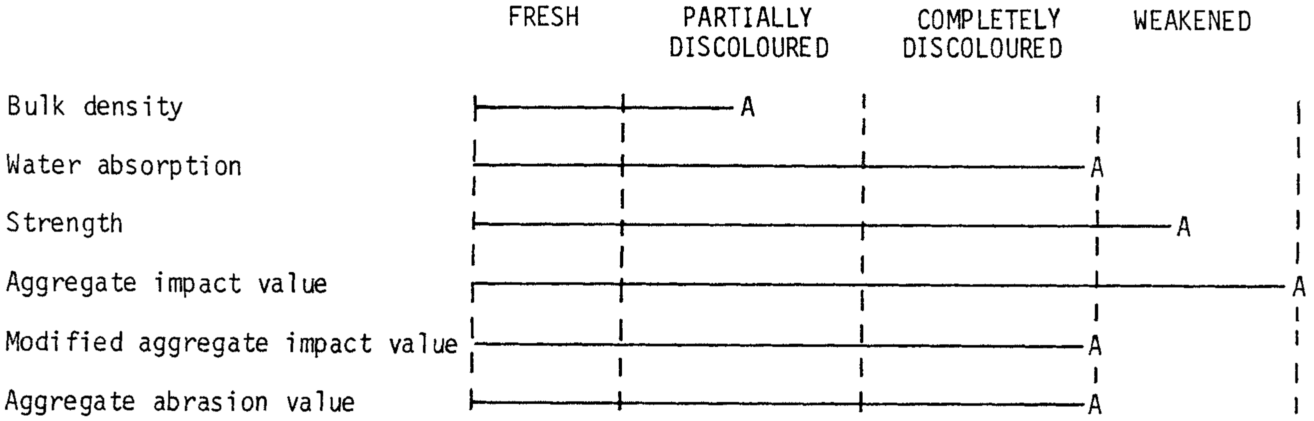

Table 4: Relationship between acceptance values in Table 2 and the material properties of various stages of weathering of granite from Hingston Down in Table 3. 'A' marks the acceptance limit.

The criterion of ease of excavation

Material that has been weathered beyond the completely discoloured stage would have to be stripped and discarded, the ease with which this could be done being crudely determined by two factors, material strength and discontinuity spacing in the mass (Fig. 6). The ranges of discontinuity spacings, discussed more fully below, combined with point load strength values show that until the rock is weathered to a mixture of rock-and-soil (grade IV) preparation for excavation has to be carried out by blasting (Franklin, Broch & Walton 1971). Where the stage of rock-and-soil development has been reached, however, the cheaper alternatives of ripping and scraping may be possible. The second important distinction is thus between the rock mass in a totally discoloured state, whether it be weakened or not, and the areas of rock mass which contain defined amounts of soil. The recognition of these two economically important divisions in the weathering profile determines the most important boundaries within the weathering grade system in the context of quarrying.

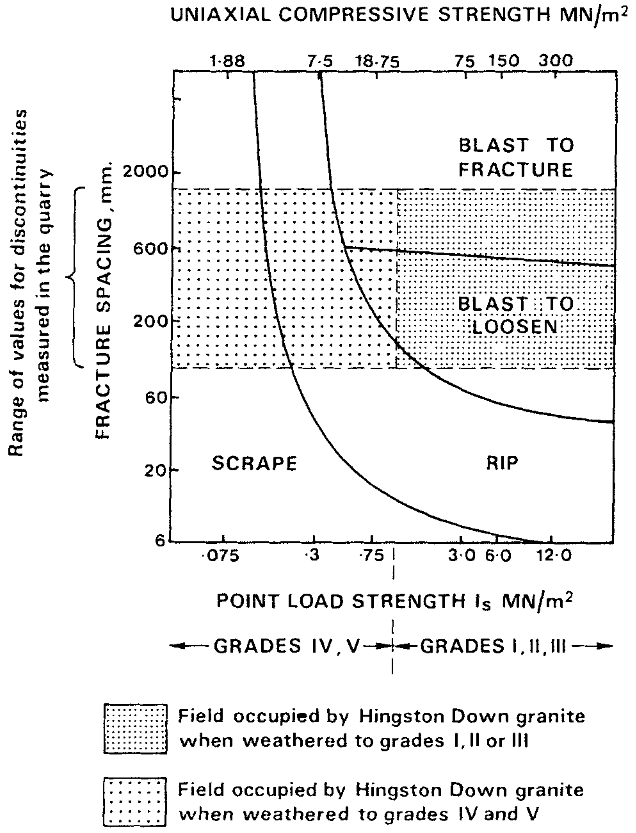

Fig. 6: Relationship between method of excavation, based on Franklin, Broch and Walton 1971, and strength and fracture spacing for the mass weathering grades encountered in Hingston Down quarry.

Method and ease of excavation are related to features of the rock mass other than weathering grade, and although strength and fracture spacing have been shown to be interrelated in sequences of weathered rocks (Fookes, Dearman & Franklin 1971, fig. 8; Dearman & Fookes 1972, fig. 4a), the discontinuity pattern in all its aspects is of prime importance in this respect.

The discontinuity pattern

Discontinuity spacing in the quarry was studied because it controls the shape and upper size of block produced by blasting. In terms of crushing, it is the maximum dimension of a block which is important for, although larger blocks can be managed, as a general rule this dimension should be less than one third of the crusher opening.

The nature and orientation of the discontinuities control the ease of blasting and subsequent stability of the rock face. Uniformly spaced, continuous, vertical joints parallel to the bench faces are ideal as they will form a **back wall** to the blast from which everything will lift off, hence reducing overbreak. Major joint sets parallel to the bench face, dipping at high angles into the quarry are undesirable as they can produce local instability thus presenting a hazard which can reduce the efficiency of the quarrying operations.

It was also hoped that assessment of the nature of the discontinuities throughout the quarry might indicate a fundamental geological reason for the form of the weathering profile.

Determination of joint frequency

Joint spacings can be measured on rock faces by counting the number of joints over a specified length and from this determining the mean spacing (Piteau 1973, Anon. 1977, Section 2). For field mapping by an experienced observer, when individual spacings are not of interest, this method is recommended.

Field measurements of mean spacing can be classified on the basis of categories of spacing (Anon. 1972. 5.2.4) and the data used to zone areas of the rock face.

Throughout the quarry, joint counts were performed over distances of up to 20 m at right angles to the average plane of a particular joint set. Some of this work was undertaken in the field and the remainder in the laboratory on controlled black-and-white and colour photographs of the quarry faces. While not wholly satisfactory, the latter approach does allow an assessment to be made of areas on the quarry faces which without a lifting platform are inaccessible in the field. Joint counts were made on the dominant sets, usually two, thus providing a two-dimensional impression of the variation in joint spacing which is all that can readily be achieved from the planar quarry faces.

Using 5 m square areas on the quarry faces as mapping units, as had been done for weathering grade assessment, minimum and maximum joint spacings were determined. The quarry faces (Fig. 3) were zoned into the standard categories (Anon. 1972) of widely spaced (>600 mm), moderately widely spaced (200-600 m) and closely spaced (>200 mm) on the basis of maximum joint spacings.

Block shapes

An attempt was also made to determine a crude two-dimensional shape factor for the blocks in each 5 m square unit by estimating mean values for maximum and minimum spacings. These when plotted (Fig. 7) show that the majority of blocks are roughly rectangular (1:1 and 1:2) rather than slabby (1:3) in shape, with dimensions ranging from 150 to 1000 mm. Mention of such block shape factors has been made by Coates (1964), Burton (1965) and Anon. (1972); Niini (1974) has estimated shape factors in Norwegian rocks.

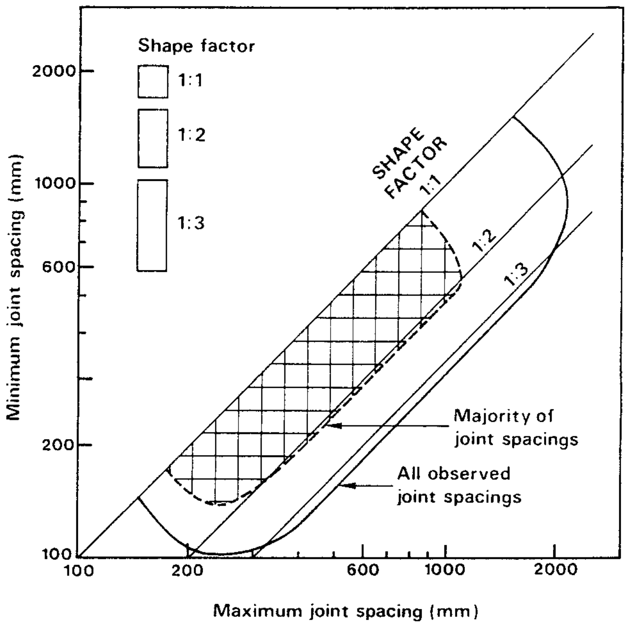

Fig. 7: Two-dimensional shape factors and the range of block sizes and shapes in the quarry.

Joint orientation in the quarry faces

The orientation of the discontinuity sets has been represented in Fig. 3 by stereographic projections of poles to joint faces for representative measurements taken in various parts of the quarry. They show that in the east and central parts, there are two major sets of vertical joints at right angles and a third flat-lying set. The quarry faces have been developed parallel to the two vertical joint sets and uniform and stable faces have been produced. In the west of the quarry, the joint sets are more variable and steeply dipping joints frequently emerge on the quarry benches. This coincides with greater amounts of overbreak, irregular and variable bench form, reduced stability, and consequent difficulties of extraction.

In the south of the quarry at the highest levels of the face, flatlying joints dip east and west more steeply that the present day topography away from the centre of the convex hill. If these are assumed to be sub-topographic joint sets (Waters 1954), they provide additional evidence for an original steeper convex hill on which the weathering profile was developed.

Relation between close jointing and deep weathering

The survey also shows that the deeply weathered areas correspond with the more closely jointed areas, on the east and west of the quarry. Various explanations for this association may be suggested:

(i) closely jointed areas are more susceptible to weathering due to the higher permeability of the ground if the joints are open;

(ii) closely jointed areas are more suceptible to weathering due to an inherent geological weakness in the rock which led to the formation of an original higher intensity of jointing.

Both factors are considered to be responsible for the form of the weathering profile and indeed for the proposed form of the convex hill on which the profile is supposed to have developed prior to periglacial stripping.

As the weathering profile developed, differential weathering picked out two bands of more intensely jointed rock, on either side of the present day quarry for reasons (i) and (ii) above. Contemporaneous denudation affected these weathered, fractured zones more readily and eventually produced a convex hill with a weathering profile developed over its entire surface, although more deeply weathered areas occurred on either side due to the more intense jointing. In these areas the jointing intensity was increased further by the weathering process itself.

The original cause of the NNE aligned areas of more intense jointing, brought out by the strikes of weathering grade structure contours in Fig. 3, is tentatively ascribed to the presence of NNW aligned cross-courses with which they form a complementary set of compressional shear zones. The origin and nature of the cross courses of the south-west of England has been described by Dearman (1963).

Summary and conclusions

In the context of quarrying, only two boundaries in the weathering profile should separate the rock mass into economically significant grades related both to the use which is to be made of the processed rock material and the method of working.

Suitability of the rock material for roadstone or concrete aggregate is controlled by a combination of standard specifications of acceptable test values for some properties, and generally adopted but informal standards for other properties. It is therefore possible to distinguish between suitable and unsuitable rock materials in the weathering profile; but, as individual weathering grades or subgrades may comprise more than one material type present in a range of proportions, the acceptance boundary may not coincide with a weathering grade boundary. Depending on which test values are used, Hingston Down granite forms an acceptable aggregate when partially discoloured (more than 50 per cent but less than 100 per cent discoloration), even without allowing for the improvement in quality brought about by the inclusion of fresh material from the cores of blocks. Completely discoloured material (mass grade IIiv) is suspect from the joint of view of bulk density, whilst the weakened completely discoloured variety (mass grade III) does not comply with the specification.

One quarrying boundary is thus definable solely in terms of a weathering subgrade which is easily determined visually.

Another important practical boundary is that concerned with ease of excavation of unsuitable rock material, or overburden, in which properties of the rock mass other than weathering grade are of importance. Franklin et al. (1971) have shown the combined influence of material strength and fracture spacing on method of excavation (Fig. 6). Grades I, II and III require blasting to fracture or loosen, or both depending upon fracture spacing. Grade IV lies across a boundary with the more widely jointed masses requiring blasting. Weaker grade IV and the whole of grade V may be ripped and scraped.

Although the boundaries between the four methods of excavation in Fig. 6 are based on experience, and might need adjustment to account for particular conditions, they can be accepted as a preliminary guide. Properties of both the rock mass and the rock material determine the lower limit of easy overburden removal at a variable level within the grade IV weathering zone, with the precise level defined by block size.

Practical quarrying grades: soil-and-rock overburden, unsuitable rock material and suitable rock material, partly defined by weathering grade zones, are true rock mass grades based essentially on the evaluation of strength, as one determinant of suitability of material for purpose, and discontinuities. Because of the elongate domeshaped form of the weathering grade boundaries, however, quarrying is limited to the east and west (Figs. 3 and 4) when an unacceptable depth of overburden has to be removed to expose an acceptable ratio of unsuitable rock on the highest quarry bench. An engineering grade in the context of quarrying is thus a blend of rock mass grade, shape of the weathering profile, and the practical consequences of developing horizontal quarry benches each with a limited height of quarry face.

In a more normal civil engineering context, assessment of ground conditions would depend mainly on the logging of drill cores. Percentage core recovery, recognition of weakened granite using the point load test, and estimation of proportion of discoloured: fresh rock would permit determination of distinctive mass weathering grade zones I to V. Calculation of R.Q.D. (rock quality designation) would have to be relied upon to complete the rock mass characterization in terms of engineering grade.

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