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RESEARCH ARTICLE

A FINITE RECTANGULAR STRIKE SLIP FAULT IN A LINEAR VISCOELASTIC HALF SPACE CREEPING UNDER TECTONIC FORCES

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ABSTRACT

Stress accumulation during the aseismic period in a seismically active regions becomes a subject of research during the last few decades. Mathematical modelling has been formulated to study the nature of stress accumulation during this quasi static aseismic period. In the present case a rectangular strike slip fault of finite length has been taken to be situated in a linearly viscoelastic half space representing the Lithosphere-Asthenosphere system. The model consist of the properties of both the Maxwell and the Kelvin (Voigt) type material. Analytical expressions for displacement, stresses and strain have been formulated and computational work with suitable model parameters have been carried out. A details study of these expressions may be useful in formulating an effective earthquake prediction programme.

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INTRODUCTION

Occurrence of earthquake is a cyclic phenomena, two major seismic events are usually separated by a comparatively long aseismic periods of the order of few decades or so. To understand the mechanism of earthquake process it is necessary to develop mathematical models to study the small ground deformation observed during the aseismic periods in seismically active regions. Modelling of aseismic ground deformation were carried out by a number of seismologist including Maruyama, (1964, 1966), Rybicki, (1971), Sato, (1972), Rosen and Singh (1973), Iwasaki and Sato (1979), Mukhopadhyay et al. (1979a), Mukhopadhyay, A. et al. (1979b), Mukhopadhyay, A., S. Sen and Paul , B.P. (1980a), Mukhopadhyay, Sen and Paul, (1980b), Ghosh, Mukhopadhyay and Sen (1992), Segal (2010) did a wonderful work in analyzing the displacement, stress and strain in the layered medium. In the earlier works in most of the cases elastic or viscoelastic half space or layered medium were considered to represent the lithosphere-asthenosphere system. Observations in seismically active regions suggest that linear viscoelastic material of Maxwell and or Kelvin type may be a suitable representation of the system. In many cases faults are taken to be too long compare to its depth so that the problem reduce to a 2D model. However there may be faults which are not so long. In view of these we consider a strike slip fault of finite length situated in a linear viscoelastic solid combining both the properties of Maxwell and Kelvin type material. The system is under the action of tectonic forces generated due to mantle convection or similar other processes.

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Formulation

We consider a strike-slip fault F of length 2L (L- finite) and width D situated in a linearly viscoelastic half space. A Cartesian co-ordinate system is used with the midpoint O of the fault as the origin, the strike of the fault along the Y_1 axis,

Y_2 axis perpendicular to the fault and Y_3 axis pointing downwards so that the fault is given by $F: (-L \leq y_1 \leq L,\ y_2 = 0, 0 \leq y_3 \leq D)$.

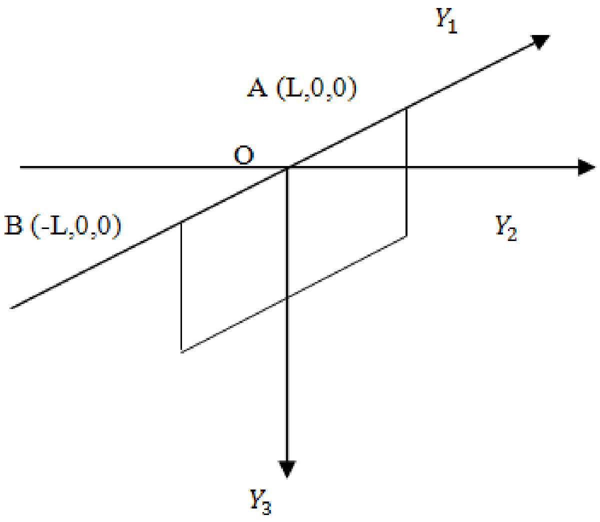


Fig. 1. The fault and the co-ordinate axes

Constitutive equations (stress-strain relations)

For the linear viscoelastic type medium combining both the properties of Maxwell and Kelvin(Voigt) type materials the constitutive equations have been taken as:

$$\tau_{11} + \frac{\eta}{\mu}\frac{\partial}{\partial t}(\tau_{11}) = \mu\frac{\partial u}{\partial y_1} + 2\eta\frac{\partial}{\partial t}\left(\frac{\partial u}{\partial y_1}\right) \qquad (1.1)$$

$$\tau_{12} + \frac{\eta}{\mu}\frac{\partial}{\partial t}(\tau_{12}) = \mu\frac{1}{2}\left(\frac{\partial u}{\partial y_2} + \frac{\partial v}{\partial y_1}\right) + 2\eta\frac{\partial}{\partial t}\frac{1}{2}\left(\frac{\partial u}{\partial y_2} + \frac{\partial v}{\partial y_1}\right) \qquad (1.2)$$

$$\tau_{13} + \frac{\eta}{\mu}\frac{\partial}{\partial t}(\tau_{13}) = \mu\frac{1}{2}\left(\frac{\partial u}{\partial y_3} + \frac{\partial w}{\partial y_1}\right) + 2\eta\frac{\partial}{\partial t}\frac{1}{2}\left(\frac{\partial u}{\partial y_3} + \frac{\partial w}{\partial y_1}\right) \qquad (1.3)$$

$$\tau_{22} + \frac{\eta}{\mu}\frac{\partial}{\partial t}(\tau_{22}) = \mu\frac{\partial v}{\partial y_2} + 2\eta\frac{\partial}{\partial t}\left(\frac{\partial v}{\partial y_2}\right) \qquad (1.4)$$

$$\tau_{23} + \frac{\eta}{\mu}\frac{\partial}{\partial t}(\tau_{23}) = \mu\frac{1}{2}\left(\frac{\partial v}{\partial y_3} + \frac{\partial w}{\partial y_2}\right) + 2\eta\frac{\partial}{\partial t}\frac{1}{2}\left(\frac{\partial v}{\partial y_3} + \frac{\partial w}{\partial y_2}\right) \qquad (1.5)$$

$$\tau_{33} + \frac{\eta}{\mu}\frac{\partial}{\partial t}(\tau_{33}) = \mu\frac{\partial w}{\partial y_3} + 2\eta\frac{\partial}{\partial t}\left(\frac{\partial w}{\partial y_3}\right) \qquad (1.6)$$

where η is the effective viscosity and μ is the effective rigidity of the material.

Stress equation of motion

The stresses satisfy the following equations (assuming quasistatic deformation for which the inertia terms are neglected) and body forces does not change during our consideration.

$$\frac{\partial}{\partial y_1}(\tau_{11}) + \frac{\partial}{\partial y_2}(\tau_{12}) + \frac{\partial}{\partial y_3}(\tau_{13}) = 0 \qquad (2.1)$$

$$\frac{\partial}{\partial y_1}(\tau_{21}) + \frac{\partial}{\partial y_2}(\tau_{22}) + \frac{\partial}{\partial y_3}(\tau_{23}) = 0 \qquad (2.2)$$

$$\frac{\partial}{\partial y_1}(\tau_{31}) + \frac{\partial}{\partial y_2}(\tau_{32}) + \frac{\partial}{\partial y_3}(\tau_{33}) = 0 \qquad (2.3)$$

Where, $(-\infty < y_1 < \infty, -\infty < y_2 < \infty,\ y_3 \geq 0,\ t \geq 0)$

Boundary conditions

The boundary conditions are taken as, with t=0 representing an instant when the medium is in aseismic state:

$$\lim_{y_1 \to L-} \tau_{11}(y_1, y_2, y_3, t) = \lim_{y_1 \to L+} \tau_{11}(y_1, y_2, y_3, t) = \tau_L\ (say),$$
$$y_2 = 0, 0 \leq y_3 \leq D, t \geq 0 \qquad (3.1)$$

$$\lim_{y_1 \to -L-} \tau_{11}(y_1, y_2, y_3, t) = \lim_{y_1 \to -L+} \tau_{11}(y_1, y_2, y_3, t) = \tau_L\ (say),$$
$$y_2 = 0, 0 \leq y_3 \leq D, t \geq 0 \qquad (3.2)$$

Assuming that the stresses maintaining a constant value $\tau_L$at the tip of the fault along Y_1axis (the value of this constant stress is likely to be small enough so that no further extension is responsible along the Y_1axis).

$$\tau_{12}(y_1, y_2, y_3, t) \to \tau_\infty\ as\ |y_2| \to \infty,$$
$$-\infty \leq y_1 \leq \infty, y_3 \geq 0, t \geq 0 \qquad (3.3)$$

On the free surface

$$y_3 = 0, (-\infty \leq y_1, y_2 \leq \infty, \quad t \geq 0)$$

$$\tau_{13}(y_1, y_2, y_3, t) = 0 \qquad (3.4)$$

$$\tau_{23}(y_1, y_2, y_3, t) = 0 \qquad (3.5)$$

$$\tau_{33}(y_1, y_2, y_3, t) = 0 \qquad (3.6)$$

Also as $y_3 \to \infty, (-\infty \leq y_1, y_2 \leq \infty,\ t \geq 0)$

$$\tau_{13}(y_1, y_2, y_3, t) = 0 \qquad (3.7)$$

$$\tau_{23}(y_1, y_2, y_3, t) = 0 \qquad (3.8)$$

$$\tau_{33}(y_1, y_2, y_3, t) = 0 \qquad (3.9)$$

$$\tau_{22}(y_1, y_2, y_3, t) = 0, \quad as\ |y_2| \to \infty,$$

$$-\infty \leq y_1 \leq \infty, y_3 \geq 0, t \geq 0 \qquad (3.10)$$

(where $\tau_\infty(t)$ is the shear stress maintained by mantle convection and other tectonic phenomena far away from the fault).

Initial conditions

Let $(u)_0, (v)_0, (w)_0, (\tau_{ij})_0, (e_{ij})_0$ $i,j = 1,2,3$ are the values of u, v, w, τ_{ij}, e_{ij} respectively at time t=0. They are functions of y_1, y_2, y_3 and satisfy the relations (1.1) to (3.10).

Displacements, Stresses and Strains in the absence of any fault movement

In the absence of any fault movement the displacement and stresses are continuous throughout the model. In order to obtain the expressions for displacement, strain and stresses we take Laplace transform of (1.1) to (3.10) with respect to t. The resulting boundary value problem can be solved by taking integral transforms of the constitutive equations and the boundary conditions with respect to t. The solutions obtained are given below. (as shown in Appendix)

$$\left.\begin{aligned}
&u(y_1,y_2,y_3,t) = (u)_0 e^{-\frac{\mu t}{2\eta}} \\
&\quad + y_1\left[\tau_L\left(\frac{1}{\mu} - \frac{1}{2\mu}e^{-\frac{\mu t}{2\eta}}\right) - \frac{(\tau_{11})_0}{2\mu}e^{-\frac{\mu t}{2\eta}} + \frac{y_2\tau_\infty}{\mu}\left(1 - e^{-\frac{\mu t}{2\eta}}\right)\right] \\
&v(y_1,y_2,y_3,t) = (v)_0 e^{-\frac{\mu t}{2\eta}} + \frac{y_1\tau_\infty}{\mu}\left(1 - e^{-\frac{\mu t}{2\eta}}\right) \\
&w(y_1,y_2,y_3,t) = (w)_0 e^{-\frac{\mu t}{2\eta}} \\
&\tau_{11}(y_1,y_2,y_3,t) = (\tau_{11})_0 e^{-\frac{\mu t}{\eta}} + \tau_L\left(1 - e^{-\frac{\mu t}{\eta}}\right) \\
&\tau_{12}(y_1,y_2,y_3,t) = (\tau_{12})_0 e^{-\frac{\mu t}{\eta}} + \tau_\infty\left(1 - e^{-\frac{\mu t}{\eta}}\right) \\
&\tau_{13}(y_1,y_2,y_3,t) = (\tau_{13})_0 e^{-\frac{\mu t}{\eta}} \\
&\tau_{22}(y_1,y_2,y_3,t) = (\tau_{22})_0 e^{-\frac{\mu t}{\eta}} \\
&\tau_{23}(y_1,y_2,y_3,t) = (\tau_{23})_0 e^{-\frac{\mu t}{\eta}} \\
&\tau_{33}(y_1,y_2,y_3,t) = (\tau_{33})_0 e^{-\frac{\mu t}{\eta}}
\end{aligned}\right\} \quad (4)$$

From the above expressions we find that as $t \to \infty$, $\tau_{11} \to \tau_L, \tau_{12} \to \tau_\infty$ and all the others stress components $\tau_{13}, \tau_{22}, \tau_{23}, \tau_{33} \to 0$. However the rheological behaviour of the material near the fault F are assumed to be capable of withstanding stress of magnitude τ_c, called critical value of the stress where τ_c is less than τ_∞. We assume that when the accumulated stress τ_{12} near the fault exceeds this critical level after a time, T, say, a creeping movement across F sets in, and thereby releasing the accumulated stress to a value less than τ_c. The magnitude of creep is expected to satisfy the following conditions:

(C1) Its value will be maximum near the middle of the fault on the free surface.

(C2) It will gradually decrease to zero at the tips of the fault ($y_1 = \pm L,\ y_2 = 0, 0 \le y_3 \le D$) along its length.

(C3) The magnitude of the creep will decrease with y_3 as we move downwards and ultimately tends to zero near the lower edge of the fault. ($y_1 = \pm L,\ y_2 = 0,\ y_3 = D$)

If $f(y_1, y_3)$ be the creep function, it should satisfy the above conditions. If we assume $(\tau_{12})_0$=20 bar, τ_c=150 bar, it is found that τ_{12} reaches the value τ_c in about 59 years (T=59 years). In our subsequent discussions we shall take T to be 59 years. The relevant boundary value problem after commencement of the creeping movement across F , $t \ge T$ has been described in Appendix.

Displacements, Stresses and Strains after the commencement of the fault creep

We assume that after a time T, the stress component τ_{12} which is the main driving force for the strike-slip motion of the fault, exceeds the critical value τ_c and the fault starts creeping characterized by a dislocation across the fault as discussed in Appendix. We solved the resulting boundary value problem by modified Green's function method following Maruyama, (1964, 1966), Rybicki, (1971) and correspondence principle (as shown in Appendix) and get the solutions for displacements, strain and stresses as given in the following equation (5).

$$\begin{aligned}
&u(y_1,y_2,y_3,t) = (u)_0 e^{-\frac{\mu t}{2\eta}} \\
&\quad + y_1\left[\tau_L\left(\frac{1}{\mu} - \frac{1}{2\mu}e^{-\frac{\mu t}{2\eta}}\right) - \frac{(\tau_{11})_0}{2\mu}e^{-\frac{\mu t}{2\eta}} + \frac{y_2\tau_\infty}{\mu}\left(1 - e^{-\frac{\mu t}{2\eta}}\right)\right] \\
&\quad + \frac{U(t-T)}{2\pi}H(t-T)\varphi_1(y_1,y_2,y_3) \\
&v(y_1,y_2,y_3,t) = (v)_0 e^{-\frac{\mu t}{2\eta}} + \frac{y_1\tau_\infty}{\mu}\left(1 - e^{-\frac{\mu t}{2\eta}}\right) \\
&w(y_1,y_2,y_3,t) = (w)_0 e^{-\frac{\mu t}{2\eta}} \\
&\tau_{11}(y_1,y_2,y_3,t) = (\tau_{11})_0 e^{-\frac{\mu t}{\eta}} + \tau_L\left(1 - e^{-\frac{\mu t}{\eta}}\right) \\
&\quad + \frac{\mu}{2\pi}H(t-T)\psi_1(y_1,y_2,y_3)\left[\int_0^{t-T} v_1(\tau)d\tau + \int_0^{t-T} v_1(\tau)e^{-\frac{\mu(t-T-\tau)}{\eta}}d\tau\right] \\
&\tau_{12}(y_1,y_2,y_3,t) = (\tau_{12})_0 e^{-\frac{\mu t}{\eta}} + \tau_\infty\left(1 - e^{-\frac{\mu t}{\eta}}\right) \\
&\quad + \frac{\mu}{2\pi}H(t-T)\psi_2(y_1,y_2,y_3)\left[\int_0^{t-T} v_1(\tau)d\tau + \int_0^{t-T} v_1(\tau)e^{-\frac{\mu(t-T-\tau)}{\eta}}d\tau\right] \\
&\tau_{13}(y_1,y_2,y_3,t) = (\tau_{13})_0 e^{-\frac{\mu t}{\eta}} \\
&\quad + \frac{\mu}{2\pi}H(t-T)\psi_3(y_1,y_2,y_3)
\end{aligned}$$

$$\left[\int_0^{t-T} v_1(\tau)d\tau + \int_0^{t-T} v_1(\tau)e^{-\frac{\mu(t-T-\tau)}{\eta}}d\tau\right]$$

$$\tau_{22}(y_1,y_2,y_3,t) = (\tau_{22})_0 e^{-\frac{\mu t}{\eta}}$$

$$\tau_{23}(y_1,y_2,y_3,t) = (\tau_{23})_0 e^{-\frac{\mu t}{\eta}}$$

$$\tau_{33}(y_1,y_2,y_3,t) = (\tau_{33})_0 e^{-\frac{\mu t}{\eta}}$$

$$e_{11}(y_1,y_2,y_3,t) = (e_{11})_0 e^{-\frac{\mu t}{2\eta}} + \left[\tau_L\left(\frac{1}{\mu} - \frac{1}{2\mu}e^{-\frac{\mu t}{2\eta}}\right) - \frac{(\tau_{11})_0}{2\mu}e^{-\frac{\mu t}{2\eta}}\right] + \frac{U(t-T)}{2\pi}H(t-T)\psi_1(y_1,y_2,y_3)$$

$$e_{12}(y_1,y_2,y_3,t) = (e_{12})_0 e^{-\frac{\mu t}{2\eta}} + \frac{\tau_\infty}{\mu}\left(1 - e^{-\frac{\mu t}{2\eta}}\right) + \frac{U(t-T)}{4\pi}H(t-T)\psi_2(y_1,y_2,y_3) \quad (5)$$

Where,

$$\varphi_1(y_1,y_2,y_3) = \int_{-L}^{L}\int_0^D f(x_1,x_3)\left[\frac{y_2}{\{(y_1-x_1)^2+y_2^2+(y_3-x_3)^2\}^{3/2}} - \frac{y_2}{\{(y_1+x_1)^2+y_2^2+(y_3-x_3)^2\}^{3/2}}\right]dx_3dx_1$$

$$\psi_1(y_1,y_2,y_3) = \int_{-L}^{L}\int_0^D 3.f(x_1,x_3)\left[\frac{y_2(y_1+x_1)}{\{(y_1+x_1)^2+y_2^2+(y_3-x_3)^2\}^{5/2}} - \frac{y_2(y_1-x_1)}{\{(y_1-x_1)^2+y_2^2+(y_3-x_3)^2\}^{5/2}}\right]dx_3dx_1$$

$$\psi_2(y_1,y_2,y_3) = \int_{-L}^{L}\int_0^D f(x_1,x_3)\left[\frac{(y_1-x_1)^2+(y_3-x_3)^2-2y_2^2}{\{(y_1-x_1)^2+y_2^2+(y_3-x_3)^2\}^{5/2}} - \frac{(y_1+x_1)^2+(y_3-x_3)^2-2y_2^2}{\{(y_1+x_1)^2+y_2^2+(y_3-x_3)^2\}^{5/2}}\right]dx_3dx_1$$

$$\psi_3(y_1,y_2,y_3) = \int_{-L}^{L}\int_0^D 3.f(x_1,x_3)\left[\frac{y_2(y_3-x_3)}{\{(y_1+x_1)^2+y_2^2+(y_3-x_3)^2\}^{5/2}} - \frac{y_2(y_3-x_3)}{\{(y_1-x_1)^2+y_2^2+(y_3-x_3)^2\}^{5/2}}\right]dx_3dx_1$$

Numerical computations

Following Catlhes, (1975) Aki, Richards, (1980) and the recent studies on rheological behaviour of crust and upper mantle by Chift, Lin, Barcktiausen, (2002), Karato, (2010) the values to the model parameters are taken as:

We consider $f(x_1,x_3)$ to be

$$f(x_1,x_3) = \left(1 - \frac{x_1^2}{L^2}\right)\left(1 - \frac{3x_3^2}{D^2} + \frac{3x_3^3}{D^3}\right)\left(\frac{D-x_3}{D}\right)$$

which satisfies all the conditions (C1) to (C3) stated above.

$\mu = 3.5 \times 10^{11}$ dyne/sq. cm.,
$\eta = 5 \times 10^{20}$ poise
D = Depth of the fault = 10 km. (noting that the depth of the major earthquake faults are in between 10-15 km.)
2L = Length of the fault = 40 km.,

$t_1 = t - T$
$\tau_\infty = 200$ bar , $(\tau_{11})_0 = 20$ bar
$(\tau_{12})_0 = 20$ bar, $(\tau_{13})_0 = 20$ bar

We assume, $U(t_1) = V.t_1$ where

$$\frac{d}{dt_1}(U(t_1)) = V,$$

The velocity of creep assume to be constant. In our model we take v = 0 cm/year, 1 cm/year, 3 cm/year, 6 cm/year, 10 cm/year.

$\tau_c = 150\ bar$, with this value of τ_c we find that T, the time of commencement of fault creep is approximately 58.026 years.

We compute the following quantities:

$$u(y_1,y_2,y_3,t) - (u)_0 e^{-\frac{\mu t}{2\eta}} = y_1\left[\tau_L\left(\frac{1}{\mu} - \frac{1}{2\mu}e^{-\frac{\mu t}{2\eta}}\right) - \frac{(\tau_{11})_0}{2\mu}e^{-\frac{\mu t}{2\eta}} + \frac{y_2\tau_\infty}{\mu}\left(1 - e^{-\frac{\mu t}{2\eta}}\right)\right] + \frac{U(t-T)}{2\pi}H(t-T)\varphi_1(y_1,y_2,y_3)$$

$$e_{12}(y_1,y_2,y_3,t) - (e_{12})_0 e^{-\frac{\mu t}{2\eta}} = \frac{\tau_\infty}{\mu}\left(1 - e^{-\frac{\mu t}{2\eta}}\right) + \frac{U(t-T)}{4\pi}H(t-T)\psi_2(y_1,y_2,y_3)$$

$$\tau_{11}(y_1,y_2,y_3,t) = (\tau_{11})_0 e^{-\frac{\mu t}{\eta}} + \tau_L\left(1 - e^{-\frac{\mu t}{\eta}}\right) + \frac{\mu}{2\pi}H(t-T)\psi_1(y_1,y_2,y_3)\left[\int_0^{t-T} v_1(\tau)d\tau + \int_0^{t-T} v_1(\tau)e^{-\frac{\mu(t-T-\tau)}{\eta}}d\tau\right]$$

$$\tau_{12}(y_1,y_2,y_3,t) = (\tau_{12})_0 e^{-\frac{\mu t}{\eta}} + \tau_\infty\left(1 - e^{-\frac{\mu t}{\eta}}\right) + \frac{\mu}{2\pi}H(t-T)\psi_2(y_1,y_2,y_3)\left[\int_0^{t-T} v_1(\tau)d\tau + \int_0^{t-T} v_1(\tau)e^{-\frac{\mu(t-T-\tau)}{\eta}}d\tau\right]$$

$$\tau_{13}(y_1,y_2,y_3,t) = (\tau_{13})_0 e^{-\frac{\mu t}{\eta}} + \frac{\mu}{2\pi}H(t-T)\psi_3(y_1,y_2,y_3)\left[\int_0^{t-T} v_1(\tau)d\tau + \int_0^{t-T} v_1(\tau)e^{-\frac{\mu(t-T-\tau)}{\eta}}d\tau\right]$$

RESULTS AND DISCUSSION

Displacement on the free surface due to the creeping movement across the fault

Fig. 2 shows the displacement component u on the free surface within the region $-25\ km. \leq y_1 \leq 25\ km.$ and $-10\ km. \leq y_1 \leq 10\ km.$ The positive values of u has been marked by blue colour while the negative value of u has been marked red. From the figure it appears that the positive and negative displacement components have a nature similar to a quadrennial distribution as observed in seismically active regions during an earthquake.

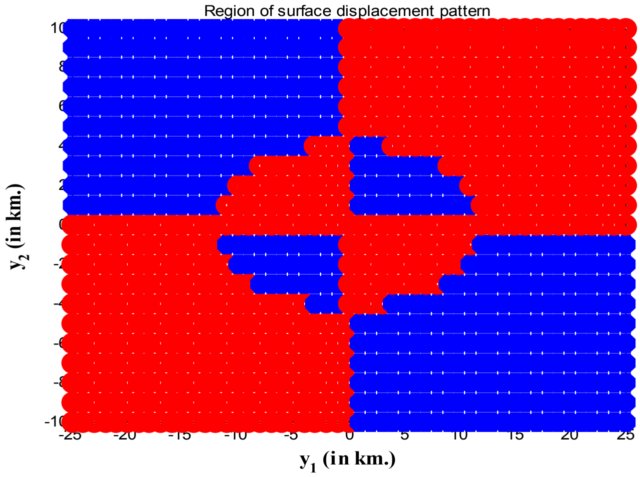


Figure 2. Displacement on the free surface due to the creeping movement across the fault

In Fig. 3 a contour diagram for the displacement component has been shown.

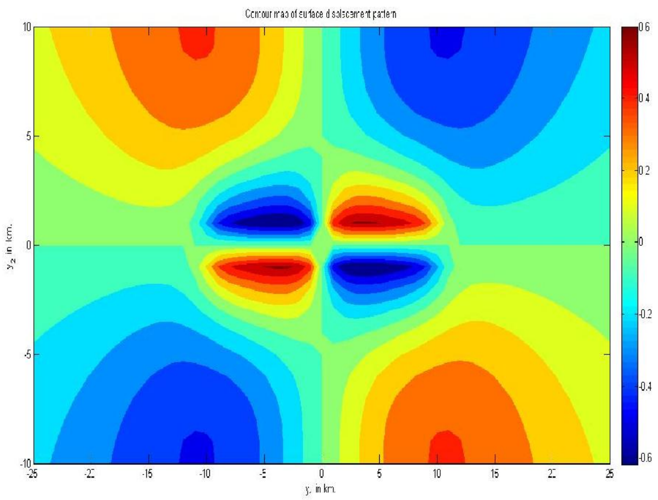


Figure 3. Contour diagram for displacement on the free surface due to the creeping movement across the fault

Surface share strain under the action of tectonic forces in the absence of fault movement

In Fig. 4 the accumulation of surface share strain under the action of τ_∞ against time has been plotted. We find that share strain e_{12} increases slowly and attain a value of about 2×10^{-4} on the average before the commencement of the fault movement which is inconformity with the observational value during the aseismic period. The magnitude of the share strain e_{12} due to the creeping movement across the fault has been found to be of the order of 10^{-7}/year.

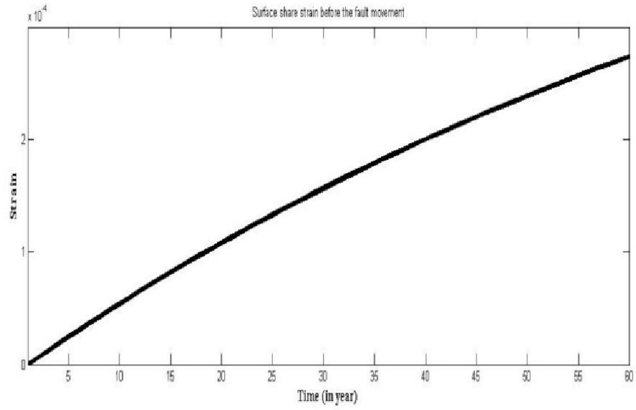


Figure 4. Surface share strain under the action of tectonic forces in the absence of fault movement

Pattern of stress accumulation/release due to movement of the fault-Normal stress τ_{11}

From Fig. 5 the stress component is found to be slowly decreasing from its initial value and tend to zero with time if there be no creep across the fault. But a creeping movement across the fault causes a further reduction in the stress component after time T. The magnitude of reduction depends upon the velocity of creep with increasing v the stress decreases further and ultimately becomes negative. For example, when v = 1 cm/year the stress become negative about 36 years after T and when v = 10 cm/year the stress become negative only after 7 years from the commence the creeping movement across the fault.

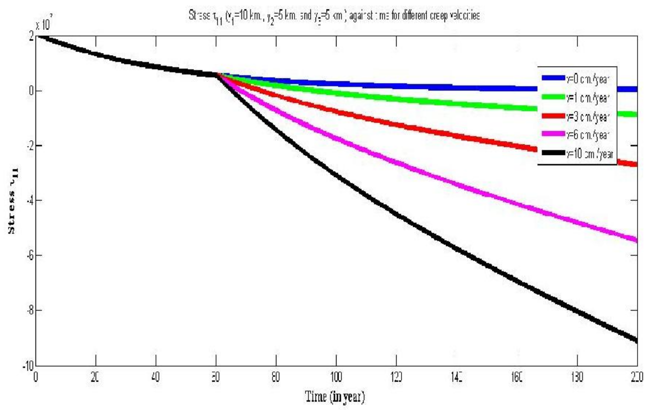


Figure 5. Pattern of stress accumulation/ release due to movement of the fault-Normal stress τ_{11}

Pattern of stress accumulation/release due to movement of the fault-Share stress τ_{13}:

From Fig. 6 we find that the share stress τ_{13} has a similar feature to that of τ_{11}. The stress decreases with time and ultimately becomes negative. But here the rate of decrease is considerably smaller compare to τ_{11}. For example, v = 1 cm/year the time taken for the stress becomes negative is approximately 116 years after T.

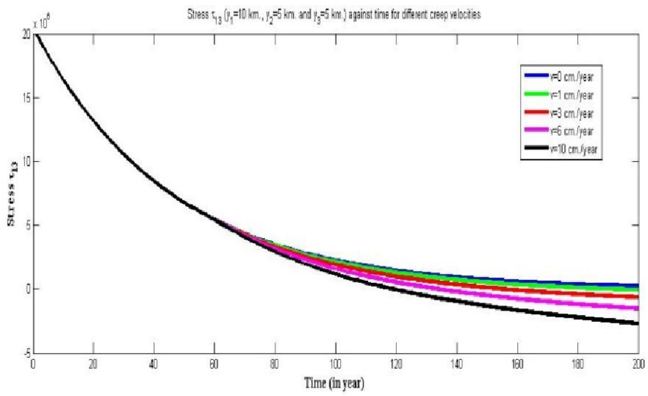
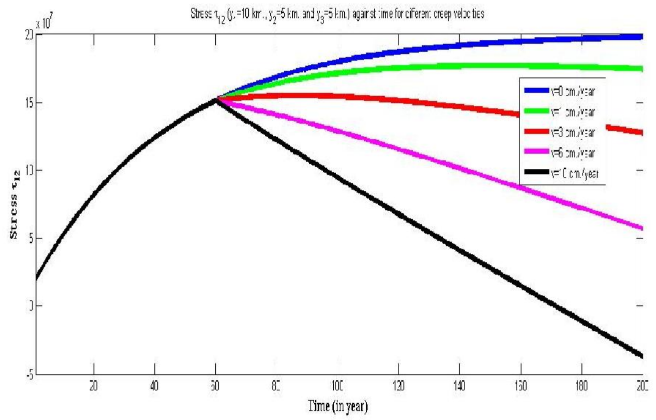


Figure 6. Pattern of stress accumulation/ release due to movement of the fault-Share stress τ_{13}

Pattern of stress accumulation/release due to movement of the fault-Share stress τ_{12}

From Fig. 7 we find that the nature of shear stress τ_{12} is different from that of τ_{11} and τ_{13}. The stress starts increasing from its initial value 150 bars at time T = 59 years. The creeping movement across the fault decreases the rate of increase further. With v = 1 cm/year it becomes 171.2 bar at t = 100 years. As v increases the rate decreases further. For example, v = 3 cm/year, the stress becomes 154.2 bar at t = 100 years. The stress get released with further increase in v for example v = 6 cm/year the stress becomes 128.6 bar at t = 100 years.



Figurr 7. Pattern of stress accumulation/ release due to movement of the fault-Share stress τ_{12}

Appendix-A

Displacements, stresses, and strains before the commencement of the fault creep

We take Laplace Transform of all constitutive equations and boundary conditions

$$\overline{\tau_{11}} = \frac{\frac{\partial \bar{u}}{\partial y_1}(\mu + 2\eta p)}{\left(1 + \frac{\eta p}{\mu}\right)} + \frac{\frac{\eta}{\mu}(\tau_{11})_0}{\left(1 + \frac{\eta p}{\mu}\right)} - \frac{2\eta\left(\frac{\partial \mathrm{u}}{\partial y_1}\right)_0}{\left(1 + \frac{\eta p}{\mu}\right)} \quad (A1)$$

where $\overline{\tau_{11}} = \int_0^\infty \tau_{11} e^{-pt}\,dt$, (p > 0) being the Laplace transform variable and similar other equations.

Also the stress equation of motion in Laplace transform domain as:

$$\frac{\partial}{\partial y_1}(\overline{\tau_{11}}) + \frac{\partial}{\partial y_2}(\overline{\tau_{12}}) + \frac{\partial}{\partial y_3}(\overline{\tau_{13}}) = 0 \quad (A2)$$

$$\frac{\partial}{\partial y_1}(\overline{\tau_{21}}) + \frac{\partial}{\partial y_2}(\overline{\tau_{22}}) + \frac{\partial}{\partial y_3}(\overline{\tau_{23}}) = 0 \quad (A3)$$

$$\frac{\partial}{\partial y_1}(\overline{\tau_{31}}) + \frac{\partial}{\partial y_2}(\overline{\tau_{32}}) + \frac{\partial}{\partial y_3}(\overline{\tau_{33}}) = 0 \quad (A4)$$

$$\lim_{y_1 \to L-} \overline{\tau_{11}}(y_1, y_2, y_3, p) = \lim_{y_1 \to L+} \overline{\tau_{11}}(y_1, y_2, y_3, p) = \tau_L\ (say),$$
$$y_2 = 0, 0 \le y_3 \le D, t \ge 0 \quad (A5)$$

$$\lim_{y_1 \to -L-} \overline{\tau_{11}}(y_1, y_2, y_3, t) = \lim_{y_1 \to -L+} \overline{\tau_{11}}(y_1, y_2, y_3, t) = \tau_L\ (say),$$
$$y_2 = 0, 0 \le y_3 \le D, t \ge 0 \quad (A6)$$

On the free surface $y_3 = 0$,

$$(-\infty \le y_1, y_2 \le \infty, \quad t \ge 0)$$
$$\overline{\tau_{12}}(y_1, y_2, y_3, p) \to \tau_\infty \ as\ |y_2| \to \infty,$$
$$-\infty \le y_1 \le \infty, y_3 \ge 0, t \ge 0 \quad (A7)$$

$$\overline{\tau_{13}}(y_1, y_2, y_3, p) = 0 \quad (A8)$$

$$\overline{\tau_{23}}(y_1, y_2, y_3, p) = 0 \quad (A9)$$

$$\overline{\tau_{33}}(y_1, y_2, y_3, p) = 0 \quad (A10)$$

Also as $y_3 \to \infty, (-\infty \le y_1, y_2 \le \infty,\ t \ge 0)$

$$\overline{\tau_{13}}(y_1, y_2, y_3, p) = 0 \quad (A11)$$

$$\overline{\tau_{23}}(y_1, y_2, y_3, p) = 0 \quad (A12)$$

$$\overline{\tau_{33}}(y_1, y_2, y_3, p) = 0 \quad (A13)$$

$$\overline{\tau_{22}}(y_1, y_2, y_3, p) = 0,$$
$$as\ |y_2| \to \infty, -\infty \le y_1 \le \infty, y_3 \ge 0, t \ge 0 \quad (A14)$$

Using (A1) and other similar equations assuming the initial fields to be zero, we get from (A2)

$$\nabla^2(\overline{U}) = 0 \quad (A15)$$

Thus we are to solve the boundary value problem (A15) with the boundary conditions (A5) to (A14)

Let,

$$\bar{u} = \frac{(u)_0}{p + \frac{\mu}{2\eta}} + A_1 y_1 + B_1 y_2 + C_1 y_3 \qquad (A16)$$

be the solution of (A15), where

$$\bar{U} = \bar{u} - \frac{(u)_0}{p + \frac{\mu}{2\eta}}$$

Using the boundary conditions (A5) and (A14) and the initial conditions we get,

$$A_1 = \frac{\tau_L}{p} \frac{\left(p + \frac{\mu}{\eta}\right)}{2\mu\left(p + \frac{\mu}{2\eta}\right)} - \frac{(\tau_{11})_0}{2\mu\left(p + \frac{\mu}{2\eta}\right)} \qquad (A17)$$

$$B_1 = \frac{\tau_\infty}{2\eta p\left(p + \frac{\mu}{2\eta}\right)} \qquad (A18)$$

$$C_1 = 0 \qquad (A19)$$

On taking inverse Laplace transform, we get

$$\mathrm{u}(y_1, y_2, y_3, t) = (\mathrm{u})_0 \mathrm{e}^{-\frac{\mu t}{2\eta}} + \mathrm{y}_1\left[\tau_L\left(\frac{1}{\mu} - \frac{1}{2\mu}\, \mathrm{e}^{-\frac{\mu t}{2\eta}}\right) - \frac{(\tau_{11})_0}{2\mu}\mathrm{e}^{-\frac{\mu t}{2\eta}} + \frac{\mathrm{y}_2 \tau_\infty}{\mu}\left(1 - \mathrm{e}^{-\frac{\mu t}{2\eta}}\right)\right] \qquad (A20)$$

$$\mathrm{v}(y_1, y_2, y_3, t) = (\mathrm{v})_0 \mathrm{e}^{-\frac{\mu t}{2\eta}} + \frac{\mathrm{y}_1 \tau_\infty}{\mu}\left(1 - \mathrm{e}^{-\frac{\mu t}{2\eta}}\right) \qquad (A21)$$

$$\mathrm{w}(y_1, y_2, y_3, t) = (\mathrm{w})_0 \mathrm{e}^{-\frac{\mu t}{2\eta}} \qquad (A22)$$

$$\tau_{11}(y_1, y_2, y_3, t) = (\tau_{11})_0 \mathrm{e}^{-\frac{\mu t}{\eta}} + \tau_L\left(1 - \mathrm{e}^{-\frac{\mu t}{\eta}}\right) \qquad (A23)$$

$$\tau_{12}(y_1, y_2, y_3, t) = (\tau_{12})_0 \mathrm{e}^{-\frac{\mu t}{\eta}} + \tau_\infty\left(1 - \mathrm{e}^{-\frac{\mu t}{\eta}}\right) \qquad (A24)$$

$$\tau_{13}(y_1, y_2, y_3, t) = (\tau_{13})_0 \mathrm{e}^{-\frac{\mu t}{\eta}} \qquad (A25)$$

$$\tau_{22}(y_1, y_2, y_3, t) = (\tau_{22})_0 \mathrm{e}^{-\frac{\mu t}{\eta}} \qquad (A26)$$

$$\tau_{23}(y_1, y_2, y_3, t) = (\tau_{23})_0 \mathrm{e}^{-\frac{\mu t}{\eta}} \qquad (A27)$$

$$\tau_{33}(y_1, y_2, y_3, t) = (\tau_{33})_0 \mathrm{e}^{-\frac{\mu t}{\eta}} \qquad (A28)$$

Appendix-B

Displacements, stresses and strains after the commencement of the fault creep

We assume that after a time T the stress component τ_{12}, which is the main driving force for the strike-slip motion of the fault, exceeds the critical value τ_c, the fault F starts creeping then (8) to (11) and (A15) are satisfied with the following dislocation conditions of creep across F:

$$[u]_F = U(t_1) f(y_1, y_3) H(t_1) \qquad (B1)$$

where $[u]_F =$ The discontinuity in u across F, and $H(t_1)$ is Heaviside unit step function.

That is

$$[u]_F = \lim_{y_2 \to 0+0} u - \lim_{y_2 \to 0-0} u,$$

$$-L \le y_1 \le L, 0 \le y_3 \le D \qquad (B2)$$

Taking Laplace transform in (13) with respect to t_1, we get

$$[\bar{u}] = \bar{U}(p) f(y_1, y_3) \qquad (B3)$$

The fault creep commence across F after time T, we take

$[u]_F = 0$ for $t_1 \le 0$ that is $t \le T$, F is located in the region $(-L \le y_1 \le L, y_2 = 0,\ 0 \le y_3 \le D)$.

We try to find the solution as:

$$\left.\begin{aligned} u &= (u)_1 + (u)_2 \\ v &= (v)_1 + (v)_2 \\ w &= (w)_1 + (w)_2 \\ e_{12} &= (e_{12})_1 + (e_{12})_2 \\ \tau_{11} &= (\tau_{11})_1 + (\tau_{11})_2 \\ \tau_{12} &= (\tau_{12})_1 + (\tau_{12})_2 \\ \tau_{13} &= (\tau_{13})_1 + (\tau_{13})_2 \\ \tau_{22} &= (\tau_{22})_1 + (\tau_{22})_2 \\ \tau_{23} &= (\tau_{23})_1 + (\tau_{23})_2 \\ \tau_{33} &= (\tau_{33})_1 + (\tau_{33})_2 \end{aligned}\right\} \qquad (B4)$$

Where $(u)_1, (v)_1, (w)_1, (e_{12})_1, (\tau_{ij})_1$ are continuous everywhere in the model and are given by (4); i, j = 1,2,3. For the second part $(u)_2, (v)_2, (w)_2, (e_{12})_2, (\tau_{ij})_2$ are obtained by solving modified boundary value problem as stated below. We note that $(v)_2, (w)_2$ are both continuous even after the fault creep, so that $[v]_2 = 0, [w]_2 = 0$, while $[u]_2$ satisfies the dislocation condition given by (B2).

The resulting boundary value problem can now be stated as: $[u]_2$ satisfies 3D Laplace equation as: $\nabla^2(\bar{u})_2 = 0$ (B5)

Where $(\bar{u})_2$ is the Laplace transformation of $(u)_2$ with respect to t, with the modified boundary condition.

$$\overline{\tau_{12}}(y_1, y_2, y_3, p) = 0,$$
$$as\ |y_2| \to \infty, -\infty \leq y_1 \leq \infty, y_3 \geq 0 \qquad (B6)$$

And other boundary conditions are same as (A8) to (A14).

Now we solve the boundary value problem by using a modified Green's function technique developed by Maruyama, (1964, 1966), Rybicki, (1971) and the Correspondence Principle.

Let, $Q(y_1, y_2, y_3)$ is any point in the medium and $P(x_1, x_2, x_3)$ is any point on the fault, then we have

$$(\bar{u})_2(Q) = \int\int [(\bar{u})_2(P)] G(P,Q) dx_3 dx_1 \qquad (B7)$$

where the integration is taken over the fault F.

Therefore , $[(\bar{u})_2(P)] = \bar{U}(P) f(x_1, x_3)$

where G is the Green's function satisfying the above boundary value problem and

$$G(P,Q) = \mu \frac{\partial}{\partial x_2} G_1(P,Q) \qquad (B8)$$

Where

$$G_1(P,Q) =$$
$$\left[\frac{1}{\{(y_1 - x_1)^2 + (y_2 - x_2)^2 + (y_3 - x_3)^2\}^{1/2}} - \frac{1}{\{(y_1 + x_1)^2 + (y_2 - x_2)^2 + (y_3 - x_3)^2\}^{1/2}}\right]$$

Therefore,

$$G(P,Q) =$$
$$\left[\frac{(y_2 - x_2)}{\{(y_1 - x_1)^2 + (y_2 - x_2)^2 + (y_3 - x_3)^2\}^{3/2}} - \frac{(y_2 - x_2)}{\{(y_1 + x_1)^2 + (y_2 - x_2)^2 + (y_3 - x_3)^2\}^{3/2}}\right] (B9)$$

Now,

$$(\bar{u})_2(Q) = \int\int \bar{U}(P) f(x_1, x_3) \left[\frac{(y_2 - x_2)}{\{(y_1 - x_1)^2 + (y_2 - x_2)^2 + (y_3 - x_3)^2\}^{3/2}} - \frac{(y_2 - x_2)}{\{(y_1 + x_1)^2 + (y_2 - x_2)^2 + (y_3 - x_3)^2\}^{3/2}}\right] dx_3 dx_1$$
$$= \bar{U}(P) \varphi_1(y_1, y_2, y_3)\ (say)$$

Taking Inverse Laplace transformation,

$$(u)_2(Q) = \frac{U(t-T)}{2\pi} H(t-T) \varphi_1(y_1, y_2, y_3) \qquad (B10)$$

We also have,

$$(\overline{\tau_{11}})_2 = \frac{(\mu + 2\eta p)}{1 + \frac{\eta p}{\mu}} \frac{\partial(\bar{u})_2}{\partial y_1} \qquad (B11)$$

and similar other equations.

Now, taking inverse Laplace transformation we get

$$(\tau_{11})_2 = \frac{\mu}{2\pi} H(t-T) \psi_1(y_1, y_2, y_3)$$
$$\left[\int_0^{t-T} v_1(\tau) d\tau + \int_0^{t-T} v_1(\tau) e^{-\frac{\mu(t-T-\tau)}{\eta}} d\tau\right] \qquad (B12)$$

Where,

$$\psi_1(y_1, y_2, y_3) = \int_{-L}^{L}\int_0^{D} 3.f(x_1, x_3)$$
$$\left[\frac{y_2(y_1 + x_1)}{\{(y_1 + x_1)^2 + y_2^2 + (y_3 - x_3)^2\}^{5/2}} - \frac{y_2(y_1 - x_1)}{\{(y_1 - x_1)^2 + y_2^2 + (y_3 - x_3)^2\}^{5/2}}\right] dx_3 dx_1$$

Similarly the other components of the displacements, stresses and strains can be found out. These are given in (5).

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REFERENCES

Aki, K., Richards, P.G. 1980. Quantitative Seismology: Theory and Methods. W. H. Freeman., San Francisco, California.

Catlhes, L.M., III. 1975. The viscoelasticity of the Earths mantle. Princeton University Press.

Princeton, N.J., Chift, P., Lin, J. Barcktiausen, U. 2002. Marine and Petroleum Geology., 19: 951-970.

Ghosh, U., Mukhopadhyay., A. and Sen, S. 1992. On two interacting creeping vertical surface breaking strike-slip faults in a two-layered model of lithosphere. Physics of the Earth and planetary Interior., 70:119-129.

Iwasaki, T. and Sato, R. 1979. Strain field in a semi infinite medium due to an inclined rectangular fault. *Journal of the physics of the Earth*., 27: 285-314.

Karato, S.I. 2010. Rheology of the Earth's mantle. A historical review Gondwana Research., 18(1): 17-45.

Maruyama, T. 1964. Statical elastic dislocations in an infinite and semi- infinite medium. *Bull. Earthquake. Res. Inst. Tokyo Univ*., 42: 289-368.

Maruyama, T. 1966. On two dimensional dislocations in an infinite and semi-infinite medium. *Bull. Earthquake Res. Inst. Tokyo Univ*., 44(part 3): 811-871.

Mukhopadhyay, A. et al. 1979a. On stress accumulation near finite rectangular fault. *Indian Journal of Meteorology. Hydrology and Geophysics* (Mausam)., 30: 347-352.

Mukhopadhyay, A. et al. 1979b. On stress accumulation and fault slip in lithosphere. *Indian Journal of Meteorology. Hydrology and Geophysics* (Mausam)., 30: 353-358.

Mukhopadhyay, A., S. Sen and Paul, B.P. 1980a. On stress accumulation in a viscoelastic lithosphere containing a continuously slipping fault. *Bull. Soc. Earthquake Technology*., 17(1):1-10.

Mukhopadhyay, A., Sen. S. and Paul, B.P. 1980b. On stress accumulation near a continuously slipping fault in a two layered model of lithosphere. *Bull. Soc. Earthquake Technology*., 17(4): 29-38.

Rosen, M. and Singh, S.J. 1973. Quasi static strains and tilts due to faulting in a viscoelastic half space. *Bull. Seis. Soc. Am*., 63(5): 1737-1752.

Rybicki, K. 1971. The elastic residual field of a very long strike slip fault in the presence of a discontinuity. *Bull. Seis. Soc. Am*., 61: 79-92.

Sato, R. 1972. Stress drop of finite fault. *J. Phys. Earth*., 20: 397-407.

Segal, P. 2010. Earthquake and volcano deformation. Princeton University Press.

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