Development of rock joints with time and consequences for engineering

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ABSTRACT: Evidence is presented that seemingly ancient sets of joints only fully develop as mechanical fractures when subject to weathering at the Earth's surface. It is argued that spatial variability of joints may therefore only properly be understood if their geological origins and temporal nature are taken into account. With reference to geotechnical logging, the usual approach, which is to treat all joints as individual geometrical features without reference to origin, is considered simplistic and generally inadequate. Examples are given of slope failures associated with geologically recently developed joint systems and where joints that are rare statistically have high engineering significance. Recommendations are made to improve practice in assessing the jointed nature of rock masses

1 INTRODUCTION

Fractures in rock are fundamentally important to the ways in which rock masses behave in terms of settlement, stability and excavation in engineering projects and for the through-flow and storage of liquids and gases. However the nature of and, in particular, the origin of rock joints, faults and other naturally occurring structural discontinuities or fractures are dealt with rather superficially in most rock mechanics and engineering geology textbooks and in standards for rock description. The nature of joints and their origins remains the province of the structural geologist.

Consequently when it comes to characterizing rock masses in rock engineering, joints and other structural discontinuities tend to be dealt with simplistically. Generally only open fractures are routinely recorded in core logging. The choice of "type" of fracture is limited to joint, fault, bedding or cleavage (BS5930:1999). In addition only geometrical attributes such as dip and dip direction, roughness, aperture, persistence and termination are recorded routinely (e.g. Priest, 1993). Data are then often analysed statistically using a programme such as DIPS (Rocscience). The focus of interpretation is on geometry and frequency and little attention is paid to origin, strength evolution or environmental setting of the fractures. It is not generally appreciated that joints and other fractures develop mechanical properties with time due to weathering and this is the focus of the paper.

2 THE NATURE AND ORIGINS OF JOINTS

Joints are fractures found in most rocks near to the surface of the Earth and their origins have long been the subject of debate (Pollard and Aydin, 1988). Joints are clearly the result of overstressing of the rock (even in its soil-like state). Some form in sedimentary environments, others in igneous bodies due to cooling or other forces whilst others are the result of tectonic forces (e.g. Rawnsley et al, 1990; 1992). Some joints are the direct result of stress conditions at the Earth's surface as discussed later. Einstein & Dershowitz, 1990 review the formation of joints in tensile and shear stress regimes based on modern concepts of fracture mechanics. What remains poorly recognised however is that many joints do not fully develop as visible structures and controlling mechanical discontinuities until the rock is significantly de-stressed and exposed to the elements. They are locked in as weaknesses but only fully develop at later stages. Almeida et al (2006) describe recent work on orthogonal built-in planes of weakness in granite – rift, grain and hardway – that are exploited in the splitting of seemingly intact granite for the production of dimension stone. In more weathered terrain orthogonal sets of joints are typical of granite (Figure 1) and it is reasonable to infer that the joints seen in such partially weathered rocks have developed with time along weakness directions defined at some very early stage during the emplacement and cooling of the granite.

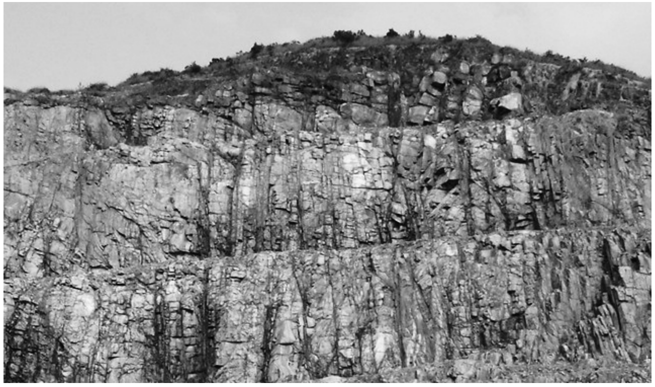

Figure 1 Predominantly orthogonal (vertical and horizontal) joint development in granite, Mount Butler Quarry, Hong Kong.

3 PROCESSES FOR JOINT DEVELOPMENT

The geohistory of a rock mass can be defined as the set of geological conditions (stress, fluid pressure, temperature and fluid–rock interactions) experienced from formation to the present. The history of these parameters and the time spent under different conditions which define a geohistory path can contribute to the development and stability of joints in the system. For example, the exposure to geological loading and unloading during and after ice-ages or the combination of weathering by the influx of different fluids may induce time-dependant changes to the strength of the rock mass. Small changes in the cohesion between mineral phases across grain boundaries, the expansion of porosity by slow mineral dissolution or chemical reaction to weaker phases, or the removal of load bearing ‘micro-bridges’ within incipient joints may all induce failure via a dynamic evolution of the strength. Two important end-member processes need to be considered in the time-dependant behaviour and stability of joint systems.

3.1 *Mechanical responses/processes.*

In the end-member case these do not involve chemical alteration but include the processes that impact on the susceptibility of opening discontinuities that can promote the initiation and propagation of fractures or joints. These are fundamentally controlled by the rock fabric and mineralogy where changes in the distribution, frequency, orientation and cohesion of grain boundaries during the geohistory (especially the recent and present conditions) impact on the susceptibility to failure. Slow crack growth and the linking of discontinuities may promote a deterioration of the rock-mass and may depend on the detailed elastic response of adjacent mineral grains to changing geological conditions (loading or unloading during freeze-thaw, wetting-drying or fluid pressure cycles). Figures 2 and 3 shows mechanically induced fractures (sheeting joints) through conglomerate in Australia.

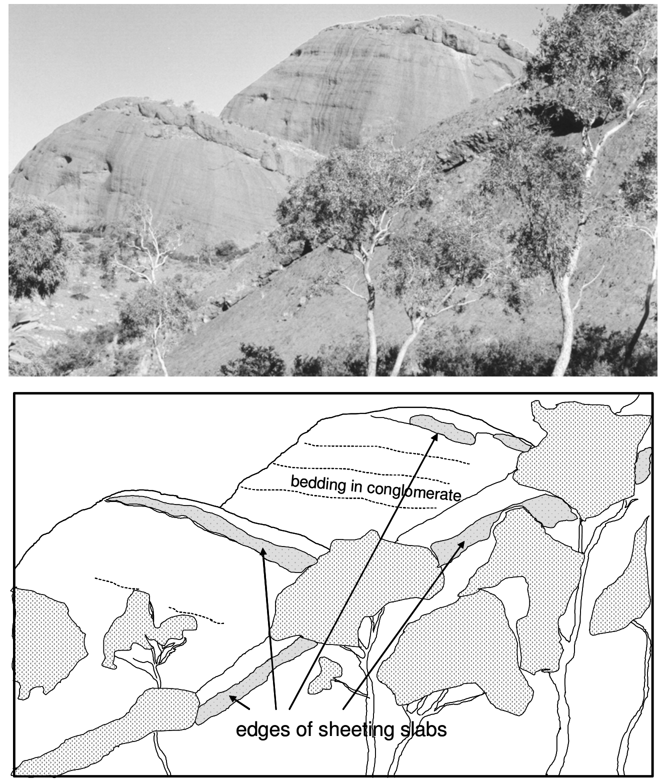

Figure 2 Sheeting joints through conglomerate, the Olgas, Australia

Figure 3 Close up of shallowly dipping sheeting joint through conglomerate, the Olgas, Australia

3.2 *Chemical responses/processes*

In the end member case these processes involve chemical reactions that change the strength of interfaces that can promote or stabilize fracture growth. Processes such as dissolution, corrosion, transformations, precipitation or wetting may all induce changes in rock mass behaviour. Conditions that promote rapid chemical alteration will be particularly significant. In Material Sciences the chemical processes that promote such strength changes (generally at higher temperatures) are termed reaction-enhanced ductility and transformational-enhanced ductility and similar processes may act in the weathering development of rock joints. Figure 4 shows the effect of gradual chemical weathering on a relict rock bridge in an incipient joint in Hong Kong.

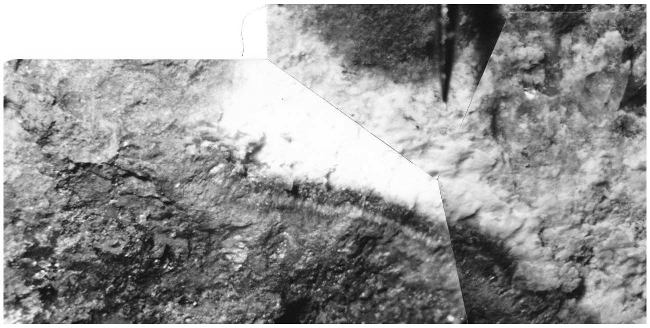

Figure 4 Rock bridge (grey unweathered) in incipient joint with weathering around periphery of bridge. Pin for scale. (Hencher, 1981).

Both the mechanical and the chemical processes are well known, but it is the combination and feedback between these processes under different conditions that will control the susceptibility to joint development and propagation at any particular location.

4 GENERAL IMPLICATIONS

It is argued that joint systems measured at any location will owe their properties to geohistory both with respect to the initial development of flaws in geological time and to relatively recent weathering and loading history. Dip and azimuth of many sets are pre-defined in their geological past but aperture, frequency and persistence are largely a function of exposure and local stresses at the Earth's surface. Sheeting joints may exploit previous weakness directions, particularly in igneous bodies but others develop as new fractures, totally in response to the stress state at the Earth's surface. The argument that some sheet joints must be ancient because of the evident antiquity of other cross cutting joint sets (see the well-argued review in Twidale, 1982) no longer holds true once it is accepted that "ancient" joints only fully develop as visible, mechanical fractures on exposure and due to weathering.

The importance of considering the geohistory of joint systems when characterising rock masses for engineering purposes cannot be over-emphasised. A consideration of the processes that have resulted in the joint sets and their attributes at one measuring location may indicate that some joints that might be expected may be under-sampled. Models such as those of Hancock (1991) allow a better analysis of the data. Figure 5 provides examples of potential ways for joints to form in thick sediment piles and the likely distribution of poles on stereonets.

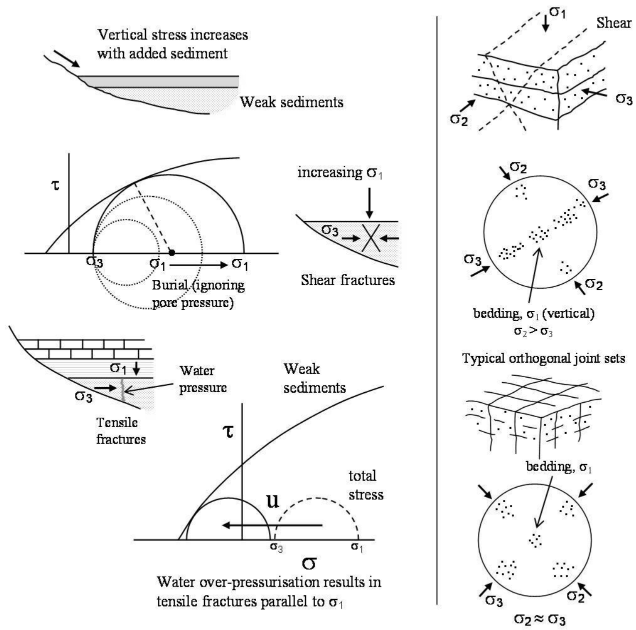

Figure 5 Possible modes of joint formation in sedimentary sequences and likely appearance of joint sets on stereographic projections.

5 IMPLICATIONS FOR SLOPE STABILITY

The dangers of an overly-statistical approach to dealing with discontinuity data have been highlighted by Hencher (1985) following a significant rock slope failure where rare but important joints had been discounted in the design of the slope (Hencher, 1983).

Furthermore the development and extension of joints in engineering time can be very significant in slope development. Figure 6 shows an example of a sheeting joint along which there was movement prior to eventual detachment of a large landslide (Halcrow China Ltd, 2002; Hencher, 2006). The rock above the sheeting joint along which intermittent movement had taken place over many years had become fractured with the opening up of pre-existing flaws and development of new fractures due to tensile stresses induced in the displaced slab. These fractures had then become infilled with sediments that contributed to the failure in restricting throughflow and allowing the development of cleft water pressures (see further discussion in Malone, 2007).

Figure 6 Fractured rock above geologically recent sheeting joint (Hencher, 2006).

6 IMPLICATIONS FOR UNDERGROUND WORKS

There are reported cases where the presence of pre-existing flaws have only fully developed as mechanical fractures on excavation with consequences for instability in tunnels (Everitt & Latjai, 2004). Martin (1994) provides evidence from the same site of the varying fracture state at different levels within the same rock mass. Clearly there are implications for nuclear waste repositories in that fracture systems may extend and develop during development of sites in response to stress state changes. Models formed following ground investigation may represent the mass inaccurately if temporal development of the fracture system is not accounted for.

Furthermore classification systems such as RMR (Bienawski, 1989) and Q (Barton, 2000) use a cursory treatment of rock fractures to characterise rock masses. Joints are undifferentiated in terms of origin and spatial variation. A consideration of geohistory when forming geological and geotechnical models of tunnel routes would no doubt be beneficial. Rock joint frequency and therefore rock mass quality which is important both with respect to excavatability and support will vary with degree of weathering. Care must be taken when interpreting conditions on the basis of data collected elsewhere.

7 RECOMMENDATIONS

The authors advocate an approach to measurement of joints in the characterisation of rock masses that focuses on geological process and modelling, especially when dealing with rock exposures rather than boreholes where, of course, all data should be logged and the analysis comes later. This rather conflicts with the emphasis in most standards where recommendations are made for scanline surveys and concentration is more on orientation bias rather than proper geological analysis. The authors believe that this emphasis rather belies the importance of such data collection. Because the scanline, supposedly objective, approach looks so routine and foolproof, the tendency is to assume that it can be done by any technician and provide the requisite data that can then be fed into a statistical programme so that the geotechnical engineer, in his office, can get on with the important and demanding task of analysis. That is rock engineering by numbers and not to be recommended.

The recommended procedure for assessing rock masses at exposures, for example in quarries is:

1. Carry out a reconnaissance of the exposure. View it from different directions.
2. Form an initial geological model, split into structural and weathering zones/elements. Sketch model.
3. Broadly identify those joint sets that are present, where they occur and what their main characteristics are.
4. Measure data to characterise each set geologically and geotechnically. This should include data on fractography (hackle marks etc.) and coatings. Record locations on plans and on photographs. Record variations in degree of weathering and with structural regime.
5. Plot data and look at geometrical relationships. Consider geohistory and how the various sets relate to one another and to geological structures such as faults, folds and intrusions.
6. Considering geohistory, decide whether all joints that might be expected have actually been identified. Search for missing sets.
7. Analyse and reassess whether additional data are required to characterise the joints that are particularly important for the engineering problem.
8. Where data collection is remote from the actual project, consider how data are likely to vary spatially.
9. Consider sensitivity of the joint systems and the mechanical behaviour to changes that might be brought about by the engineering works.
10. Create a scorecard to highlight critical components of the discontinuities present and their potential impact.

8 CONCLUSIONS

Rock joints develop in time according to the geohistory at any location. In particular weathering will influence joint frequency, aperture and persistence. Data should be collected and analysed with due consideration to how the fracture system has developed and may further develop with time. Data should only be extrapolated within structural regimes as emphasised by Piteau (1973) and should similarly only be extrapolated between different weathering zones with great caution. The consequences of not following a proper geological thought process when characterising and describing rock masses can be serious. Important but rare fractures may be under-sampled in exposures and/or hidden following statistical analysis. Data collected "objectively" but without due consideration of the geological structure including weathering regimes can be confusing and generally unhelpful.

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