Extended summary of presentation at Second Annual ASCE Engineering Mechanics Specialty Conference, N.C. State University, Raleigh, N.C., 23-25 May 1977.

*Fracture mechanics model for slip surface propagation in soil and rock masses**

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Landslides on slopes of overconsolidated clay or clay shale seem typically to occur by the development of a narrow slip surface, possibly initiated by a stress concentration from cutting or erosion at the base of a slope, which then propagates upwards through the soil until the landslide instability occurs. Often the time scale of such "progressive failures" extends over several years and the problem of modelling them includes the identification of the physical origin of this time dependence. See the reviews by Skempton [1] and Bjerrum [2] for background.

The shear crack mode of failure, dictated by the unstably falling stress vs. deformation diagrams for such materials, invalidates conventional "limiting equilibrium" approaches since the peak strength cannot generally be mobilized simultaneously over all the failure surface. A different approach was proposed by Palmer and Rice [3] based on tensile crack models with cohesive zones. In their model spatially continuous deformation is assumed to give way, at peak strength, to localized shearing in a thin slip surface for which the strength τ is some monotonically decreasing function, $\tau(\delta)$, of the relative slip δ. Here $\tau(o) = \tau_p$, the peak strength, wheras $\tau(\delta)$ approaches τ_r, the residual strength, at sufficiently large δ; the function $\tau(\delta)$ is dependent additionally on the "effective" compressive stress acting normal to the slip surface.

The conditions to propagate a shear band have been worked out, according to this model, for a number of cases [3, 4, 5]. One in which the results simplify greatly is that for which the breakdown zone at the shear band tip (i.e., the zone where τ differs significantly from τ_r) is small by comparison to geometric dimensions such as slip surface length, and for which the material outside the slip surface is modelled as linear elastic. Then, if K is the mode II stress intensity factor for an identically loaded slip surface, of the same geometry, which sustains everywhere a resisting stress at the residual level τ_r, the critical value of K for slip surface propagation is

$$\frac{1-\nu}{2G} K_{crit}^2 = \int_0^{\delta_1} [\tau(\delta)-\tau_r]d\delta \quad . \tag{1}$$

Here ν and G are the elastic Poisson ratio and shear modulus of the surrounding material and the upper limit δ_1 on the integral

* Research supported by NSF and USGS.

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is to be chosen so that $\tau(\delta) = \tau_r$ for $\delta > \delta_1$. In general K has the form (see [3, 4])

$$K = (\tau_{avg} - \tau_r) \times \text{geometric factor} \tag{2}$$

where τ_{avg} is some representative level of shear stress which would have been transmitted across the slip surface had that surface not developed.

Observations suggest that there is a significant time scale associated with such progressive failures. They are seldom abrupt, in a dynamic sense, but develop gradually, often with detectable mass motions extending over several years [1, 2], and even when the failure takes place on a short time scale (say, immediately following an excavation cut) the propagation seems to be essentially quasi-static (e.g., Bishop [6]).

There are several possible sources of the time dependence and some of these have been analyzed in [4]. They include considerations of time-dependent strength degradation or creep of material within the slip surface and also of bulk viscoelastic behavior of the surrounding material. Yet another source of time dependence arises, however, from the fact that the slopes of interest are, in general, saturated with groundwater. This gives rise to two possible mechanisms, both of which have been discussed [7, 8] in connection with the somewhat analogous problem of quasi-static slip motions on earth faults in the form of "fault creep": (i) One possibility arises from the transient shear strengthening of material in the breakdown zone by pore fluid suctions that are induced by the dilation that normally accompanies shear in overconsolidated soils. This has been studied in [4] and [7] and, although there is considerable uncertainty in the choice of material parameters in the theoretical model, the mechanism seems to be important only at comparatively high propagation speeds, of the order of 1 m/day or so. (ii) A more promising possibility, as a long term progressive failure mechanism, arises from the effects of time dependent response of material surrounding the growing slip surface in the consolidation controlled transition from undrained to drained conditions. This mechanism has been analyzed by Rice and Simons [8] by solution of the problem of a shear fault propagating at steady speed in a Biot elastic porous medium.

Specifically, in [8] a solution is given to the idealized model of a semi-infinite shear fault, which grows at steady speed V under plane strain conditions, and which is subjected to a uniform shear loading along its surfaces, over a distance ℓ adjacent to the fault tip, but is freely slipping at greater distances. The shear loadings are, of course, intended to simulate loadings like $\tau_{avg} - \tau_r$ associated with a natural slip surface, and hence the model corresponds approximately to a slip surface of length ℓ which is propagating at depth, without rapid changes of speed, in a slope of fluid-infiltrated, nominally elastic, porous material. If the material of the idealized model was elastic in the usual sense, the stress intensity factor, here referred to as the "nominal" stress intensity factor, would be

$$K_{nom} = (\tau_{avg} - \tau_r)\sqrt{8\ell/\pi} \ . \tag{3}$$

As shown in [8], however, in the case of a fluid infiltrated elastic porous medium the same characteristic inverse square root stress field singularity results at the fault tip, and the pore pressure alteration vanishes at the tip, so that there is a zone of size proportional approximately to c/V at the tip within which the material behaves as a drained, classically elastic solid and sustains a local stress intensity factor given by an expression of the form

$$K = K_{nom} h(V\ell/c) \quad , \qquad (4)$$

where c is the pore fluid diffusivity and where the function $h(..)$ is a monotonically decreasing function of its argument. Specifically, $h(o)=1$, corresponding to classical elastic behavior in the low speed, fully drained limit, but

$$h(V\ell/c) \to (1-\nu_u)/(1-\nu) \quad \text{as} \quad V\ell/c \to \infty$$

where ν is the Poisson ratio under drained conditions and ν_u is the ratio under undrained conditions.

Now, as discussed in [8], if both the slip surface length ℓ as well as the drained zone dimension, c/V , at the tip are large by comparison to the breakdown zone size, the fault growth criterion has the same form as in eq. (1), where now K_{crit} refers to the local K , related to K_{nom} by eq. (4). Thus, when the criterion is phrased in terms of the nominal stress intensity level, required to drive the slip surface at speed V ,

$$K_{nom} \equiv (\tau_{avg} - \tau_r)\sqrt{8\ell/\pi} = K_{crit}/h(V\ell/c) \quad .$$

Thus $K_{nom} = K_{crit}$ for growth at low speed fully drained conditions but, according to this expression, the requisite value of K_{nom} increases monotonically with speed approaching a maximum value of $[(1-\nu)/(1-\nu_u)]K_{crit}$ (which is 1.7 K_{crit} for the representative values $\nu = 0.15$, $\nu_u = 0.5$).

There are significant alterations of these results when one or both of c/V and ℓ are not large in size compared to the breakdown zone, and the reader is referred to [8] for fuller details. The net conclusion reached there, however, is that the mechanism should be significant as a factor tending to stabilize fault motion (in the sense that K_{nom} increases strongly with V) over a broad speed range extending approximately from c/ℓ to 100 c/ℓ . Indeed, the steepest increase of K_{nom} with V occurs toward the lower end of this range, say, at speeds up to approximately 10 c/ℓ . Now, using the conventional soil mechanics expressions in the case of full saturation,

$$c/\ell = kM/\gamma\ell$$

where k is the permeability, in units of apparent seepage velocity in response to a unit head gradient, γ is the weight density of the pore fluid, and M is the drained elastic modulus for uniaxial strain (inverse of the compressibility usually denoted by m_v). Thus, taking

$k = 10^{-6}$mm/s and $M = 100$ bar (10MN/m^2) as representative for over-consolidated clay soils, $\gamma = 10$kN/m^3 for water, and $\ell = 10$ m, the speed range c/ℓ to $100\ c/\ell$, quoted above, corresponds approximately to the range 3m/yr to 1m/day, and the $10\ c/\ell$ figure corresponds to approximately 3m/month. The results seem consistent, at least as regards the general time scale, with this being a mechanism for long term progressive failure.

References

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