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Volcanic rock-mass properties from Snowdonia and Tenerife: implications for volcano edifice strength

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Abstract: Although volcano instability is increasingly recognized as a societal hazard, numerical data on the relevant mechanical properties remain sparse. We report new field data on the rock-mass properties of volcanic materials from Snowdonia (North Wales, UK) and Tenerife (Canary Islands). Using rock types that range in composition from phonolite to rhyolite, we summarize a method for estimating the overall strength of a volcanic edifice based on the rock-mass rating index (RMR) and the Hoek–Brown criterion. We show that the average rock-mass compressive (σ_{cm}) and cohesive (c) strengths decrease exponentially with RMR according to $\sigma_{cm} = 0.652^{(0.06\mathrm{RMR})}$ and $c = 0.035^{(0.07\mathrm{RMR})}$, respectively, and appear insensitive to both initial magma composition and relative age. This exponential relationship provides a new predictive tool for directly estimating rock-mass strength from the RMR. Our analysis further predicts a marked reduction of up to 96% in the rock-mass compressive strength relative to the intact rock value based on laboratory tests and that, overall, the combined results from both study areas yield cohesive strength values from 4.8 to 0.44 MPa. Estimated values of rock-mass angle of friction range from 28° to *c*. 38°. Recent modifications to the Hoek–Brown criterion, in particular the inclusion of the disturbance factor *D*, suggest that even these low values of rock-mass strength and cohesion may be optimistic, and the true values of rock parameters relevant for accurate predictions of volcano edifice strength may be up to 30% weaker still.

Keywords: rock failure, rock mechanics, volcanic hazard, geotechnics.

A growing number of studies over the last decade have helped raise awareness of the life- and property-threatening hazards that result from volcano instability (e.g. Tilling 1995; McGuire *et al*. 1996; Siebert 1996; McGuire 1998). However, although improved models of the processes leading to volcano instability have helped increase our understanding of events that can lead to catastrophic edifice failure, data on the physical properties, in particular the strength and cohesion of volcanic rock masses crucial for informed modelling of the collapse process, remain sparse. At its most basic level, a volcanic edifice is made up from discrete layers of different rock types cut through on a range of scales by pervasive and penetrative discontinuities including faults, fractures and contact surfaces (Fig. 1), making it difficult to assign an overall strength. Characterization of the rock mass can be further hindered by long time gaps in volcanic activity that result in the development of residual soils (Hürlimann *et al*. 2001), and hydrothermal alteration, where the rock is chemically altered primarily to clay minerals (Crowely & Zimbeman 1997; Reid *et al*. 2001). Both residual soil and hydrothermally altered material will cause a decrease in the strength properties of an edifice relative to its unaltered state. However, it is our intention to show that even without these degrading effects, a volcanic rock mass, and by implication the edifice itself, is an inherently weak structure when compared with the intact strength of its constituent rocks.

This paper summarizes an approach for estimating the strength characteristics of a volcano based on well-known techniques used in rock-mass classification at the outcrop scale and larger. We begin by reviewing the various classification schemes, and show how field data on volcanic rocks, combined with relevant Mohr failure envelopes, can be used to make estimates of important material variables including rock-mass strength, rock-mass cohesion and instantaneous angle of friction. We finish by considering the implications of a new term in the Hoek–Brown criterion that relates the degree of rock face disturbance (*D*) to the rock-mass rating (RMR). A provisional sensitivity analysis suggests that although the degree to which *D* affects a typical volcanic slope is unknown, a value > 0.5 will significantly affect the strength of the rock mass.

Rock-mass classification

Classification schemes such as the RMR form the basis of an empirical approach to estimating strength criteria and other rock-mass properties. Widely used in engineering, they have found applications in the stability analysis of tunnels, slopes, foundations and mines, and most recently, volcanic systems. At outcrop, a rock mass is an aggregate material consisting of intact material, associated discontinuities (such as bedding planes, faults, joints and solution surfaces) and any areas of alteration. The concept of a rock mass and associated classification schemes are powerful tools for estimating strength criteria on a large (decimetre) scale. Although several rock-mass classification schemes exist, the most widely used is the RMR system ofBieniawski (1976, 1989), and this is the scheme used for this study. Other classification schemes, including the geological strength index (GSI) of Hoek *et al*. (1992) and Hoek (1994), are discussed in a later section.

The RMR system

The RMR system uses five main parameters to classify the rock mass (Table 1), including the strength of the intact rock, the rock quality designation (RQD) of Deere & Deere (1988), the spacing

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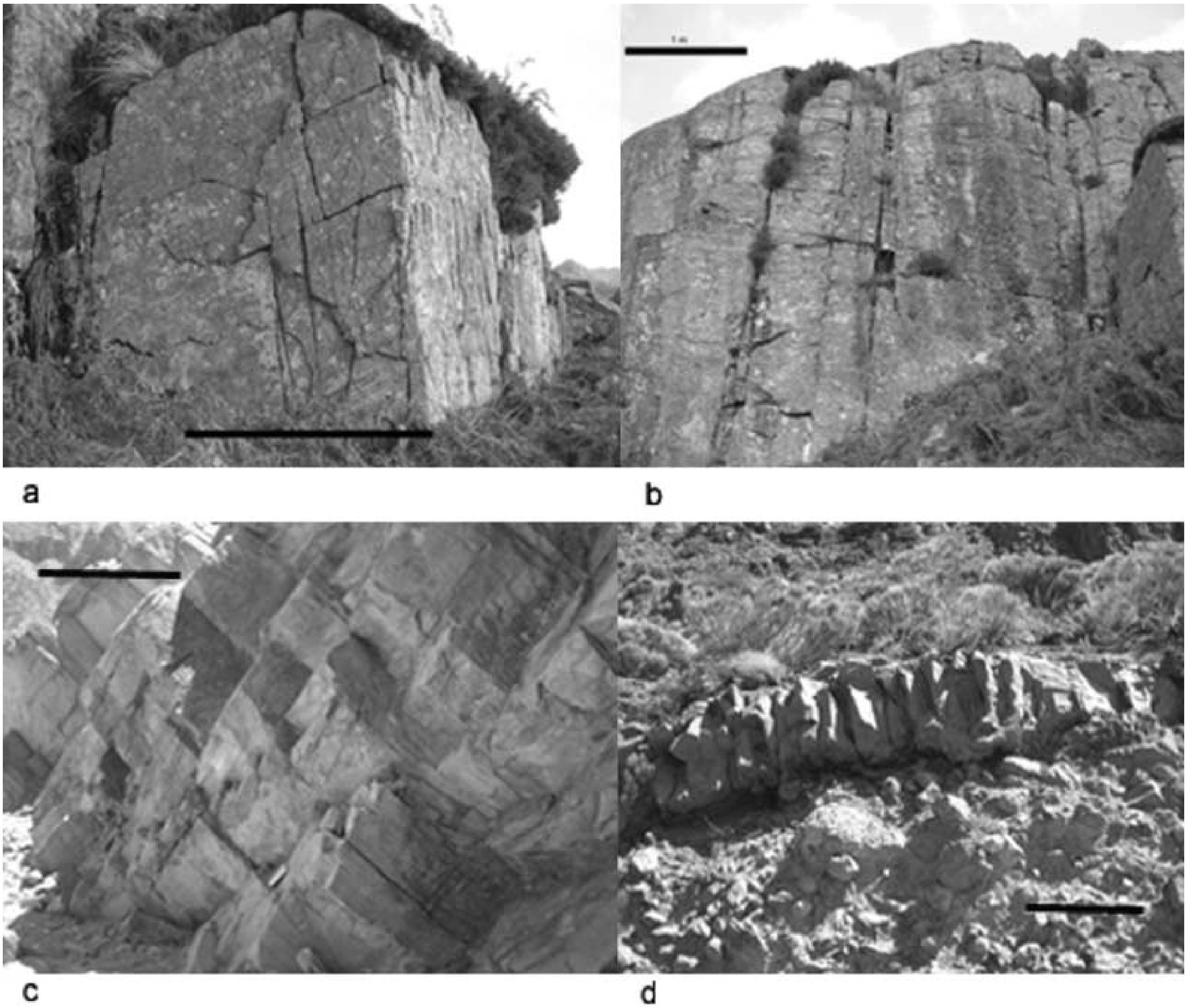

Fig. 1. Photographs from field locations showing the fractured nature of the rock mass: (**a**, **b**) Snowdonia (Wales, UK); (**c**, **d**) Tenerife. (**d**) shows a dense lava flow overlying a loose, poorly sorted debris deposit of pyroclastic material, which has been partially altered to a soil. If the weight on top of the weak layer is increased by successive flows, this unstable conformation of a stronger rock overlying a much weaker one is a prime site for the initiation of a future failure surface. In all photographs the black bar represents 1 m.

of discontinuities, the condition of the discontinuities and the groundwater conditions (Schultz 1995, 1996). By their nature, all rock masses are discontinuous, and a volcanic edifice is no different. Therefore to estimate the strength of an edifice it is necessary to first divide it into distinct segments according to rock type, although within a rock type there may be smaller distinct regions; for example, regions of similar discontinuity spacing. These descriptive classification schemes can be used to make predictions about the mechanical properties of the rock mass if used in conjunction with relevant empirical expressions. A particularly powerful combination involves an integration of the RMR and the Hoek–Brown criterion (Hoek & Brown 1980; Hoek 1983), devised to assess rock-mass strength (see below). For example, Schultz (1995, 1996) used RMR data in this way to show that the rock-mass compressive strength of basalt is up to 80% weaker than its intact compressive strength as measured under laboratory conditions. This result has important implications for volcano edifice strength, and is developed more fully in later sections using RMR data collected in this study.

Data collection

The RMR data presented here were collected from two field sites in Snowdonia (North Wales, UK) and Tenerife (Canary Islands). In total, five rock types were examined from a total of 42 field localities. Lithotypes sampled range in composition from alkali basalt to rhyolite (Table 2). With the exception of several microgranite samples from Snowdonia, the rock masses examined were exclusively volcanic in origin, and comprised a mixture of lava flows, dykes and airfall tuffs. Although a granitic rock is unlikely to be found on most volcanic slopes it is included in this study to demonstrate the potential weakness of all igneous rock masses. The volume of rock mass examined in each locality varied between locations, with surface areas ranging from 6 to 180 m^2. The Snowdonia volcanic province is mainly Ordovician in age (e.g. Owen 1979) whereas the units examined on Tenerife are generally < 4 Ma old and in some cases historical (Carracedo & Day 2002). The extensive time gap between the two field locations, one ancient and the other geologically young, allowed us to assess the degree to which the

Table 1. *The RMR classification parameters and their ratings (shaded), after Bieniawski (1989)*

Strength of intact rock	Uniaxial compressive strength, MPa	> 250	100–250	50–100	25–50	5–25	1–5	< 1
1.	Rating	15	12	7	4	2	1	0

	RQD, %	90–100	75–90	50–75	25–50	< 25
2.	Rating	20	17	13	8	3
	Spacing of discontinuities, m	> 2	0.6–2	0.2–0.6	0.06–0.2	< 0.06
3.	Rating	20	15	10	8	5
	Condition of discontinuities	Very rough, Discontinuous, No separation, Unweathered	Rough walls, separation < 0.1 mm, Slightly weathered	Slightly rough, separation < 1 mm, Highly weathered	Slickenslides or Gouge < 5 mm thick or continuous separation 1–5 mm	Soft Gouge > 5 mm thick Or Separation > 5 mm continuous, decomposed wall rock
4.	Rating	30	25	20	10	0
Ground Water	General conditions	Completely dry	Damp	Wet	Dripping	Flowing
5.	Rating	15	10	7	4	0

This table has been customized from the chart of Bieniawski (1989) to show only the methods used in this paper. RMR = 1 + 2 + 3 + 4 + 5 and ⩽100.

Table 2. *A summary of the rock-mass properties obtained from volcanic rocks in the Snowdonia volcanic group and from Tenerife*

Property	Snowdonia			Tenerife	
	Rhyolite	Tuff	Microgranite	Basalt	Phonolite
RMR	52–74	47–74	57–79	48–60	38–60
Laboratory compressive strength (MPa)*	175	150	250	150	175
Rock-mass compressive strength (MPa)	12–41	7–35	23–78	8–16	6–19
Rock-mass tensile strength (MPa)	−0.29 to −1.5	−0.18 to −1.4	−0.3 to −1.55	−0.2 to −0.5	−0.1 to −0.5

*Values taken from Brown (1981).

gross age of the rock mass (climactic influences excluded) may have influenced the rock-mass strength.

At each locality the RMR was calculated according to the rating system detailed in Table 1. To gain a comprehensive overview of the rock-mass condition and characteristics, the RMR was calculated both horizontally and vertically for each segment of the examined rock mass. The horizontal and vertical RMR values were then averaged to give one RMR value for that region. This was done with the aim of producing an overall estimate of rock-mass strength rather than an estimate that may favour one particular orientation. A summary of the RMR values calculated for each rock type can be found in Tables 2 and 3. For simplicity, we have used the averaged RMR as determined for each rock-mass segment in this study. However, we accept that it may not be realistic to assign a single value, and that a range of RMR values may be more appropriate. We further caution that any stability analysis carried out with strength estimates determined by following the method presented in this paper should use the corresponding range of strength estimates in all calculations.

Table 3. *A summary of the Mohr–Coulomb properties of the rock-mass obtained from volcanic rocks in the Snowdonia volcanic group and from Tenerife*

Property	Snowdonia			Tenerife	
	Rhyolite	Tuff	Microgranite	Basalt	Phonolite
RMR	52–74	47–74	57–79	48–60	38–60
Laboratory compressive strength (MPa)*	175	150	250	150	175
Rock-mass cohesive strength (MPa)	1.16–4.84	0.74–4.28	1.16–6.75	0.79–1.72	0.44–1.84
Rock-mass angle of friction (degrees)	31.3–38.1	27.8–36.1	41.2–49.4	28.1–31.8	28–34.9

*Values taken from Brown (1981).

Estimating rock-mass strength

Hoek–Brown criterion

Hoek & Brown (1980, 1988) proposed a novel method for estimating rock-mass strength that makes use of the RMR classification. The Hoek–Brown method, widely used by geotechnical engineers to predict rock-fracture behaviour at the outcrop scale, has recently found application in the strength assessment of volcanic rock masses (Voight 2000). The general empirical criterion for rock-mass strength proposed by Hoek & Brown (1980) is defined by the relationship between the principal stresses at failure:

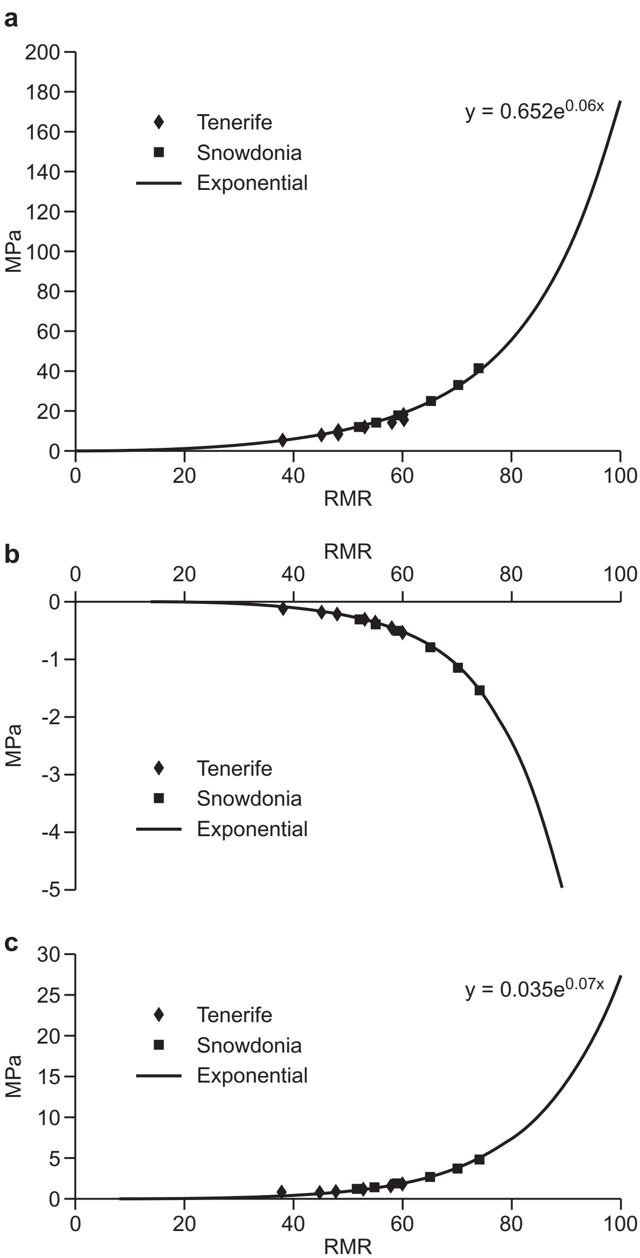

Fig. 2. Dependence of rock-mass compressive (**a**), tensile (**b**) and cohesive (**c**) strength on RMR for lavas (basalt, phonolite and rhyolite) from Snowdonia and Tenerife. An exponential best-fit curve has the form $\sigma_{cm} = 0.652^{(0.06RMR)}$. This predictive relationship also appears to hold true for the rock-mass tensile and cohesive strengths.

$$\sigma_1 = \sigma_3 + (m\sigma_c\sigma_3 + s\sigma_c)^{1/2} \quad (1)$$

where σ_1 and σ_3 are the major and minor principal stresses respectively at failure, σ_c is the uniaxial compressive strength of the intact rock, and m and s are empirical constants dependent on rock type and available from published sources (e.g. Hoek 1983; Hoek & Brown 1988). In this paper, standard values of σ_c determined from laboratory studies were taken from the reference library within the Rocscience program RocLab, but can also be obtained from numerous published sources (e.g. Brown 1981). For a given rock mass (Hoek & Brown 1988), the constants m and s are related to the RMR as follows:

$$m = m_i \exp[(\mathrm{RMR} - 100)/28] \quad (2)$$

and

$$s = \exp[(\mathrm{RMR} - 100)/9] \quad (3)$$

where m_i is the value for the intact rock. The special cases of unconfined compressive strength σ_{cm} and uniaxial tensile strength σ_{tm} for a rock mass can be found by putting $\sigma_3 = 0$ and $\sigma_1 = 0$ respectively into equation (1). Thus

$$\sigma_{cm} = (s\sigma_c)^{1/2} \quad (4)$$

and

$$\sigma_{tm} = \frac{\sigma_c}{2}[m - (m^2 + 4s)^{1/2}]. \quad (5)$$

Results

Using the Hoek–Brown criterion to estimate the strength characteristics of rock masses from Snowdonia (North Wales) and Tenerife (Tables 2 and 3) we find compressive strength reductions of up to 96% in the rock mass (σ_{cm}) relative to intact laboratory tested samples (σ_c). Table 2 also lists rock-mass tensile strength obtained directly from the Hoek–Brown equations. Figure 2 shows plots of rock-mass strength against RMR for the rock masses from Snowdonia and Tenerife. From Figure 2, it can be seen that the compressive and cohesive strength of the rock types examined in this study decreases exponentially with RMR according to

$$\sigma_{cm} = 0.652^{(0.06\mathrm{RMR})} \quad (6)$$

$$c_i = 0.035^{(0.07\mathrm{RMR})} \quad (7)$$

and appears largely insensitive to both the initial magma composition (basaltic or rhyolitic), and relative ages of the rock masses tested. This apparent exponential decrease suggests that relatively small changes in rock-mass properties will significantly affect edifice strength. This insensitivity to both rock composition and age suggests that these exponential relationships may be useful in providing quick and relatively accurate estimates of rock-mass strength directly from the RMR (Fig. 2). In Figure 2a, where the data for rock-mass compressive strength are plotted alongside the fitted exponential curve, the mean error between the actual value and that predicted by the exponential fit is 13.2% with a standard deviation of 9.6. However, if the imprecision of the RMR classification scheme is taken into account, this error falls to within an acceptable range, and provides a valid method of estimating, to a first approximation, rock-mass strength directly from the RMR. We note that this tentative exponential relationship also holds for tensile and compressive rock strengths.

Mohr–Coulomb criterion

As it is the aim to use the estimated rock-mass strength properties in edifice stability studies, and most geotechnical software is still written in terms of Mohr–Coulomb criterion, it is necessary to determine an estimated angle of friction and cohesive strength for the rock mass. A graphical means of representing stress relationships was discovered by Culmann (1866) and later developed in detail by Mohr (1882), which led to the implementation of a graphical method (the Mohr stress circle). Uniaxial tension, unconfined axial (uniaxial) compression, or confined (triaxial) compression may affect failure of intact cylindrical rock specimens. Typical examples of effective stress circles for these types of failure are shown in Figure 3. The envelope to the stress circles at failure (Mohr failure envelope) corresponding to the empirical failure criterion defined in equation (1) was derived by Bray (Hoek 1983) and is given by

$$\tau = (\cot \varphi_i - \cos \varphi_i)\frac{m\sigma_c}{8} \tag{8}$$

where τ is the shear stress at failure, φ_i is the instantaneous friction angle at given values of τ and σ, i.e. the inclination of the tangent to the Mohr failure envelope at the point (σ_n,τ). The value of the instantaneous friction angle φ_i is given by

$$\varphi_1 = \tan^{-1}[4h\cos^2(30° + \frac{1}{3}\sin^{-1}h^{-3/2}) - 1]^{-1/2} \tag{9}$$

where

$$h = 1 + \frac{16(m\sigma + s)}{3m^2} \tag{10}$$

at any given value of σ. Mohr failure envelopes for intact rhyolite and a rhyolitic rock mass are compared in Figure 4. As expected, the intact material is stronger than the jointed rock mass. Shear stress tending to cause failure across a plane is resisted by the cohesion of the material and a constant times the normal stress (σ_n) across the plane. This is expressed in the Mohr–Coulomb equation for shear strength:

$$\tau = c + \mu\sigma_n \tag{11}$$

where μ is the coefficient of friction:

$$\mu = \tan \varphi. \tag{12}$$

However, rather than being constants for jointed rock masses, c and φ both vary with stress level (Hoek & Brown 1980). It is thus convenient to calculate the instantaneous values for cohesion (c_i) using the instantaneous friction angle defined in equation (7). Thus equation (11) can be rewritten as

$$c_i = \tau - \sigma_n \tan \varphi_i. \tag{13}$$

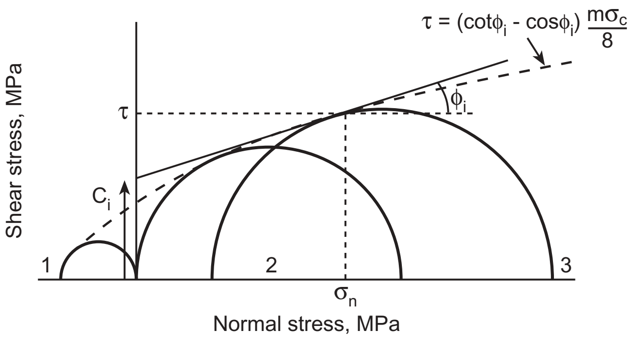

Fig. 3. Typical failure circles for rock and the Bray strength envelope (Hoek 1983): 1, uniaxial tension; 2, unconfined axial (uniaxial) compression; 3, confined (triaxial) compression. Also shown are the instantaneous values of angle of friction (φ_i) and cohesion (c_i).

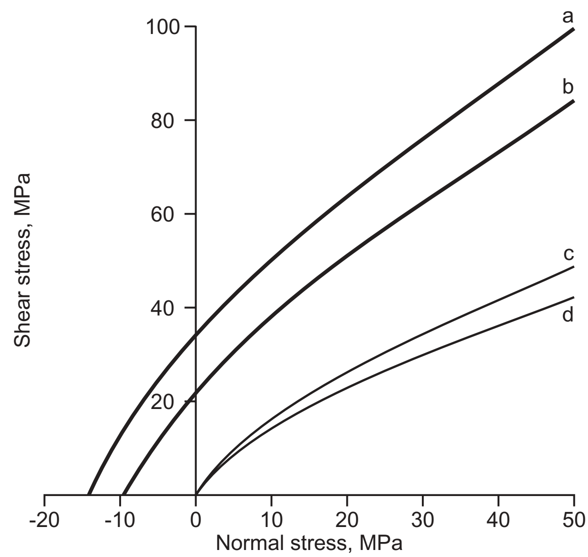

Fig. 4. Mohr failure envelopes for intact rhyolite and a rhyolitic rock mass using relevant values from Hoek & Brown (1981). Intact: $m_i = 16$, $s = 1$, $\sigma_c = 225$MPa (curve a); curve b is as curve a, but $\sigma_c = 150$MPa. Rock mass: $m = 2.68$, $s = 0.0039$, $\sigma_c = 225$MPa (curve c); curve d is as curve c, but $\sigma_c = 150$MPa. The Hoek–Brown constants m and s were determined from equations (2) and (3) using an RMR of 50.

Figure 5 shows a Mohr failure envelope (equation (8)) for a rhyolitic rock mass from Snowdonia, along with a plot showing the instantaneous friction angle (equation (9)) and instantaneous cohesion (equation (13)). It can be seen that at low values of normal stress, the angle of friction is high and the cohesion is low. As the normal stress is increased, however, this relationship is reversed, suggesting an increase in cohesion but a decreasing angle of friction at progressive deeper parts of the edifice interior. This may be an important factor in determining the shape of a failure surface within a volcanic edifice, and could be a simple explanation for why non-volcanic slope failures tend to be shallow and steep, in that they lack any additional thermal and mechanical pore pressures that probably precede volcanic slope failures. Although c and φ will vary with stress level, it is useful to fit a straight-line Mohr–Coulomb relationship to the failure envelope, as it gives a good approximation of the rock-mass angle of friction and provides an upper limit of cohesive strength (Hoek *et al*. 2002). This is done not by fitting the 'best-fit' tangent to the Mohr failure envelope, which can lead to an overestimate of the cohesive strength, but by fitting a linear Mohr–Coulomb relationship (equation (11)) by a least-squares method (Fig. 6) (Hoek *et al*. 2002). As stated above, the value of cohesive strength produced from this method provides an upper limit, and it is prudent to reduce it to 75% of this value to serve any practical purpose.

A more convenient way to gain an estimate of the cohesive strength of the rock mass is to set $\sigma_n = 0$ in equation (13). Thus the cohesion becomes equal to the shear stress, and it can be read directly from the Mohr failure envelope as the intercept on the shear strength axis. The angle of friction and cohesive

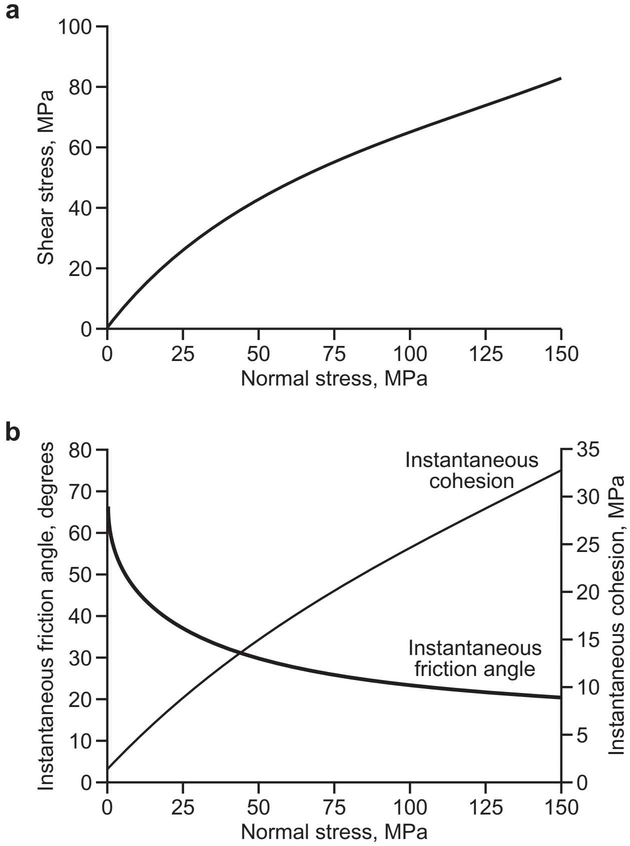

Fig. 5. (**a**) Mohr failure envelope for a rhyolite rock mass from Snowdonia; (**b**) plot showing the instantaneous friction angle and instantaneous cohesion.

strength of rock masses from Snowdonia and Tenerife determined using this method are listed in Table 3.

Discussion

Implications for volcano edifice strength

Our estimates of rock-mass strength compare favourably with previous estimates by, for example, Jaeger & Cook (1979), Voight *et al*. (1983), Schultz (1995, 1996) and Watters *et al*. (2000). Jaeger & Cook (1979) and Voight *et al*. (1983) gave wholesale estimates of edifice cohesive strength in the region of 1 MPa. Watters *et al*. (2000) presented data from mainly altered rock masses, and as expected their values of cohesive strength (0.08–0.4 MPa) are slightly lower than those presented here. Schultz (1995, 1996) reported estimated cohesive strength values of basaltic rock masses of 0.6–6 MPa. Taking the averages of data given in Table 3, the basaltic rock masses from Tenerife have an average cohesion of 1.3 MPa, which compares well with the data ofSchultz (1995, 1996). The average overall cohesion for the Tenerife and the Snowdonia rock masses of 1.30 and 1.37 MPa, respectively, also agree well with previous estimates using an approach similar to that outlined above. The overall edifice cohesive strength is also useful in predicting the rock-mass response to failure, i.e. whether it will disaggregate or remain mostly a coherent block. As shown by Watters *et al*. (2000), failure is more likely to develop at sites where discontinuities contain secondary clay or gauge material, rather than along barren joints with no infilling. The same applies to sites of hydrothermal alteration. However, some forms of hydrothermal alteration, in particular silicification, generally produce a stronger and more elastic rock mass (Watters *et al*. 2000), and future work incorporating the GSI will allow the effects of alteration in the rock mass to be taken into account.

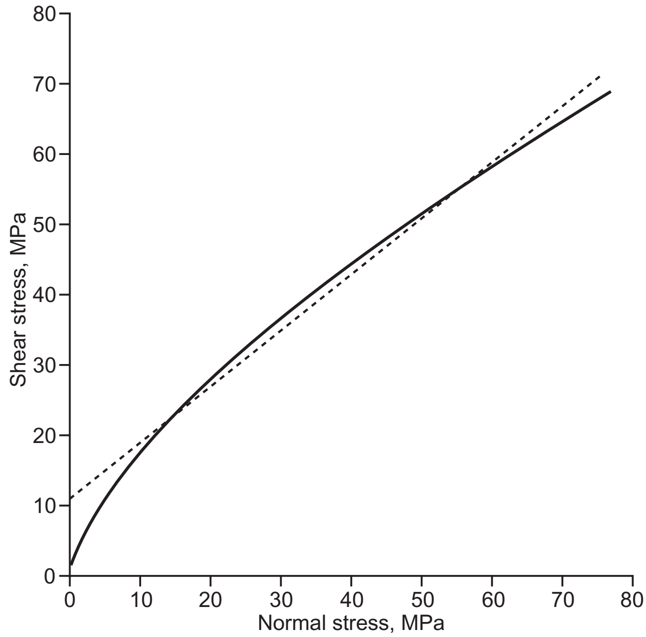

Fig. 6. Representative plot showing a straight-line Mohr–Coulomb fit to a Mohr failure envelope obtained using a least-squares method.

A new approach to the Hoek–Brown failure criterion

Recently Hoek *et al*. (2002) published an update to the Hoek–Brown failure criterion. The revised version differs from the method defined previously in two important ways. The first is the replacement of the RMR by a new term, the geological strength index (GSI). The GSI (introduced by Hoek *et al*. (1992) and later refined by Marinos & Hoek (2000)) is designed to take into account the fact that the RMR has proved inadequate in estimating the failure criteria of some very weak rock masses. It should be noted, however, that for a GSI > 25, the RMR and GSI are essentially interchangeable, and thus not relevant in this study where RMR values are > 38. However, a second variable introduced by Hoek *et al*. (2002), called the disturbance factor (D), may be highly significant in the classification of non-altered volcanic rock masses. The disturbance factor originated from experience in the design of slopes in large mines, where the classical Hoek–Brown criterion often proved over-optimistic in estimating rock-mass properties. The value of D is a qualitative measure of the degree of disturbance to which the rock mass has been subjected, and varies from zero (no disturbance) to unity (for the most disrupted). Despite its relevance to the problem in hand, at present it is far from clear how best to characterize a volcanic rock mass in terms of D. In mines and engineering works, the effects of heavy blasting damage, along with stress relief owing to the removal of overburden, result in disturbance of the rock mass. In the case of a volcanic slope, it is easy to visualize a relatively high disturbance factor caused by analogous natural events such as eruptions and landslips. The variable D affects the Hoek–Brown constants m and s (equations (2) and (3)) so that

$$m = m_i \exp[(\mathrm{RMR} - 100)/(28 - 14D)] \quad (14)$$

and

$$s = \exp[\mathrm{RMR} - 100)/(9 - 3D)]. \quad (15)$$

The influence of the disturbance factor on rock-mass strength can be large. This is shown in Figure 7, where a Mohr failure envelope with the instantaneous angle of friction and cohesive strength for a rock mass is plotted ($\sigma_c = 150$MPa and $m_i = 15$, RMR $= 65$), for two end-member cases $D = 0$ and $D = 1$. As seen in Figure 7, $D = 1$ results in a decrease in rock-mass cohesive strength of approximately 30%. A comparison of the Mohr–Coulomb criterion calculated with and without D for the volcanic rock masses examined in this study is shown in Table 4. Both angle of friction and cohesive strength are reduced significantly where $D = 1$, in some cases by up to 50%. Clearly, the idea of defining a disturbance factor for volcanic rocks is deserving of in-depth study. Work aimed at producing estimates for the value of D for a volcano slope is currently under way.

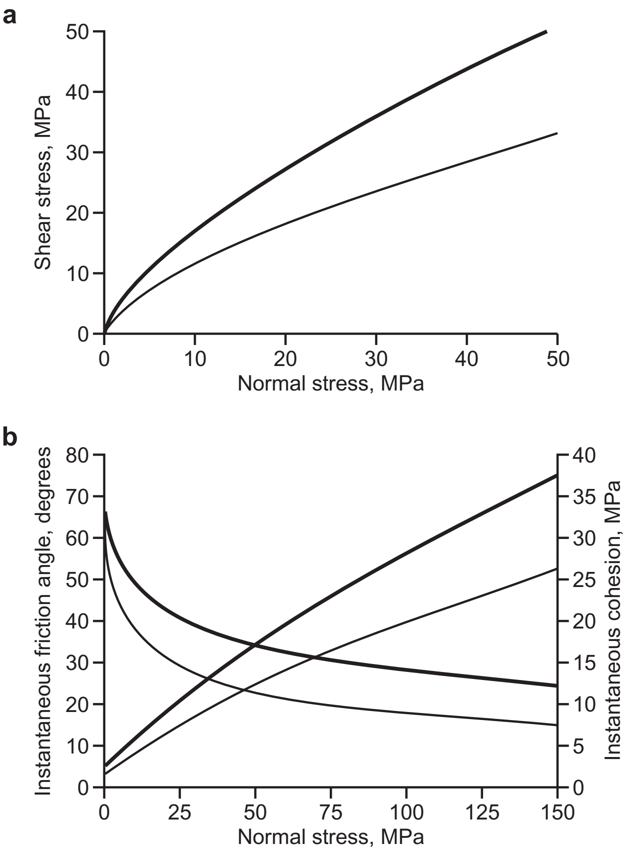

Fig. 7. (**a**) Mohr failure envelope and (**b**) instantaneous friction angle and instantaneous cohesive strength, for a rock mass where $\sigma_c = 150$MPa, $m_i = 15$, RMR $= 65$ and $D = 0$ (bold line) or $D = 1$ (fine line).

Conclusions

We have proposed a method to assess the strength of a volcanic rock mass using field observations and the Hoek–Brown failure criterion. Our results suggest that in general, the rock masses of a volcanic edifice can be very weak, with cohesive strengths less than 1 MPa and rock-mass angles of friction varying from 28° to *c*. 38°. The rock-mass strength of crystalline volcanic material examined in this study also appears largely insensitive to initial magma composition and age. Our data suggest that the measured RMR and strength characteristics of unaltered volcanic rock are related through an exponential dependence that can provide a good first approximation of compressive and cohesive rock-mass strength. The exponential relationship between the RMR and the rock-mass strength characteristics suggests that small changes in the condition of the rock mass may have a large impact on the rock-mass strength. This emphasizes the need for detailed mapping at any potentially hazardous volcano, because, if conditions are concurrent, failure will occur in the weakest area of the edifice regardless of how strong the overall rock mass is. The sensitivity of the mechanical properties of the rock mass to the disturbance factor (D) in the revised Hoek–Brown criterion identifies it as an important new variable that should be used in all future field assessments of volcano edifice strength.

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Table 4. *A comparison of the Mohr–Coulomb criterion produced with and without the consideration of the disturbance factor from the Snowdonia volcanic group and Tenerife*

Property	Snowdonia			Tenerife	
	Rhyolite	Tuff	Microgranite	Basalt	Phonolite
Rock-mass cohesive strength (MPa) ($D = 0$)	1.16–4.84	0.74–4.28	1.16–6.75	0.79–1.72	0.44–1.84
Rock-mass angle of friction (degrees) ($D = 0$)	31.3–38.1	27.8–36.1	41.2–49.4	28.1–31.8	28–34.9
Rock-mass cohesive strength (MPa) ($D = 1$)	0.31–2.59	0.21–2.29	0.57–4.08	0.23–0.66	0.1–0.71
Rock-mass angle of friction (degrees) ($D = 1$)	16.8–30.1	14.2–28.2	29.7–43.3	14.7–20.3	12.6–22.9

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