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Joint origin as a predictive tool for the estimation of geotechnical properties

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ABSTRACT: An understanding of the factors controlling the development of joint networks will allow increased confidence in geotechnical characterisation of rock masses, particularly where exposure is limited. The formation of joints within the network is discussed at the levels of single joint plane, joint set and joint system. The interpretation of joint networks in terms of the stress conditions during propogation is reviewed with reference to field examples. These examples illustrate how the history of formation controls geotechnical properties such as orientation, persistence, spacing and morphology.

1 INTRODUCTION

The geotechnical characterisation of jointed rock masses and in particular the extrapolation of data from exposed to unexposed locations is essential for the safe and economic design of rock structures. Statistical methods are commonly used (see for example La Pointe 1988, Call et al 1976, Hudson and Priest 1983) although the validity of extrapolation has often been questioned (see for example La Pointe 1980). Piteau (1973) made the important point that "the analyst must assess whether the location at which the joint data are collected has been subjected to the same geological history of deformation as the location where extrapolation is to be made. If their histories are found to differ, extrapolation is not valid."

Despite the acknowledged importance of geological origin to the characterics of joints (Dershowitz and Einstein 1988, Hencher 1987), little attempt has been made to utilise the extensive recent work by structural geologists on the origin of joints (eg Pollard and Aydin 1988, Bahat 1987, 1988, Price and Ladeira 1981) to improve geotechnical methods.

In this paper the origin of certain categories of joints, at various scales, is reviewed with reference to investigations carried out at a number of field locations. The relevance of such analysis to the geotechnical assessment of rock masses, particularly with respect to spatial variation, is discussed.

2 DEFINITIONS AND STRESS FIELDS

A joint is defined here as a fracture formed to release stress within rock and along which there has occurred insignificant lateral displacement. Dissipation of strain energy is achieved by the development of one or more series of joints whereas when faulting occurs considerable strain is relieved by movement along a single fracture. The total stress field within a rock mass may result from external forces such as tectonic movements or the weight of overburden or from internal forces such as those resulting from contraction during cooling. The stress field at any point can be described in terms of three orthogonal stresses termed the major (σ_1), intermediate (σ_2) and minor (σ_3) principal stresses. Pore pressure will reduce effective stresses (σ') directly (see, for example, Secor, 1965).

The type and orientation of any joint is governed by the relative magnitudes of the effective principle stresses during propogation (Hoek 1968). This relationship can be described by the superposition of a Mohr's circle construction representing the state of stress in the rock mass on to the envelope for intact failure (see, for example, Hancock 1985) Figure 1.

The geometry of a resultant joint depends

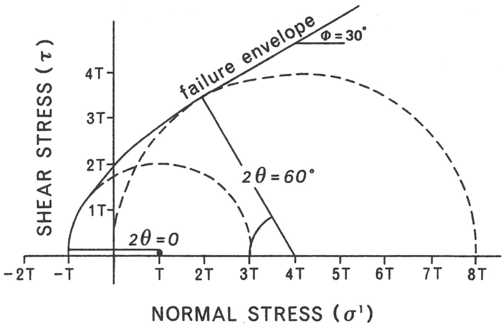

Figure 1, Stress controls for joint development ($-T = \sigma_t$)

upon the ratio of normal and shear stresses acting on the shear plane as defined by the intersection of the stress circle with the failure envelope, with Θ representing the angle between the maximum principal stress and the joint. A tension joint will form under conditions of zero shear stress (Θ = 0) where σ_3' is tensile and equal to the tensile strength of the rock (σ_t) and where σ_1' is less than $3\sigma_t$. Where $(\sigma_1 - \sigma_3) > 4\sigma_t$ then a component of shear stress acts. For $(\sigma_1 - \sigma_3)$ between $4\sigma_t$ and $8\sigma_t$ a hybrid joint will develop with Θ between 1 and approx. 30°. Joints forming directly due to shear can only occur when σ_3' is compressive and then $(\sigma_1 - \sigma_3)$ must be $>8\sigma_t$. The linearity of failure envelopes for most rocks constrain shear joints to a constant Θ of approximately 30°.

The final pattern created by the development of joints within a rock mass which may be simple or complex is termed here the joint network. The range of possible networks even for a single tectonic event is enormous and without establishing the development stages on the basis of field data, prediction of jointing characteristics is likely to be in error. Examples will be given where joints vary considerably in their characteristics over relatively short distances. The unravelling of joint networks is considered here at four levels which relate to a hierarchy of stress release. The highest and final level, the joint network comprises joint systems, sets and individual joint planes and these will be discussed in that order. Microfractures and minor joints represent an even lower level of development and although the same principles apply, these microstructures will not be considered further.

3 JOINT SYSTEMS AND JOINT SYSTEM VARIATION

A joint system is defined here as a pattern of joints that has formed in response to the stresses associated with a single event. The three simplest joint systems that may be recognised are:

(i) polygonal systems,
(ii) grid lock systems, and
(iii) joint spectral systems.

3.1 Polygonal systems

Polygonal joint systems form where $\sigma_2 = \sigma_3 = -\sigma_t$. Each joint forms parallel to σ_1 but is otherwise unrestricted. Such joint systems are typical of lava flows and of dessicated sediments but are otherwise of limited geological occurrence and will not be considered further.

3.2 Grid lock systems

The term grid lock was suggested by Hancock (1985) for the development of two orthogonal sets of joints as illustrated in figures 2 and 3. The effective stress conditions are similar to that for the formation of a polygonal system except that whilst σ_2' and σ_3' are both tensile, they are not equal and $0 > |\sigma_2 - \sigma_3| > \sigma_t$. The development of one joint locally releases the value of tensile stress perpendicular to it within a stress release field that is proportional to the length of the joint (Pollard and Aydin 1988). As σ_2' and σ_3' are close in value, such a reduction may reverse their relative magnitude such that the next joint to form is perpendicular to the first (Hancock 1985, Simon et al 1988). This process continues until stresses capable of causing joint formation are released and leaves an orthogonal joint system as illustrated in figures 2 and 3. Commonly, as in this case, σ_1 is the overburden stress leading to vertical joint formation.

3.3 Joint spectra

Joint spectral systems (Hancock 1985) result from a gradual increase or decrease in σ_1' relative to σ_3' leading to the formation of a full range of joints from tensile to shear. Figure 4 shows a characteristic rose diagram for a joint spectrum developed in Jurassic mudstones at Kimmeridge Bay, U.K. The development of such a system is complex with each joint propagating through

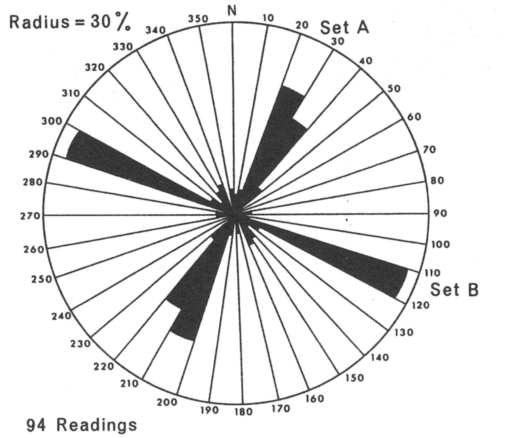

Figure 2 Rose diagram - Grid lock system. Bembridge Limestone, Whitecliff Bay.

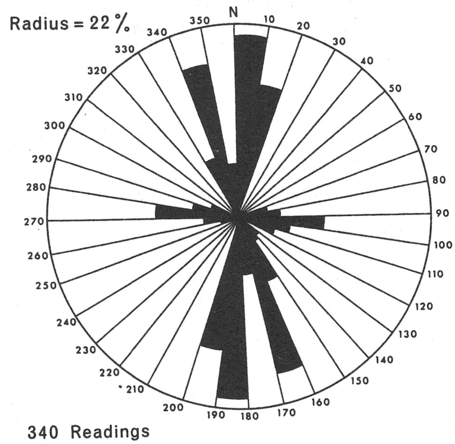

Figure 4. Rose diagram - Joint spectrum. Kimmeridge Clay, Kimmeridge Bay.

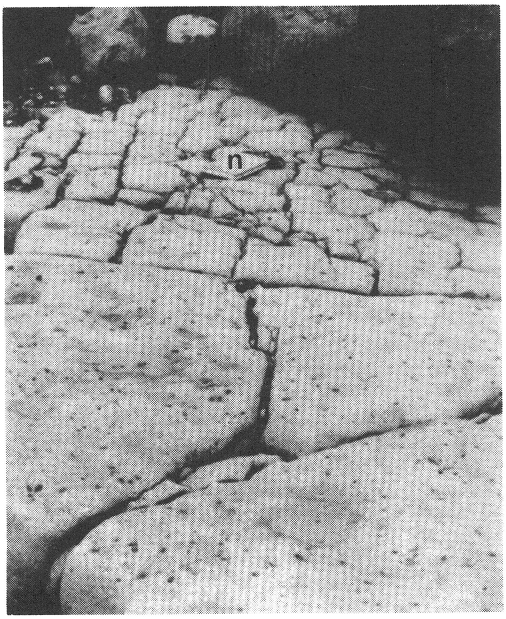

Figure 3 Grid lock system, Bembridge Limestone. View west, notebook (n) for scale.

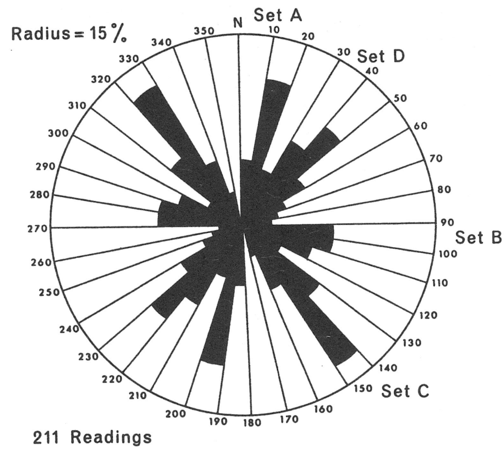

Figure 5. Rose diagram - Overprinted spectra. Bembridge Limestone, Whitecliff Bay

a constantly varying stress field resulting from the applied stress and the stress relief fields of neighbouring existing and developing joints. A single joint may alternate through stages of tensile, hybrid or shear failure in response to the changing stress field, curving over a few metres as it does so. At Kimmeridge Bay the applied stress field has been interpreted with σ_1 acting N-S and σ_2 as overburden (Hancock et al 1987). In many situations, σ_1 will be due to the weight of overburden leading to a joint spectrum with varying dip rather than strike.

Within mixed lithologies different spectra may be specific to individual beds, presumably due to differing strength characteristics at the time of joint system development. Such variation is largely unpredictable and can only be resolved by careful field study of the complete sequence of strata. Variation can also occur in a single lithology due either to lateral stress variation or to changes in material properties. An example is shown in figure 5 which shows the orientation of

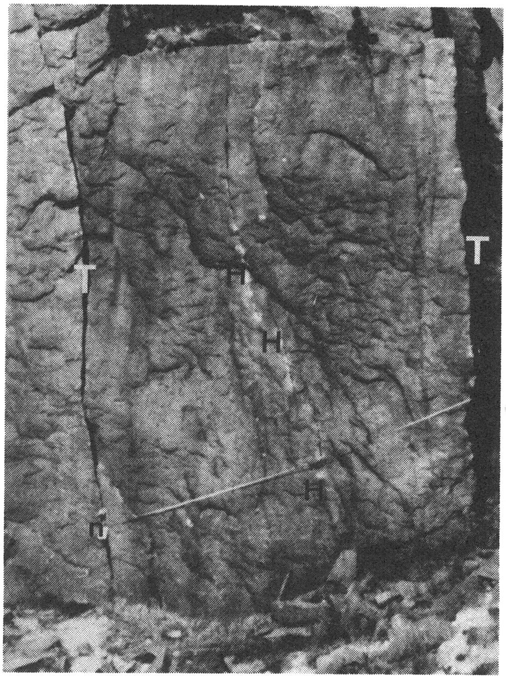

Figure 6. En echelon, hybrid joints (H) developed between tension joints (T) - Millstone quarry, Derbyshire. Notebook (n) for scale

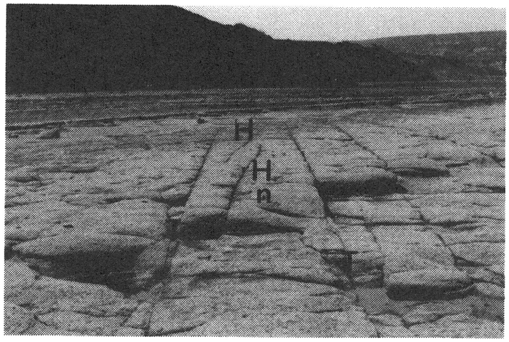

Figure 7. Development of hybrid joints (H) between tension joints (T). Lower Lias, Robin Hoods Bay, Yorkshire

joints in Bembridge Limestone only 400m away from the grid lock illustrated in figures 2 and 3 and in the same stratum. figure 5 represents two overprinted spectral systems at 90° to each other with σ_1 essentially horizontal. Principle stress directions for figure 5 are the same as for figure 2 but with different relative magnitudes. Figure 5 is interpreted with σ_2 representing the overburden and σ_1 and σ_3 alternating during development of the spectra.

4 JOINT SETS AND JOINT SET VARIATIONS

Joint systems are made up of one or more joint sets which are defined here as groups of joints that are either nearly parallel or have similar Θ angles. It is rarely possible to constrain a single set according to strict orientation limits and indeed sets may merge in many situations. It is at the level of joint set that many geotechnically important parameters must be quantified (eg spacing and persistence) but it is perhaps rarely appreciated how such properties may vary within the same set even within the same lithology and over short distances. For example in figure 3 the grid lock system comprises two sets at 90° but the characteristics of each set are significantly different either side of the central, high persistence joint with both spacing and persistence much higher in the eastern regime.

A common variation in joint set characteristics is the occurrence of lower persistence joints between high persistence joints, the former usually at a low angle to the latter. During stressing with the shear component gradually increasing, hybrid joints will tend to develop midway between the primary, high persistence tension joints because this is the zone of maximum tensile stress (Lloyd et al 1982). However as they propogate they will extend beyond this zone and propogation may cease. Figures 6 and 7 are field examples of this type of joint development. Joints in the Millstone Grit of Yorkshire that developed as alternate vertical tensile and steep hybrid joints with σ_1 vertical are shown in figure 6. The joints shown in figure 7 from Robin Hoods Bay, Yorkshire developed with σ_1 horizontal, σ_2 vertical and hence the angle Θ in the horizontal plane.

5 JOINT PLANES AND THEIR VARIATION

Most joint planes are not consistent in orientation, waviness or roughness along their length. In many cases joints are most variable close to their termination where they either began or finished propagation. For example, a joint that terminates in intact rock commonly curves sharply before termination and/or breaks down into an array of en-echelon joints

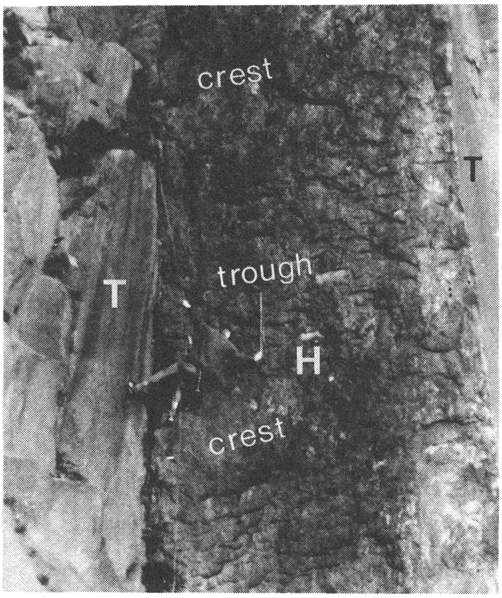

Figure 8. Comparison between planar tension joints (T) and scaley, wavey surface of hybrid joints (H). Millstone Quarry, Derbyshire.

that become smaller and eventually disappear. A joint that terminates against another joint, forming a T shaped junction, may show no variation before terminating.

Other individual joints may show systematic recurrence of zones of anisotropy along their length. An extreme example is illustrated in Figure 8 which shows a joint through Millstone Grit which exhibits large scale, scaley texture that appears between the crests and troughs of large scale waviness. The scaley regions comprise discontinuous en-echelon joints that formed as the main joint plane deviated from the direction of σ_1. This type of development, which is quite commonly seen where joints change direction slightly, is perhaps best explained as indicating the development of an overall hybrid joint through the interconnection of minor low angle tensile joints as the joint deviates towards higher shear component levels. Note the similar surface morphology to the facing joint shown in Figure 6.

6 PREDICTION OF JOINT PROPERTIES

Joint variations can be described effectively on four levels representing successive levels of stress release. At the lowest level the joint plane can vary widely over its length in a largely unpredictable manner although through careful observation of series of joints within sets and their inter-relationships their main features may be characterised. Variations in joint spacing, persistence and morphology within a joint set can usually be explained in terms of stress history. Observed spatial variation may be explicable and this will clearly strengthen confidence in extrapolation for geotechnical characterisation.

The identification of a joint system often allows the direction and relative magnitues of the principle stresses at the time of joint formation to be determined. By establishing the nature of the principle stresses at each exposure in an area, the degree of consistency in joint development can be assessed and conclusions drawn regarding the likely joint pattern in unexposed ground.

The final joint network may at first appear random to the geotechnical investigator but may well be explained in terms of successive periods of joint development. For example the extremely complex joint pattern in the Ingletonian of North Yorkshire in an isoclinally folded series of greywackes and mudstones, whilst appearing to previous workers as random, was explained following careful study using the methods of Rawnsley as having developed due to six successive stress events (Sloan et al 1990). Each event was responsible for the development of joints of different characteristics and this analysis provided a useful basis for the assessment of slope stability in a major operating quarry.

7 CONCLUSIONS

It is doubtful that an understanding of joint origin will ever allow accurate assessment of joint development in unexposed ground. The range of variation at all four levels of joint development is high and often cannot be freely explained. Nevertheless, the benefits to be gained by interpretating the network at the system, set and plane levels can reveal important relationships between their origins and geotechnical properties. Even where such explanation is not forthcoming, geotechnical engineers should appreciate the spatial variation during sampling and collection of field data that will be used for subsequent engineering analysis and design.

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