Mathematical Forum, Vol. VI, No. 2. September 1983, pp. 26-32

ON A CREEPING VERTICAL STRIKE-SLIP FAULT BURIED IN A VISCO-ELASTIC HALF SPACE

By

PURABI MUKHERJI

CA 17, Sector I, Salt Lake,

Calcutta 700 064.

ABSTRACT

A long vertical creeping strike-slip fault, buried in a visco-elastic half space, representing the lithosphere-asthenosphere system, is considered. It is assumed that tectonic forces maintained a steady shear stress far away from the fault. Exact solutions for the displacements and stresses are obtained in the absence of fault slip or creep. It is shown that, under suitable conditions, there would be a steady accumulation of shear stress near the fault, resulting eventually in a sudden fault movement, generating an earthquake or aseismic fault creep. The case of fault creep is considered in detail, and solutions for the displacements and stresses valid after the commencement of fault creep are obtained. It is found that, under suitable conditions, the fault creep may lead to aseismic release of shear stress near the fault, reducing the possibility of a sudden fault movement, generating an earthquake.

1. *Introduction :*

Sudden movements across strike-slip faults constitute one of the major causes of tectonic earthquakes. Observational studies of surface movements in some seismically active regions, carried out during the last ten or fifteen years, using repeated geodetic surveys and instrumental observations with strainmeters and tiltmeters, have revealed that, in such regions, during apparently quiet aseismic periods, there are slow aseismic surface movements, of the order of a few mms. per year. Sudden fault movements, generating earthquakes, are preceded by considerable periods of accumulation of shear stress near the fault, and a sudden fault movement occurs when the accumulation of stress reaches a critical level. After the sudden seismic movement, which results, in release of the accumulated stress, the fault usually becomes locked again. However, in some cases, such as the central part of the

San Andreas fault, a slow aseismic relative movement across the fault has been observed, and this is called "fault creep".

Theoretical models have been developed for the lithosphere-asthenosphere system in the regions with active seismic faults, by Nur et. al. (1974), Budiansky et. al. (1976), Mukherji et. al. (1978, 1979), Spence et. al. (1979), Pal et. al. (1980 a, b) and a few others. In these theoretical models, strike-slip faults reaching the free surface have generally been considered, and the faults are assumed to become locked after sudden movements. Theoretical models of the lithosphere-asthenosphere system have been developed by Pal et. al, (1980 a, b). In these models, creeping faults reaching free surface are considered, However, there is indirect evidence for the existence of buried creeping faults which do not reach the surface, and the case of such a buried creeping fault has been considered here.

2. Formulation :

We consider a long plane vertical strike-slip fault, buried in a visco-elastic half space, which is taken to represent the lithosphere-asthenosphere system, as in Pal et. al. (1980 a). We introduce Cartesian co-ordinates (y_1, y_2, y_3) with the free surface as the plane $y_3=0$, and the plan of the fault as the plane $y_2=0$. The y_1=axis is along the trace of the fault along the free surface. The upper and lower edges of the fault are taken to be horizontal, at depths d and D below the free surfaces $(d<D)$. Fig. 1 shows a section of the model by the plane $y_1=0$.

We take the length of the fault to be large compared to its depth and width, and take the displacements and stresses to be independent of y_1, so that they are functions of (y_2, y_3, t). It is easily seen that, in this case, the displacement component u_1 parallel to the y_1—axis, associated with strike-slip fault movement, and the stress components τ_{12}, τ_{13} associated with u_1, will be independent of the other components of displacement and strees. Taking the material of the half-space to be linearly visco-elastic and of the Maxwell type, as explained by Mukherji et. al. (1979), we have the following relevant relations between stress and displacement.

$$\left.\begin{aligned} &\left(\frac{1}{\eta}+\frac{1}{\mu}\frac{\partial}{\partial t}\right)\tau_{12}=\frac{\partial^2 u_1}{\partial t\partial y_2} \\ \text{and}\quad &\left(\frac{1}{\eta}+\frac{1}{\mu}\frac{\partial}{\partial t}\right)\tau_{13}=\frac{\partial^2 u_1}{\partial t\partial y_3} \end{aligned}\right\} \tag{1}$$

where μ, η are the effective rigidity and viscosity of the material.

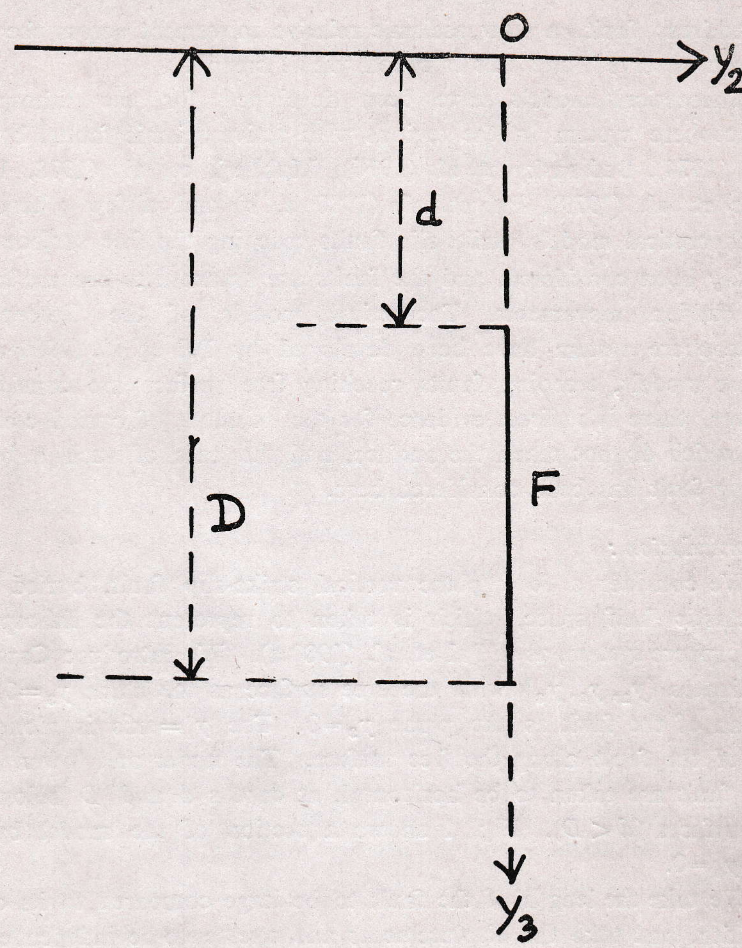

Figure 1.

For the slow aseismic displacements we consider, we neglect the inertial forces, which are very small, explained by Pal et. al. (1980 a), so that we have

$$\frac{\partial}{\partial y_2}(\tau_{12})+\frac{\partial}{\partial y_3}(\tau_{13})=0. \tag{2}$$

We assume that the shear, stress τ_{12} has a constant value τ_∞ far away from the fault plane, while stresses near the fault change due to fault creep. Then the stresses satisfy the boundary condition.

$$\left.\begin{array}{lll} \tau_{13}=0 & \text{at} & y_3=0 \\ \tau_{13}\to 0 & \text{as} & y_3\to\infty \end{array}\right\} \tag{3}$$

$$\tau_{12}\to\tau_\infty \quad \text{as} \quad |y_2|\to\infty \quad \text{in } y_3\geqslant 0 \tag{4}$$

From (1) and (2) we have

$$\frac{\partial}{\partial_t}(\nabla^2 u_1)=0$$

which is satisfied if

$$\nabla^2 u_1=0 \tag{5}$$

3. *Displacements and Stresses in the absence of fault creep* :

Before the commencement of fault creep, the displacements and stresses satisfying the relations (1)–(5), and are continuous everywhere in the system. Solutions for u_1, τ_{12}, τ_{13} are obtained as in Pal et. al. (1980 *a*), taking Laplace transforms of (1)—(5) with respect to *t*, solving the resulting boundary value problem for $\bar{u}_1$, $\bar{\tau}_{12}$, $\bar{\tau}_{13}$, the Laplace transforms of u_1, τ_{12}, τ_{13} and then inverting the Laplace transform. This gives

$$\left.\begin{aligned} u_1(y_2, y_3, t) &= (u_1)_0 + \frac{\tau_\infty y_2 t}{\eta} \\ \tau_{12}(y_2, y_3, t) &= (\tau_{12})_0\, e^{-\frac{\mu t}{\eta}} + \tau_\infty\left(1-e^{-\frac{\mu t}{\eta}}\right) \\ \tau_{13}(y_2, y_3, t) &= (\tau_{13})_0\, e^{-\frac{\mu t}{\eta}} \end{aligned}\right\} \tag{6}$$

where $(u_1)_0$, $(\tau_{12})_0$, (τ_{13}), which are the values of u_1, τ_{12}, τ_{13} at $t=0$, may depend on (y_2, y_3) the time t being measured from the instant at which (1)—(5) become valid for the system. If $(\tau_{12})_0$ has a value less than τ_∞ near the fault, we find that τ_{12} increases steadily with time near the fault, and ultimately $\rightarrow \tau_\infty$ as $t \rightarrow \infty$. Thus, if the characteristics of the fault be such that fault creep would commence when τ_{12} reaches a critical value τ_c near the fault, where $\tau_c > \tau_\infty$, then fault creep would commence after a finite time.

4. *Displacements and stresses after the commencement of fault creep:*

After the commencement of slow aseismic fault creep, the relations (1)—(5) are still satisfied. But there is now a time-dependent slow creeping relative displacement across *F*, which changes with time as long as the fault creep continues. We now measure the time *t* from the instant of commencement of fault creep, and take the boundary condition across *F* to be

$$[u_1]=f(y_3)\,U(t) \tag{7}$$

across $F(y_2=0,\ d \leqslant y_3 \leqslant D)$

where $[u_1] = \underset{y_2 \to 0+0}{\lambda t}(u_1) - \underset{y_2 \to 0-0}{\lambda t}(u_1)$

We take τ_{12}, τ_{13} to remain continuous across F, since the materials on opposite sides of F remain pressed together during creep. The velocity of creep across the fault is given by

$$\frac{\partial}{\partial t}[u_1]=f(y_3)v(t) \qquad [d \leqslant y_3 \leqslant D]$$

where $\qquad V(t)=U'(t)$.

To obtain the displacements and stresses we proceed as in Pal et. al. (1980a). We take Laplace transform of (1)—(5) and (7) with respect to t. The resulting boundary value problem for $\bar{u}^1, \bar{\tau}_{12}, \bar{\tau}_{13}$ is solved by using the Green's Function technique discussed in Maruyama (1966) and Pal et. al. (1980a). Finally, on inverting the Laplace transform, we obtain $u_1, \tau_{12}, \tau_{13}$. The solution is obtained in a relatively simple form if the creep velocity is constant across the fault, i.e.,

$$[u_1]=V.\,t$$

across $F[y_2=0,\ d \leqslant y_3 \leqslant D]$

where V is the constant creep velocity.

We obtain. in this case,

$$\left.\begin{aligned} u_1 &= (u_1)_0+\frac{\tau_\infty\, y_2 t}{\eta}+\frac{vt}{2\pi}\,\phi_1(y_2, y_3) \\ \tau_{12} &= (\tau_{12})_0 e^{-\frac{\mu t}{\eta}}+\tau_\infty\left(1-e^{-\frac{\mu t}{\eta}}\right) \\ &\quad -\frac{\eta V}{2\pi}\left(1-e^{-\frac{\mu t}{\eta}}\right)\phi_2(y_2, y_3) \\ \text{and}\quad \tau_{13} &= (\tau_{13})_0 e^{-\frac{\mu t}{\eta}}-\frac{\eta V}{2\pi}\left(1-e^{-\frac{\mu t}{\eta}}\right)\phi_3(y_2, y_3) \end{aligned}\right\} \tag{8}$$

where

$$\left.\begin{aligned} \phi_1(y_2, y_3) &= \tan^{-1}\left(\frac{D+y_3}{y_2}\right)+\tan^{-1}\left(\frac{D-y_3}{y_2}\right) \\ &\quad -\tan^{-1}\left(\frac{d-y_3}{y_2}\right)-\tan^{-1}\left(\frac{d+y_3}{y_2}\right) \\ \phi_2(y_2, y_3) &= \frac{D+y_3}{(D+y_3)^2+y_2^2}+\frac{D-y_3}{(D-y_3)^2+y_2^2} \\ &\quad -\frac{d+y_3}{(d+y_3)^2+y_2^2}-\frac{d-y_3}{(d-y_3)^2+y_2^2} \\ \text{and}\quad \phi_3(y_2, y_3) &= \frac{1}{(D-y_3)^2+y_2^2}-\frac{1}{(D+y_3)^2+y_2^2} \\ &\quad -\frac{1}{(d-y_3)^2+y_2^2}+\frac{1}{(d+y_3)^2+y_2^2}. \end{aligned}\right\} \tag{9}$$

We note that, near the fault F, $(y_2 \simeq 0,\ d \angle y_3 \angle D)$, we have

$$\phi_2 \simeq \frac{2d}{d^2-y_3^2}-\frac{2D}{D^2-y_3^2}<0.$$

We note that the last three terms in (8) in the expression for ϕ_2, represent the effect of fault creep. Since $\phi_2<0$ near the fault, and V 0 fault creep, we conclude that the fault creep results in a slow aseismic release of shear strees near the fault, and this release is greater for larger values of V. The aseismic release of shear stress near the fault would be expected to reduce the possibility of the stress accumulation reaching sufficiently large values to cause a sudden large fault movement, generating a major earthquake. This conclusion is consistent with the observed phenomenon that steadily creeping parts of strike-slip faults do not appear to generate major earthquakes.

We also note from (8), that the rate of accumulation of the shear strain $e_{12}=\frac{2u_1}{2y_2}$ on the surface near the fault ($y_3=0$, $y_2\simeq 0$) is given by

$$\frac{\tau_\infty}{\eta}-\frac{V}{2\pi}\left(\frac{1}{d}-\frac{1}{D}\right).$$

Hence the fault creep ($V>0$) reduces the rate of accumulation of shear strain on the surface near the fault, and for a suitable value of V, there is no accumulation of surface shear strain. This is in qualitative agreement with observation near creeping strike-slip faults, where the rate of accumulation of surface shear strain has been generally found to be much smaller, compared to active strike-slip faults which are locked. In particular, the rate of accumulation of surface shear strain near the creeping central part of the San Andreas fault has been found to be much less than the corresponding rate near the locked northern and southern parts of the same fault, as reported by Turcotte et. al. (1976) and others.

5. *Acknowledgement* : The author thanks Prof. Arabinda Mukhopadhyay, Department of Applied Mathematics, University of Calcutta, for his kind help in the preparation of the paper,

REFERENCES

1. Budiansky, B. and Amazigo, J. C. (1976) : J. Geophys. Res. *81*, 4897-4900.

2. Maruyama, T. (1966) : Bull. Earthquake Res. Inst, Tokyo Univ., *44*, 811-871.

3. Mukherji, P. and Mukhopadhyay, A. (1978) : Proceedings of the Sixth International Symposium on Earthquake Engineering, Roorkee, Vol. 1, pp. 71-76.

4. Mukherji, P. and Mukhopadhyay, A. (1979) : Indian Journal of Meteorology and Geophysics (Mausam), Vol. 30, pp. 347-352.

5. Nur, A. and Mavko, G. (1974) : Science, Vol. 183, pp. 204-206.

6. Pal, B. P., Sen, S, and Mukhopadhyay, A. (1980a) : Bulletin of the Society of Earthquake Technology, Vol. 17, pp. 1-10.

7. Pal, B.P., Sen, S., Mukherji, P., and Mukhopadhyay, A. (1980b) : Bulletin of the Society of Earthquake Technology, Vol. 17, pp. 29-38.

8. Spence, D. A. and Turcotte, D. L. (1979) : Proc. Roy. Soc. Lond., A, *365*, 121-144.

9. Spence., D. A. and Turcotee, D. L. (1976) : Proc. Roy. Soc. Lond., A, *349*. 319-341.