S Y N O P S I S

The term 'jointed rock' refers to the rock mass with discontinuities. The mechanical behaviour of jointed rock, therefore depends on the properties of the discontinuities rather than on the strength of the parent rock. The basic problem involved in the sliding mechanism and associated stability, therefore is delineation of the characteristics of the discontinuities. In other words, interaction of rock and joints must necessarily be incorporated for analysis of jointed rock behaviour.

The major aspect in which the mechanical behaviour of jointed rock mass differs from that of the intact rock is its 'dilatancy' aspect. Currently, measurements of volume change associated with disintegration has invoked fundamental interest among the research workers. Experiments have evinced that the volume changes are associated with the process of sliding. This phenomenon is normally called 'dilation', 'dilatation' or 'dilatancy'. It is inferred that dilatancy is the consequence of sliding along rough joint surfaces inherent or developed in the process. In case of sliding along a joint, the riding over of asperities gives rise to changes in the value of deformation at right angles to the direction of application of shear force which has been termed as 'dilatancy'. Scientifically, the sliding between the two blocks necessarily evince the characteristic of 'thickening' that is geometrical changes in the surface. A dilatant joint tested under conditions of conventional direct shear box set up show the dilation angle besides the basic friction angle. Although dilation affect the deformation of the joints, the stress analysis as in current vogue accounts for dilatancy effects merely by adjusting the friction angle. Hence it is imperative to include dilation parameter in the stress-strain relationship of joint for realistic analysis.

A number of research workers have contributed in developing present state of art on mechanical behaviour of jointed rock. Among these, notable contributions are made by Horn and Deere (1962), Rowe, Barden and Lee (1964), Patton (1966), Parikh (1967), Byerlee (1967), Goodman (1968), Goodman and Dubois (1972), Einsten and Hirschfeld (1973), Ghaboussi and Wilson (1973), Proctor and Barton (1974), Schneider (1975), Barton and Choubey (1977), Heuze (1979), Pender et al (1981), Datir (1981), Desai et al (1984), Venkatachalam (1985), Hassani and Scoble (1985), Pande (1985), Bandis, Barton and Christian (1985), Gandhi (1987) and Barton (1988). Some of these research workers have worked on artificial joints made from model materials like plaster of paris, gypsum, sand, ballotini etc. while others have worked on natural joints. Most of the research workers have conducted research work in laboratory either in conventional direct shear apparatus or in conventional triaxial apparatus. For studying sliding aspects of rock joints many research workers have preferred to work on conventional direct shear apparatus as it is simple and convenient.

The most important expositions from the work of above research workers are :

* The value of the basic friction angle for a material is not only a function of the mineral composition of that material but also of the prevailing surface chemistry at the contact point. This chemistry in turn is a function of surface roughness as well as ambient experimental conditions.

* Polar liquids like water produces antilubricating effect on massive structured minerals like quartz while non-polar liquid like carbon tetrachloride produces lubricating effect. In case of layered lattice minerals like mica the effects are just reverse.

* Kinetic friction developed between mineral surfaces is equal to or less than the static friction.

* Deformation of asperities in the direction of shear reduces the effective inclination of the asperities resulting in subsequent lower frictional characteristics.

* Progressive failure of asperities appears to be responsible for less marked increase of peak shear strength with increase in asperity frequency.

* Smooth joints suffer very little damage during sliding.

* Dilatancy has been identified as volumetric changes during detrusion.

* Dilatancy property of a discontinuity is governed by the roughness of the rock surfaces and the character of the gouge.

* It is essential to include dilatant properties of a joint in the joint element for employing in finite element method for analysis.

* It is expected that the finite element analysis of a structure in rock by employing a joint element can help achieve a more rational design method for structures in jointed rock.

The development of the finite element method has proved to be a powerful tool for the analysis of jointed rock. In the finite element analysis a jointed rock is treated as an aggregate of massive rock blocks separated by joints, possessing special properties. Special joint elements have been developed for representing joint in FEM analysis. It is essential that the joint element should include the dilatancy parameter in direct form for its realistic application. A number of research workers have contributed by providing different types of joint elements. Among these, major contributions are made by Goodman et al (1968), Zienkiewicz et al (1970), Ghaboussi et al (1973), Herrmann (1978), Katona (1981), Heuze and Barbour (1982) and Desai et al (1984). The principal features are presented below :

* Goodman et al (1968) proposed a joint element which is characsterized by joint stiffness in normal direction, joint stiffness in tangential direction and the joint shear strength.

* Zienkiewicz et al (1970) used an isoparametric finite element for interface/joint which is treated like a solid element.

* Ghaboussi et al (1973) described a discrete finite element for joints. The joint element is characterized by joint stiffness in normal direction, joint stiffness in tangential direction and coupling of joint stiffnesses in normal and tangential directions.

* Herrmann (1978) presented an algorithm for an interface element which is similar to the element of Goodman et al (1968) with certain improvements through introduction of constraint conditions.

* Katona et al (1981) derived an interface model from the virtual work principle incorporating appropriate constraint conditions.

* Heuze and Barbour (1982) formulated an axisymmetric joint element, (a) from a strain displacement relation with a vanishing joint thickness (b) from a transversely isotropic right angle in a material with zero poisson's ratio and vanishing element thickness.

* Desai et al (1984) proposed a solid joint element of small finite thickness. The element is treated essentially like any other solid element, as in Zienkiewicz (1970). Its constitutive matrix contains normal component, shear component and coupling effects.

It is evident from this brief review that the joint elements proposed are not realistic enough since they do not directly incorporate a dilatancy parameter. The goal of the present investigation is therefore to propose a joint element which incorporates directly a dilatancy parameter in terms of geometrical quantity accrued from basic phenomenon of sliding.

The scope of the present work is therefore to delineate the factors affecting the mechanical behaviour of jointed rocks and to find a dilation parameter and a consitutive relationship for a dilatant joint element for use in finite element analysis. The scope also includes verification of such a constitutive relationship against laboratory direct shear test data as well as the data from in situ shear tests, and further its implementation to typical cases.

The objectives can be broadly categorised as :

* to understand the basic phenomenon of friction in jointed rock,

* to delineate the factors affecting the mechanical behaviour of jointed rock,

* to develop investigation techniques for delineation of the factors,

* to find a dilation parameter for the joint element,

* to formulate a constitutive relationship for the joint element,

* to verify the relationship with experimental data,

* to implement the developed joint element in a finite element method for analysis,

* to compare the modifications of joint behaviour owing to the direct incorporation of the dilatancy parameter.

Tests have been conducted on artificial rock joints using plaster of paris as model material. The tests have been conducted on samples having joints of different surface characteristics as under :

* unlubricated plane joint surface

* lubricated plane joint surface

* regularly aspirated surface

* irregularly aspirated surface

* gouged joint surface

To verify the efficacy of joint element following laboratory direct shear tests or insitu tests are considered :

* saw cut surface in Porphiritic Basalt without gouge

* saw cut surface in Porphiritic Basalt with gouge of cement sand mortar 1:2

* saw cut surface in Porphiritic Basalt with gouge of cement sand mortar 1:3

* saw cut surface in Porphiritic Basalt with gouge of cement sand mortar 1:4

* cyclic direct shear tests

* insitu direct shear **tests** on concrete-rock (Basalt) interface.

In nutshell, the major expositions from the present work are summarised below :

(i) The classical laws are followed in case of sliding on plane surfaces, whether lubricated or unlubricated, while deviation from the classical laws of friction is observed in case of sliding over aspirated surfaces. The deviation is a consequence of volume change occurring during sliding. The classical friction equations, independent of volume change, therefore, need to be generalized by incorporating an appropriate parameter for volume change.

(ii) The generalized equation of sliding friction for all types of surfaces, shall be the integration of the classical sliding friction equation, rigorously true at every instant. The process of integration should include the consideration of distrotion of plane at every instant. The resultant distortion of plane at every instant of sliding can be accounted for in terms of a geometrical parameter, consisting of ratio of principal strains, well known as Poisson's ratio in classical mechanics. The classical equation,

$$\tau = f(\mu, \sigma)$$

must have a generalized form of

$$\tau = f(\mu, \nu, \sigma)$$

(iii) The phenomenon of sliding on discontinuities in jointed rock is analogous to the phenomenon of sliding on aspirated surfaces. The sliding in jointed rock therefore, is associated with continuous alterations of surface characteristics. In physical terms, the process of sliding is occurring at new plane of orientation continuously. The phenomenological parameter representative of the alteration of surface characteristics has been identified in terms of change of Poisson's ratio at every instant.

(iv) The operative equation to describe the sliding behaviour in jointed rock as deduced from the experimental observations in laboratory as well as in field is,

$$\tau = \sigma^{\cos i_o} \tan(\phi_\mu + i_o)$$

Alternatively,

$$\tau = \sigma \tan(\phi_\mu + i_{av})$$

where,

$$i_{av} = \tfrac{2}{3} i_o \, \sigma^{-\tan^2(45 - \phi_\mu/2)}$$

(v) A new joint element has been developed from the basic phenomenon of sliding in jointed rock, by incorporating change in Poisson's ratio at every instant in the constitutive matrix. The constitutive matrix can be given in the following forms :

$$(D) = \frac{1}{E} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1-\nu^2 & 1-\nu \\ 0 & 0 & 1+\nu \end{bmatrix}$$

Alternatively,

$$(D) = \frac{1}{E} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 2D(1-\nu)(1+2\nu) & 0 \\ 0 & 0 & 1+\nu \end{bmatrix}$$

(vi) The developed joint element has a utility as a solid element in a finite element method. The utility has been demonstrated in predicting the behaviour of jointed rocks observed in laboratory as well as in field as also in engineering situations.

(vii) The efficiency and efficacy of the proposed new joint element has been established by realistic predictions of not only the generalized parameters of stresses and displacements but also the particular parameter associated with volume change, which is the distinguishing characteristics of the mechanical behaviour of jointed rock.

(viii) The superiority of the new element developed during this investigation is the incorporation of the phenomenological parameter of dilation in terms of change in Poisson's ratio, consequent upon which it is possible to delineate various deformation modes like compression, sliding and dilation.