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TWO INTERACTING CREEPING VERTICAL RECTANGULAR STRIKE-SLIP FAULTS IN A VISCOELASTIC HALF SPACE MODEL OF THE LITHOSPHERE.

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Abstract: The process of stress accumulation near earthquake faults during the aseismic period in between two major seismic events in seismically active regions has become a subject of research during the last few decades. Earthquake fault of finite length of strike-slip nature in a viscoelastic half space representing the lithosphere-asthenosphere system has been considered here. Stresses accumulate in the region due to various tectonic processes, such as mantle convection and plate movements etc, which ultimately leads to movements across the fault. In the present paper, a three-dimensional model of the system is considered and expressions for displacements, stresses and strains in the model have been obtained using suitable mathematical techniques developed for this purpose. A detailed study of these expressions may give some ideas about the nature of stress accumulation in the system, which in turn will be helpful in formulating an effective earthquake prediction programme.

Key words: Viscoelastic half-space, Aseismic period, Stress accumulation, Mantle convection, Plate movements, Tectonic process, Earthquake prediction.

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1. Introduction:

Modeling of dynamic processes leading to an earthquake is one of the main concerns of seismologist. Two consecutive seismic events in a seismically active region are usually separated by a long aseismic period during which slow and continuous aseismic surface movements are observed with the help of sophisticated measuring instruments. Such aseismic surface movements indicate that slow aseismic change of stress and strain are occurring in the region which may eventually lead to sudden or creeping movements across the seismic faults situated in the region.

It is therefore seems to be an essential feature to identify the nature of the stress and strain accumulation in the vicinity of seismic faults situated in the region by studying the observed ground deformations during the aseismic period. A proper understanding of the mechanism of such aseismic quasi static deformation may give us some precursory information regarding the impending earthquakes.

We now focus on some of the reasons of consideration viscoelastic model. The laboratory experiments on rocks at high temperature and pressure indicates the imperfect elastic behavior of the rocks situated in the lower lithosphere and asthenosphere. Investigations on the post-glacial uplift of Fennoscandia and parts of Canada indicate that at the termination of the last ice age, which happened about 10 millennia ago a 3 km. ice cover melted gradually leading and upliftment of the regions .Evidence of this upliftment has been discussed in the work of [1] , [2] , [3] , if the Earth were perfectly elastic, this deformation would be managed after the removal of the load, but it did not so happened, which indicates that the Earth crust and upper mantle is not perfect elastic but rather viscoelastic in nature.

A pioneering work involving static ground deformation in elastic media were initiated by [4], [5] , [6] , [7] , [8] , [9] , [10] . Chinnery, M.A. and Dushan B. Jovanovich [11] did a wonderful work in analyzing the displacement, stress and strain in the layered medium. Later some theoretical models in this direction have been formulated by a number of authors such as [12] , [13] , [14] , [15] , [16] , [17] , [18] , [19] , [20] , [21] , [22] , [23] , [24] , [25] , [26] , [27] , [28].[29] and[30].

In most of these works the medium were taken to be elastic and /or viscoelastic, layered or otherwise. In most of the cases the faults were taken to be too long compared to its depth, so that the problem reduced to a 2D model. Noting that there are several faults which are not so long compared to their depth, a 3D model is imminent

In the present case we consider two interacting creeping vertical rectangular strike-slip faults F_1 of length 2L, width D_1 and F_2 of length $2L_1$ (L, L_1 are finite) and width D_2 situated in a viscoelastic half space of linear Maxwell type which reach up to the free surface. The medium is under the influence of tectonic forces due to mantle convection or some related phenomena. The fault undergoes a creeping movement when the stresses in the region exceed certain threshold values.

We note here that some authors preferred layered models consisting of an elastic layer overlying an elastic/viscoelastic half space to represent the lithosphere-asthenosphere system. On numerical computations, it has been found that the additional terms arising out due to the presence of elastic layer contribute only a small quantitative change (less than 10 percent) in the rate of stress and strain accumulation in the system. Major characteristic properties remain almost unchanged. With this observation, we prefer to consider viscoelastic half space model to represent the lithosphere-asthenosphere system, particularly for the lithosphere and the upper asthenosphere, a region whose depth is 600km from the free surface.

2. Formulation:

We consider two interacting creeping vertical rectangular strike-slip faults F_1 of length 2L (L-finite) , width D_1 and F_2 of length 2L' and width D_2 situated in a viscoelastic half space of linear Maxwell type.

A Cartesian co-ordinate system is used with the mid-point 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 faults are given by $F_1 : (-L \leq y_1 \leq L, y_2 = 0, 0 \leq y_3 \leq D_1)$ and $F_2 : (-L_1 \leq y_1 \leq L_1, y_2 = 0, 0 \leq y_3 \leq D_2)$.

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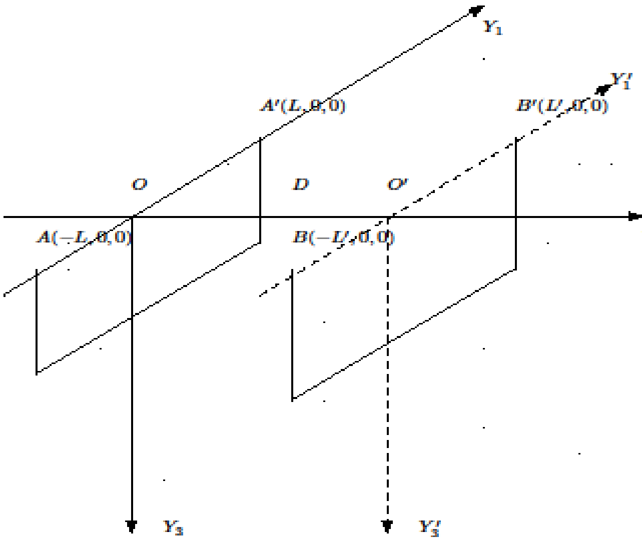

Figure1: Section of the model by the plane y_1=0.

Constitutive equations:

For a viscoelastic **Maxwell type medium the constitutive equations** have been taken as:

$$\left(\frac{1}{\eta}+\frac{1}{\mu}\frac{\partial}{\partial t}\right)\tau_{11}=\frac{\partial}{\partial t}(e_{11})=\frac{\partial}{\partial t}\left(\frac{\partial u_1}{\partial y_1}\right) \quad (1.1)$$

$$\left(\frac{1}{\eta}+\frac{1}{\mu}\frac{\partial}{\partial t}\right)\tau_{12}=\frac{\partial}{\partial t}(e_{12})$$

$$=\left(\frac{1}{2}\right)\frac{\partial}{\partial t}\left(\frac{\partial u_1}{\partial y_2}+\frac{\partial u_2}{\partial y_1}\right) \quad (1.2)$$

$$\left(\frac{1}{\eta}+\frac{1}{\mu}\frac{\partial}{\partial t}\right)\tau_{13}=\frac{\partial}{\partial t}(e_{13})$$

$$=\left(\frac{1}{2}\right)\frac{\partial}{\partial t}\left(\frac{\partial u_1}{\partial y_3}+\frac{\partial u_3}{\partial y_1}\right) \quad (1.3)$$

$$\left(\frac{1}{\eta}+\frac{1}{\mu}\frac{\partial}{\partial t}\right)\tau_{22}=\frac{\partial}{\partial t}(e_{22})=\frac{\partial}{\partial t}\left(\frac{\partial u_2}{\partial y_2}\right) \quad (1.4)$$

$$\left(\frac{1}{\eta}+\frac{1}{\mu}\frac{\partial}{\partial t}\right)\tau_{23}=\frac{\partial}{\partial t}(e_{23})$$

$$=\left(\frac{1}{2}\right)\frac{\partial}{\partial t}\left(\frac{\partial u_2}{\partial y_3}+\frac{\partial u_3}{\partial y_2}\right) \quad (1.5)$$

$$\left(\frac{1}{\eta}+\frac{1}{\mu}\frac{\partial}{\partial t}\right)\tau_{33}=\frac{\partial}{\partial t}(e_{33})=\frac{\partial}{\partial t}\left(\frac{\partial u_3}{\partial y_3}\right) \quad (1.6)$$

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

Stress equations 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.

$$\frac{\partial}{\partial y_1}(\tau_{11})+\frac{\partial}{\partial y_2}(\tau_{12})+\frac{\partial}{\partial y_3}(\tau_{13})=0 \quad (1.7)$$

$$\frac{\partial}{\partial y_1}(\tau_{21})+\frac{\partial}{\partial y_2}(\tau_{22})+\frac{\partial}{\partial y_3}(\tau_{23})=0 \quad (1.8)$$

$$\frac{\partial}{\partial y_1}(\tau_{31})+\frac{\partial}{\partial y_2}(\tau_{32})+\frac{\partial}{\partial y_3}(\tau_{33})=0 \quad (1.9)$$

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:

$$\lim_{y_1\to L-}\tau_{11}(y_1,y_2,y_3,t)=$$

$$\lim_{y_1\to L+}\tau_{11}(y_1,y_2,y_3,t)=\tau_L \text{ (Say)},$$

$$\text{for } y_2=0,\ 0\leq y_3\leq D,\ t\geq 0 \quad (1.10)$$

$$\lim_{y_1\to -L-}\tau_{11}(y_1,y_2,y_3,t)$$

$$=\lim_{y_1\to -L+}\tau_{11}(y_1,y_2,y_3,t)=\tau_L \text{ (say)}$$

$$\text{for } y_2=0,\ 0\leq y_3\leq D,\ t\geq 0 \quad (1.11)$$

assuming that the stresses maintaining a constant value τ_L at the tip of the fault along Y_1 axis [the value of this constant stress is likely to be small enough so that no further extension is possible along the Y_1 axis].

$$\tau_{12}(y_1,y_2,y_3,t)\to\tau_\infty(t) \text{ as}$$

$$|y_2|\to\infty, -\infty<y_1<\infty, y_3\geq 0, t\geq 0 \quad (1.12)$$

On the free surface $y_3 = 0, (-\infty < y_1, y_2 < \infty, t \geq 0)$

$$\tau_{13}(y_1, y_2, y_3, t) = 0 \qquad (1.13)$$

$$\tau_{23}(y_1, y_2, y_3, t) = 0 \qquad (1.14)$$

$$\tau_{33}(y_1, y_2, y_3, t) = 0 \qquad (1.15)$$

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

$$\tau_{13}(y_1, y_2, y_3, t) = 0 \qquad (1.16)$$

$$\tau_{23}(y_1, y_2, y_3, t) = 0 \qquad (1.17)$$

$$\tau_{33}(y_1, y_2, y_3, t) = 0 \qquad (1.18)$$

$$\tau_{22}(y_1, y_2, y_3, t) = 0$$

as $|y_2| \to \infty, -\infty < y_1 < \infty, y_3 \geq 0, t \geq 0$ (1.19)

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

Initial conditions:

Let $(u_i)_0$, $(\tau_{ij})_0$ and $(e_{ij})_0$ i,j = 1,2,3 be the value of (u_i), (τ_{ij}) and (e_{ij}) at time t=0 which are functions of y_1,y_2,y_3 and satisfy the relations (1.1)-(1.19).

(A)Solutions in the absence of any fault movements: The boundary value problem given by (1.1)-(1.19), can be solved (as shown in the Appendix-A) by taking Laplace transform with respect to time 't' of all the constitutive equations and the boundary conditions. On taking the inverse Laplace transform we get the solutions for displacement, stresses as:

$$u_1(y_1, y_2, y_3, t) = (u_1)_0 + \left(\frac{\tau_L}{\mu}\right) y_1 t$$

$$+ (y_2/\mu)\left[(\tau_\infty(t) - \tau_\infty(0)) + \left(\frac{\mu}{\eta}\right)\int_0^t \tau_\infty(\tau) d\tau\right]$$

$$u_2(y_1, y_2, y_3, t) = (u_2)_0 + (y_1 + y_2)/\mu \times$$

$$\times \left[(\tau_\infty(t) - \tau_\infty(0)) + \left(\frac{\mu}{\eta}\right)\int_0^t \tau_\infty(\tau) d\tau\right]$$

$$u_3(y_1, y_2, y_3, t) = (u_3)_0$$

$$\tau_{11} = \left(\frac{\mu}{\eta}\right)\tau_L (1 - e^{-(\mu/\eta)t}) + (\tau_{11})_0 e^{-(\mu/\eta)t}$$

$$\tau_{12} = \tau_\infty(t) - [\tau_\infty(0) - (\tau_{12})_0] e^{-(\mu/\eta)t}$$

$$\tau_{13} = (\tau_{13})_0 e^{-(\mu/\eta)t}$$

$$\tau_{22} = (\tau_{22})_0 e^{-(\mu/\eta)t}$$

$$\tau_{23} = (\tau_{23})_0 e^{-(\mu/\eta)t}$$

$$\tau_{33} = (\tau_{33})_0 \qquad \text{(A)}$$

From the above solution we find that τ_{12} increases with time and tends to $\tau_\infty(t)$ as t tends to ∞, while τ_{22}, τ_{23} tends to zero, but τ_{33} retains the constant value $(\tau_{33})_0$. We assume that the geological conditions as well as the characteristic of the fault in such that when τ_{12} reaches some critical value, say $\tau_c < \tau_\infty(t)$ the fault F starts creeping. The magnitude of creep is expected to satisfy the following conditions:

(C_1) Its value will be maximum near the middle of the fault on the free surface.

(C_2) It will gradually decrease to zero at the tips of the fault F_1 ($y_1=\pm L$, y_2=0, $0 \leq y_3 \leq D_1$) along its length and also F_2 ($y_1=\pm L_1$, y_2=0, $0 \leq y_3 \leq D_2$)

(C_3) 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 faults F_1($y_1=\pm L$, y_2=0, $0 \leq y_3 \leq D_1$) and F_2($y_1=\pm L_1$, y_2=0, $0 \leq y_3 \leq D_2$)

If $f(y_1, y_2)$ and g (y_1, y_2) be the creep functions, they should satisfy the above conditions.

(B): Solutions after the fault movements: We assume that after a time T_1, 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 F_1 starts creeping, after a time T_2 the fault F_2 starts creeping, characterized by a dislocation across the faults.

We solve the resulting boundary value problem by modified Green's function method following [6], [7], [31] and correspondence principle (As shown in the Appendix-B) and get the solution for displacements, stresses and strain as :

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$$u_1(y_1,y_2,y_3,t)=(u_1)_0+(\tau_L/\mu)y_1t+(y_2/\mu)$$
$$\left[(\tau_\infty(t)-\tau_\infty(0)+(\mu/\eta)\int_0^t\tau_\infty(\tau)d\tau\right]+$$
$$[H(t-T_1)/(2\times\pi)]\int_{-L}^{L}\int_0^{D_1}f(x_1,x_3)\times$$
$$[(y_2/[(y_1-x_1)^2+(y_2-x_2)^2+(y_3-x_3)^2]^{3/2}$$
$$-(y_2/[(y_1+x_1)^2+(y_2-x_2)^2+(y_3-x_3)^2]^{3/2}]$$
$$dx_3dx_1.$$
$$+[H(t-T_2)/(2\times\pi)]\int_{-L_1'}^{L_1'}\int_0^{D_2}g(x_1,x_3)\times$$
$$[(y'_2+D)/[(y_1-x_1)^2+(y'_2+D-x_2)^2+(y_3-x_3)^2]^{3/2}$$
$$-(y'_2+D)/[(y_1+x_1)^2+(y'_2+D-x_2)^2+(y_3-x_3)^2]^{3/2}]$$
$$dx_3dx_1.$$
$$u_2(y_1,y_2,y_3,t)=(u_2)_0+[(y_1+y_2)/\mu]\times$$
$$\left[\tau_\infty(t)-\tau_\infty(0))+(\mu/\eta)\int_0^t\tau_\infty(\tau)d\tau\right]$$

$$u_3(y_1,y_2,y_3,t)=(u_3)_0$$

$$\tau_{11}(y_1,y_2,y_3,t)=(\mu/\eta)\tau_L(1-e^{(-\mu/\eta)t})+$$
$$+(\tau_{11})_0e^{(-\mu/\eta)t}+[H(t-T_1)/(2\times\pi)]$$
$$\left[U_1(t_1)-\mu/\eta\int_0^tU_1(\tau)e^{(-\mu/\eta)(t-\tau)}d\tau\right]\times$$
$$\times\int_{-L}^{L}\int_0^{D_1}f(x_1,x_3)\times$$
$$\times[(y_2)(y_1+x_1)/[(y_1+x_1)^2+(y_2-x_2)^2$$
$$+(y_3-x_3)^2]^{5/2}-(y_2)(y_1-x_1)/[(y_1+x_1)^2$$
$$+(y_2-x_2)^2+(y_3-x_3)^2]^{5/2}]dx_3dx_1$$
$$+[H(t-T_2)/(2\times\pi)]\times$$
$$\left[U_2(t_2)-\mu/\eta\int_0^tU_2(\tau)e^{(-\mu/\eta)(t-\tau)}d\tau\right]\times$$
$$\int_{-L_1'}^{L_1'}\int_0^{D_2}g(x_1,x_3)\times$$
$$\times[(y'_2+D)(y_1+x_1)/[(y_1+x_1)^2$$
$$+(y'_2+D-x_2)^2+(y_3-x_3)^2]^{5/2}$$
$$-(y'_2+D)(y_1-x_1)/[(y_1+x_1)^2$$
$$+(y'_2+D-x_2)^2+(y_3-x_3)^2]^{5/2}]dx_3dx_1$$

$$\tau_{12}(y_1,y_2,y_3,t)=\tau_\infty(t)-(\tau_\infty(0)-(\tau_{12})_0)e^{(-\mu/\eta)t}$$
$$+[H(t-T_1)/(2\times\pi)]\times$$
$$[U_1(t_1)-\mu/\eta\int_0^tU_1(\tau)e^{(-\mu/\eta)(t-\tau)}d\tau]\times$$
$$\int_{-L}^{L}\int_0^{D}f(x_1,x_3)[((y_1-x_1)^2+y_2^2+(y_3-x_3)^2-$$
$$-3\times y_2(y_2-x_2))/[(y_1-x_1)^2+(y_2-x_2)^2+$$
$$+(y_3-x_3)^2]^{5/2}-((y_1+x_1)^2+y_2^2+(y_3-x_3)^2-$$
$$-3\times y_2(y_2-x_2))/[(y_1+x_1)^2+(y_2-x_2)^2+$$
$$+(y_3-x_3)^2]^{5/2}]dx_3dx_1.+[H(t-T_2)/(2\times\pi)]\times$$
$$[U_2(t_2)-\mu/\eta\int_0^tU_2(\tau)e^{(-\mu/\eta)(t-\tau)}d\tau]\times$$
$$\int_{-L'}^{L'}\int_0^{D_2}g(x_1,x_3)\times$$
$$\times[((y_1-x_1)^2+(y'_2+D)^2+(y_3-x_3)^2-$$
$$-3\times(y'_2+D)(y'_2+D-x_2))/[(y_1-x_1)^2$$
$$+(y'_2+D-x_2)^2+(y_3-x_3)^2]^{5/2}$$
$$-((y_1+x_1)^2+(y'_2+D)^2+(y_3-x_3)^2-$$
$$-3\times(y'_2+D)(y'_2+D-x_2))/[(y_1+x_1)^2$$
$$+(y'_2+D-x_2)^2+(y_3-x_3)^2]^{5/2}]dx_3dx_1.$$

$$\tau_{13}(y_1,y_2,y_3,t)=((\tau_{13})_0)e^{(-\mu/\eta)t}$$
$$+[H(t-T_1)/(2\times\pi)]\times$$
$$[U_1(t_1)-\mu/\eta\int_0^tU_1(\tau)e^{(-\mu/\eta)(t-\tau)}d\tau]\times$$
$$\int_{-L}^{L}\int_0^{D}f(x_1,x_3)[((y_2(y_3-x_3))/[(y_1+x_1)^2+$$
$$+(y_2-x_2)^2+(y_3-x_3)^2]^{5/2}-((y_2(y_3-x_3))/$$
$$[(y_1-x_1)^2+(y_2-x_2)^2+(y_3-x_3)^2]^{5/2}]dx_3dx_1$$
$$+[H(t-T_2/(2\times\pi)]\times$$
$$[U_2(t_2)-\mu/\eta\int_0^tU_2(\tau)e^{(-\mu/\eta)(t-\tau)}d\tau]\times$$
$$\int_{-L_1'}^{L_1'}\int_0^{D_2}g(x_1,x_3)\times$$
$$[((y'_2+D)(y_3-x_3))/[(y_1+x_1)^2+$$
$$+(y'_2+D-x_2)^2+(y_3-x_3)^2]^{5/2}$$
$$-((y'_2+D)(y_3-x_3))/[(y_1-x_1)^2+$$
$$(y'_2+D-x_2)^2+(y_3-x_3)^2]^{5/2}]dx_3dx_1$$

$\tau_{23} = (\tau_{23})_0 e^{-(\mu/\eta)t}$

$\tau_{33} = (\tau_{33})_0$

$$e_{11}(y_1, y_2, y_3, t) = (e_{11})_0 + (\tau_L/\eta)t$$
$$+ H(t-T_1)/(2\times\pi)\int_{-L}^{L}\int_0^D f(x_1,x_3)[(y_2)(y_1-x_1)/$$
$$[(y_1-x_1)^2+(y_2-x_2)^2+(y_3-x_3)^2]^{5/2}$$
$$-(y_2)(y_1+x_1)/[(y_1+x_1)^2+(y_2-x_2)^2+$$
$$+(y_3-x_3)^2]^{5/2}]dx_3dx_1+$$
$$+H(t-T_2)/(2\times\pi)\int_{-L'}^{L'}\int_0^{D_2} g(x_1,x_3)\times$$
$$[(y'_2+D)(y_1-x_1)/[(y_1-x_1)^2+(y'_2+D-x_2)^2$$
$$+(y_3-x_3)^2]^{5/2}$$
$$-(y'_2+D)(y_1+x_1)/[(y_1+x_1)^2+(y'_2+D-x_2)^2+$$
$$+(y_3-x_3)^2]^{5/2}]dx_3dx_1$$

$$e_{12}(y_1,y_2,y_3,t) = \left(\frac{1}{2}\right)(e_{12})_0 + (\tau_\infty(t)-\tau_\infty(0))/(\mu)$$
$$+(\mu/\eta)\int_0^t \tau_\infty(\tau)d\tau$$
$$+H(t-T_1)/(2\times\pi)\times$$
$$\int_{-L}^{L}\int_0^D f(x_1,x_3)[((y_2)(y_2-x_3))/$$
$$[(y_1-x_1)^2+(y_2-x_2)^2+(y_3-x_3)^2]^{5/2}$$
$$-(y_2)(y_2-x_2)/[(y_1+x_1)^2+(y_2-x_2)^2+$$
$$+(y_3-x_3)^2]^{5/2}]dx_3dx_1+$$
$$+H(t-T_2)/(2\times\pi)\times$$
$$\int_{-L'}^{L'}\int_0^{D_2} g(x_1,x_3)[((y'_2+D)(y_2-x_2))/$$
$$[(y_1-x_1)^2+(y'_2+D-x_2)^2+(y_3-x_3)^2]^{5/2}$$
$$-(y'_2+D)(y'_2+D-x_2)/[(y_1+x_1)^2$$
$$+(y'_2+D-x_2)^2+(y_3-x_3)^2]^{5/2}]dx_3dx$$

(B)

3. Numerical computations:

Following [32], [33] and the recent studies on rheological behaviour of crust and upper middle by [34], [35] the values of the model parameters are taken as:

$$\mu = 3\times 10^{11}\,dyne/cm^2, \eta = 3\times 10^{20}\,poise$$

D_1=Depth of the fault F_1=10km.,[noting that the depth of all major earthquake faults are in between 10-15 km]
D_2=Depth of the faultF_2=15km.,[noting that the depth of all major earthquake faults are in between 10-15 km]
D= Distance between the faults F_1 and F_2=200km. (say)
2L=Length of the faultF_1=40km.
$2L_1$=Length of the fault F_2=60km.
$\tau_\infty(t) = 2\times 10^8$ dyne/cm^2 (200 bars), [post seismic observations reveal that stress released in major earthquake are of the order of 200 bars, in extreme cases it may be 400 bars.]
$(\tau_{12})_0 = 5\times 10^7$ Dyne/cm2 (50 bars) and $\tau_\infty(0) = 0$.

We take creep functions as:

$$f(x_1,x_3) = U\left(1-\frac{1}{L^2x_1^2}\right)\left(1-\frac{3}{D_1^2}x_3^2+\frac{3}{D_1^3}x_3^3\right),$$

$$g(x_1,x_3) = U\left(1-\frac{1}{{L_1}^2x_1^2}\right)\left(1-\frac{3}{D_2^2}x_3^2+\frac{3}{D_2^3}x_3^3\right)$$

with U = 1cm, satisfying the conditions stated in (C_1)–(C_3).

We now compute the following quantities:

$$U_1(y_1,y_2,y_3,t) = u_1(y_1,y_2,y_3,t)-(u_1)_0+$$
$$+(\tau_L/\mu)y_1t+(y_2/\mu)[(\tau_\infty(t)-\tau_\infty(0))+$$
$$(\mu/\eta)\int_0^t \tau_\infty(\tau)d\tau] \quad (2.1)$$

$$t_{11}(y_1,y_2,y_3,t) = \tau_{11}(y_1,y_2,y_3,t)- -(\mu/\eta)\tau_L(1-e^{(-\mu/\eta)t})+(\tau_{11})_0e^{(-\mu/\eta)t} \quad (2.2)$$

$$t_{12}(y_1,y_2,y_3,t) = \tau_{12}(y_1,y_2,y_3,t)- -\tau_\infty(t)((\tau_\infty(0)-\tau_{12})_0)e^{(-\mu/\eta)t} \quad (2.3)$$

$$t_{13}(y_1,y_2,y_3,t) = \tau_{13}(y_1,y_2,y_3,t)- -(\tau_{13})_0)e^{(-\mu/\eta)t} \quad (2.4)$$

$$E_{11}(y_1,y_2 y_3,t)-[e_{11}(y_1,y_2,y_3,t)- -(e_{11})_0]\times 10^6 \quad (2.5)$$

$$E_{12,}(y_1,y_2,y_3,t)=[e_{12}(y_1,y_2,y_3,t) -\left(\frac{1}{2}\right)(e_{12})_0]\times 10^6 \quad (2.6)$$

where τ_{11},τ_{12} and τ_{13},e_{11},e_{12} are given by (B).

<u>Results and Discussions</u> :

Spacial variation:

(A)*Displacements on the free surface y_3=0 due to the creeping movement across the faults:*

We first consider the displacement U_1 due to the movement of the faults for y_3=0.The expression for U_1 is given in (2.1). Figure2 shows the variation of U_1 against y_2 for some selective values of y_1 representing the distance of the point from the strike of the fault. It is found that,

(i) U_1 is antisymmetric with respect to $y_1 = 0$;

(ii) For comparatively large values of y2 the magnitude of U_1, as expected becomes very small (10^{-2} cm); i.e. $|U_1|$ decreases as y_2 increases.

(iii) In each case for negative y_1, U_1 is negative for all y_2>0 but for y_1>0, U_1 is positive, i.e. U_1 changes sign as we cross the line y_1=0 with U_1=0 at y_1=0 for all values of y_2>0, For all negative y_2 say at y2= –*k* km., the displacement pattern is found to an exact mirror image for y_2=+k km. i.e., for all negative y_2 the pattern is reversed.

(iv) $|U_1| \rightarrow 0$ as $|y_1|$ increases as is shown in Fig3.

(v) $|U_1|$ always remains bounded. It attains it's extreme at points which gradually drift away from y_1=0 with increase in y_2. The magnitude of U_1 is found to be of the order of 2.0 cm. one year after the commencement of the fault creep at points very close to the fault line on the free surface.

(*B*)*Variation of stresses due to fault movement with depth (with t_1=1 year):*

(i) Variation of shear stress t_{12} due to fault movement with depth:

Numerical computational works carried out for computing the values of t_{12} at different points of the free surface. It is observed that for points close to the faults (y_1 <= 4 km, y_2 <= 4 km., Fig 4) shear stress releases with increasing depth with varying magnitude. The magnitude of release first decreases up to a depth of about 10 km and there after increases sharply up to a depth of about 45 km and after that the magnitude of stress release is found to die out gradually as depth increases. The pattern is the same as we move away from the fault, for example at points (y_1 = ±10 km, y_2 = ±10 km) as the Fig 4(a) shows.

. If we move further away from the fault (y_1 = ±30 km, y_2 = 30 km, Fig. 4(b)) the stress is found to get released in the similar manner but with a lesser numerical value. Effect of fault movement on stress pattern is found to be negligibly small as we move further downwards.

(iii) Variation of shear stress t_{13} due to fault movement with depth:

Similar computational work is carried out for t_{13} also. It is found that the shear stress t_{13} get released by a initially up to a depth of about 7 km. The magnitude of the amount of stress release depends upon the distance of the points from the fault; it decreases significantly as we move away from the fault. After the initial release of stress t_{13}, it is found to accumulate and attains a maximum at a distance of 20 km (Fig5) depending upon the position of the points. After attaining its maximum value the magnitude of stress accumulation gradually decreases and tends to zero at a depth of about 40-50km below the surface.

(C)*Surface shear strain due to fault -movement one year after the commencement of the creep:*

The shear strain E_{12} at distances from the strike of the fault y_1=10 km. is computed.

The magnitude of the surface shear strain due to the fault movement is found to be of the order of $(1-6)\times 10^{-6}$ per year, which is conformity with the observed rate of shear strain accumulation during the aseismic period in seismically active regions. The nature of shear strain is clear from the Fig6.

(D)Minimum distance between the faults so that one fault can influence other.

From the Fig2, Fig 2(a) and by the numerical calculation we see that if D=50km ,the value of U_1=0(app) and consequently stress and strains are also zero. Therefore the faults can not influence one another if D>50km.But this distance obviously depends on the length and the depth of the faults. The influence of fault length and depth on stress and strain is given in [38].

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4).Conclusions:

It is therefore found that the shear and normal stress due to the fault movement sometimes get accumulated in certain region while there are some other region where the stress is found to get released due to the fault movement. The movement of one fault causes stress accumulation/ release near the other fault which essentially depends on the dimensions of the faults as well as the distance between the faults and the nature of stress accumulation/release with depth depends upon the position of the points on the free surface relative to the strike of the fault.

5. <u>AppendixA:</u>

[36], [37],[38],[39],[40],[41] and[42]

Solutions for displacements, stresses and strains in the absence of any fault movement:

We take Laplace transform of all the constitutive equations and the boundary conditions (1.1)-(1.19) with respect to time and we get,

$$\overline{\tau_{11}} = \frac{\left(p\frac{\partial \overline{u_1}}{\partial y_1}\right) - \left(\frac{\partial u_1}{\partial y_1}\right)_0}{\frac{1}{\eta}+\frac{p}{\mu}} + \frac{\frac{1}{\mu}(\tau_{11})_0}{\frac{1}{\eta}+\frac{p}{\mu}} \qquad (3.1)$$

where, $\overline{\tau_{11}} = \int_0^\infty \tau_{11} e^{-pt} dt(p > 0$,Laplace transformation variable) and similar other equations. Also the stress equations of motions in Laplace transform domain as:

$$\frac{\partial}{\partial y_1}(\overline{\tau_{11}}) + \frac{\partial}{\partial y_2}(\overline{\tau_{12}}) + \frac{\partial}{\partial y_3}(\overline{\tau_{13}}) = 0 \qquad (1.7a)$$

$$\frac{\partial}{\partial y_1}(\overline{\tau_{21}}) + \frac{\partial}{\partial y_2}(\overline{\tau_{22}}) + \frac{\partial}{\partial y_3}(\overline{\tau_{23}}) = 0 \qquad (1.8a)$$

$$\frac{\partial}{\partial y_1}(\overline{\tau_{31}}) + \frac{\partial}{\partial y_2}(\overline{\tau_{32}}) + \frac{\partial}{\partial y_3}(\overline{\tau_{33}}) = 0 \qquad (1.9a)$$

$$\lim_{y_1 \to L-} \tau_{11}(y_1, y_2, y_3, p) =$$

$$\lim_{y_1 \to L+} \overline{\tau_{11}}(y_1, y_2, y_3, p) = \tau_L \text{ (say)},$$

For $y_2 = 0,\ 0 \le y_3 \le D_1$

(1.10a)

$$\lim_{y_1 \to -L-} \overline{\tau_{11}}(y_1, y_2, y_3, p) =$$

$$\lim_{y_1 \to -L+} \overline{\tau_{11}}(y_1, y_2, y_3, t) = \tau_L \text{ (say)}$$

For $y_2 = 0,\ 0 \le y_3 \le D_1$

(1.11a)

On the free surface $y_3 = 0$, $(-\infty < y_1, y_2 < \infty)$

$\overline{\tau_{12}}(y_1, y_2, y_3, p) \to \tau_\infty(t)$ as

$$|y_2| \to \infty, -\infty < y_1 < \infty, y_3 \ge 0, t \ge 0 \qquad (1.12a)$$

$$\overline{\tau_{13}}(y_1, y_2, y_3, p) = 0 \qquad (1.13a)$$

$$\overline{\tau_{23}}(y_1, y_2, y_3, p) = 0 \qquad (1.14a)$$

$$\overline{\tau_{33}}(y_1, y_2, y_3, p) = 0 \qquad (1.15a)$$

Also as $y_3 \to \infty$ $(-\infty < y_1, y_2 < \infty)$

$$\overline{\tau_{13}}(y_1, y_2, y_3, p) = 0 \qquad (1.16a)$$

$$\overline{\tau_{23}}(y_1, y_2, y_3, p) = 0 \qquad (1.17a)$$

$$\overline{\tau_{33}}(y_1, y_2, y_3, p) = 0 \qquad (1.18a)$$

$\overline{\tau_{22}}(y_1, y_2, y_3, p) = 0$ as $|y_2| \to \infty$, $-\infty < y_1 < \infty$, $y_3 \ge 0$ (1.19a)

Using (3.1), other similar equations and assuming the initial fields to be zero, we get from (1.7a).

$$\nabla^2(\overline{u_1}) = 0 \qquad (3.2)$$

Thus we are to solve the boundary value problem (3.2) with the boundary conditions (1.10a)-(1.19a).

Let

$$\overline{u_1}(y_1, y_2, y_3, p) = \frac{(u_1)_0}{p} + A_1 y_1 + B_1 y_2 + C_1 y_3 \qquad (3.3)$$

be the solution of (3.2).

Using the boundary conditions (1.10a)-(1.19a) and the initial conditions we get,

$$A_1 = \frac{\tau_L}{\eta}\frac{1}{p^2} \qquad (3.4)$$

$$B_1 = \frac{1}{p}\left[\left(\frac{1}{\eta}+\frac{p}{\mu}\right)\tau_\infty(p) - \frac{1}{\mu}\tau_\infty(0)\right] \qquad (3.5)$$

and $C_1 = 0$ (3.6)

On taking inverse Laplace transformation, we get,

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$$u_1(y_1, y_2, y_3, t) = (u_1)_0 + (\tau_L / \mu) y_1 t + (y_2 / \mu) \times$$
$$\times [(\tau_\infty(t) - \tau_\infty(0)) + (\mu / \eta) \int_0^t \tau_\infty(\tau) d\tau] \quad (3.7)$$

Similarly we can get the other components of the displacements.

The stress are given by,

$$\tau_{11} = (\mu/\eta)\tau_L(1 - e^{-(\mu/\eta)t}) + (\tau_{11})_0 e^{-(\mu/\eta)t} \quad (3.8)$$

$$\tau_{12} = (\tau_\infty(t) - [\tau_\infty(0) - (\tau_{12})_0] e^{-(\mu/\eta)t} \quad (3.9)$$

$$\tau_{13} = (\tau_{13})_0 e^{-(\mu/\eta)t} \quad (3.10)$$

$$\tau_{22} = (\tau_{22})_0 e^{-(\mu/\eta)t} \quad (3.11)$$

$$\tau_{23} = (\tau_{23})_0 e^{-(\mu/\eta)t} \quad (3.12)$$

$$\tau_{33} = (\tau_{33})_0 \quad (3.13)$$

Using the displacements the strains can also be found out to be,

$$e_{11}(y_1, y_2, y_3, t) = (e_{11})_0 + (\tau_L / \eta) t \quad (3.14)$$

$$e_{12,} = (y_1, y_2, y_3, t) = (1/2)(e_{12})_0 + (\tau_\infty(t) - \tau_\infty(0)) / (\mu) + (\mu/\eta) \int_0^t \tau_\infty(\tau) d\tau \quad (3.15)$$

6. Appendix-B:

Solutions after the fault movement:

[36], [37],[38],[39],[40] ,[41] and [42].

We assume that after a time T_1 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_1 starts creeping and after a time T_2 the fault F_2 starts creeping then (3.1)-(1.19a) are satisfied with the following conditions of creep across F_1 and F_2 :

$$[(u_1)]_{F1} = U_1(t_1) f(y_1, y_3) H(t_1) \quad (4.1)$$

where $[(u_1)]_F$ = The discontinuity of u_1 across F_1 given by

$$[(u_1)]_{F_1} = \lim_{(y_2 \to 0+)} (u_1) - \lim_{(y_2 \to 0-)} (u_1) \quad (4.2)$$

$$(-L \le y_1 \le L, y_2 = 0, 0 \le y_3 \le D_1)$$

where $H(t_1)$ is the Heaviside function.

Taking Laplace transformation in (4.1), we get,

$$[(\overline{u_1})]_{F1} = U_1(p) f\ (y_1, y_3) \quad (4.3)$$

The fault creep commences across F_1 after time T_1, clearly

$$[(u_1)]_{F1} = 0$$

for $t_1 \le 0$, where $t_1 = t - T_1$, F is located in the region $(-L \le y_1 \le L, y_2 = 0, 0 \le y_3 \le D_1)$.

and

$$[(u_1)]_{F2} = U_2(t_2) g(y_1, y_3) H(t_2) \quad (4.1.1)$$

where $[(u_1)]_{F2}$ = The discontinuity of u_1 across F_2 given by

$$[(u_1)]_{F2} = \lim_{(y'_2 \to 0+)} (u_1) - \lim_{(y'_2 \to 0-)} (u_1) \quad (4.2.1)$$

$$(-L_1 \le y_1 \le L_1, 0 \le y'_3 \le D_2)$$

where $H(t_2)$ is the Heaviside function.

Taking Laplace transformation in (4.1), we get,

$$[(\overline{u_1})]_{F2} = U_2(p) g\ (y_1, y_3) \quad (4.3.1)$$

The fault creep commences across F_1 after time T_1, clearly

$$[(u_1)]_{F_2} = 0$$

for $t_2 \le 0$, where $t_2 = t - T_2$, F_2 is located in the region.

$$(-L_1 \le y'_1 \le L_1, y'_2 = 0, 0 \le y'_3 \le D_2)$$

We try to find the solution as :

$$u_1 = (u_1)_1 + (u_1)_2 + (u_1)_3,$$
$$u_2 = (u_2)_1 + (u_2)_2 + (u_2)_3,,$$
$$u_3 = (u_3)_1 + (u_3)_2 + (u_3)_3,$$
$$\tau_{11} = (\tau_{11})_1 + (\tau_{11})_2 + (\tau_{11})_3,$$
$$\tau_{12} = (\tau_{12})_1 + (\tau_{12})_2 + (\tau_{12})_3,$$
$$\tau_{13} = (\tau_{13})_1 + (\tau_{13})_2 + (\tau_{13})_3,$$
$$\tau_{22} = (\tau_{22})_1 + (\tau_{22})_2 + (\tau_{22})_3,$$
$$\tau_{23} = (\tau_{23})_1 + (\tau_{23})_2 + (\tau_{23})_3,$$
$$\tau_{33} = (\tau_{33})_1 + (\tau_{33})_3 + (\tau_{33})_3 \quad (4.4)$$

where $(u_i)_1$, $(\tau_{ij})_1$, are continuous everywhere in the model and are given by (A); i,j=1,2,3. While the second part $(u_i)_2$, $(\tau_{ij})_2$ are obtained by solving modified boundary value problem as stated below. We note that $(u_2)_2$, $(u_3)_2$, are both continuous even after the fault creep, so that $[(u_2)]_2 = 0, [(u_3)]_2 = 0$, while $(u_1)_2$ satisfies the dislocation condition given by (4.2) **and the third part $(u_i)_3$, $(\tau_{ij})_3$ are obtained from $(u_i)_2$, $(\tau_{ij})_2$ by the substitution $y_1=y'_1, y_2=y'_2+D, y_3=y'_3$.** **(4.4.1)**

The resulting boundary value problem can now be stated as: $(u_1)_2$ satisfy 3D Laplace equation as

$$\nabla^2(\overline{u_1})_2 = 0 \qquad (4.5)$$

where $(\overline{u_1})_2$ is the Laplace transformation of $(u_1)_2$ with respect to t, with the modified boundary condition.

$$\overline{\tau_{12}}(y_1, y_2, y_3, p) = 0 \text{ as } [y_2]\to\infty, -\infty<y_1<\infty, \; y_3 \geq 0. \qquad (1.14b)$$

and the other boundary conditions are same as (1.13a)-(1.19a).

We solve the above boundary value problem by modified Green's function method following [6], [7], [31], and the correspondence principle.

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

$$(\overline{u}_1)_2(Q) = \int\int_{F_1} [(u_1)_2(P)] G(P,Q)\, dx_3 dx_1$$

$$= \int\int_{F_1} u_1(P) f(x_1, x_3) G(P,Q)\, dx_3 dx_1 \qquad (4.6)$$

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

$$G(P,Q) = \frac{\partial}{\partial x_2} G_1(P,Q) \qquad (4.7)$$

where,

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

Therefore,

$$G(P,Q) = \frac{(y_2-x_2)}{\left[(y_1-x_1)^2+(y_2-x_2)^2+(y_3-x_3)^2\right]^{\frac{3}{2}}} - \frac{(y_2-x_2)}{\left[(y_1+x_1)^2+(y_2-x_2)^2+(y_3-x_3)^2\right]^{\frac{3}{2}}} \qquad (4.8)$$

$$(\overline{u_1})_2(Q) = \int\int_{F_1} u_1(P) f(x_1,x_3) \times \left[\frac{(y_2-x_2)}{\left[(y_1-x_1)^2+(y_2-x_2)^2+(y_3-x_3)^2\right]^{\frac{3}{2}}} - \frac{(y_2-x_2)}{\left[(y_1+x_1)^2+(y_2-x_2)^2+(y_3-x_3)^2\right]^{\frac{3}{2}}}\right] dx_3 dx_1]$$

$$= u_1(P)\phi(y_1, y_2, y_3) \text{ (Say)} \qquad (4.9)$$

where,

$$\phi(y_1,y_2,y_3) = \int\int_{F_1} f(x_1,x_3) \times \left[\frac{(y_2-x_2)}{\left[(y_1-x_1)^2+(y_2-x_2)^2+(y_3-x_3)^2\right]^{\frac{3}{2}}} - \frac{(y_2-x_2)}{\left[(y_1+x_1)^2+(y_2-x_2)^2+(y_3-x_3)^2\right]^{\frac{3}{2}}}\right] dx_3 dx_1] \qquad (4.10)$$

Taking inverse Laplace transformation,

$$(u_1)_2(Q) = U_1(t_1)\phi(y_1,y_2,y_3)H(t_1)$$

where $H(t_1)$ is the Heaviside step function, which gives the displacement at any points Q (y_1,y_2,y_3).

We also have,

$$(\overline{\tau_{11}})_2 = \frac{p}{\frac{1}{\eta}+\frac{p}{\mu}}\left(\frac{\partial(\overline{u_1})_2}{\partial y_1}\right) \qquad (4.11)$$

and similar other equations.

Now, $\dfrac{\partial(\overline{u_1})_2}{\partial y_1} = \overline{u_1}(p)\dfrac{\partial(\phi)}{\partial y_1} = \overline{u_1}(p)\phi_1$ (say).

Where

$$\phi_1(y_1, y_2, y_3) = \frac{\partial}{\partial y_1}\Big(\int\int_{F_1} f\ (x_1, x_3 \times$$

$$\times \frac{(y_2 - x_2)}{\left[(y_1 - x_1)^2 + (y_2 - x_2)^2 + (y_3 - x_3)^2\right]^{\frac{5}{2}}} -$$

$$- \frac{(y_2 - x_2)}{\left[(y_1 + x_1)^2 + (y_2 - x_2)^2 + (y_3 - x_3)^2\right]^{\frac{5}{2}}} \times$$

$$dx_3 dx_1) \qquad (4.12)$$

Using (4.11) and taking inverse Laplace transformation, we get

$$(\tau_{11})_2 = H(t - T_1)/(2\times\pi)[U_1(t_1) - \mu/\eta$$

$$\int_0^t U_1(\tau)e^{(-\mu/\eta)(t-\tau)} d\tau] \times$$

$$\int_{-L}^{L}\int_0^{D_1} f(x_1, x_3) \times$$

$$\times \left[\frac{(y_3(y_1 - x_1))}{\left[(y_1 - x_1)^2 + (y_2)^2 + (y_3 - x_3)^2\right]^{\frac{5}{2}}} - \right.$$

$$\left. - \frac{(y_2(y_1 + x_1))}{\left[(y_1 + x_1)^2 + (y_2)^2 + (y_3 - x_3)^2\right]^{\frac{5}{2}}} dx_3 dx_1 \right] \qquad (4.13)$$

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

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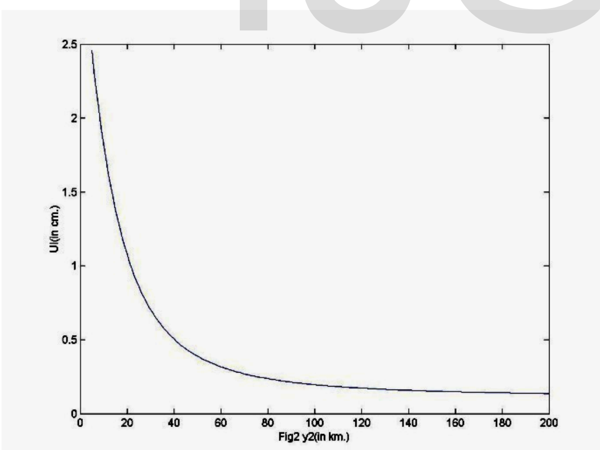

Fig2: Variation of displacement U_1 with $y_2>0$ for y_1=10km , y_3=0 and t_1=1 year due to fault movement.

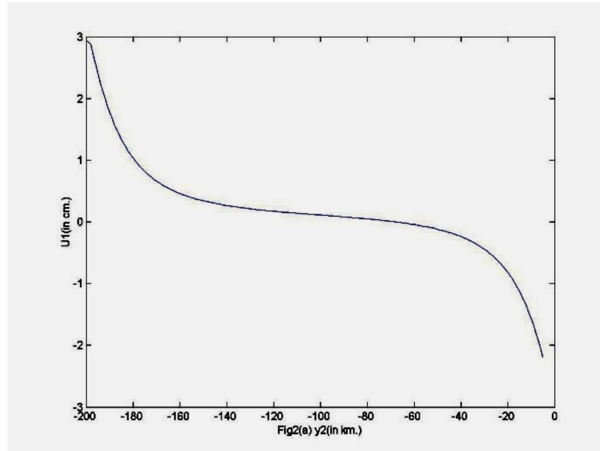

Fig 2(a): Variation of displacement U_1 with $y_2<0$ for y_1=10km , y_3=0 and t_1=1 year due to fault movement.

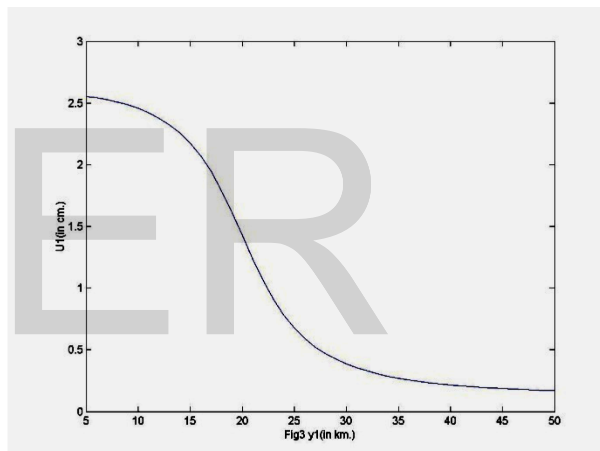

Fig3: Variation of displacement U_1 with y_1 for y_2=10km , y_3=0 and t_1=1 year due to fault movement.

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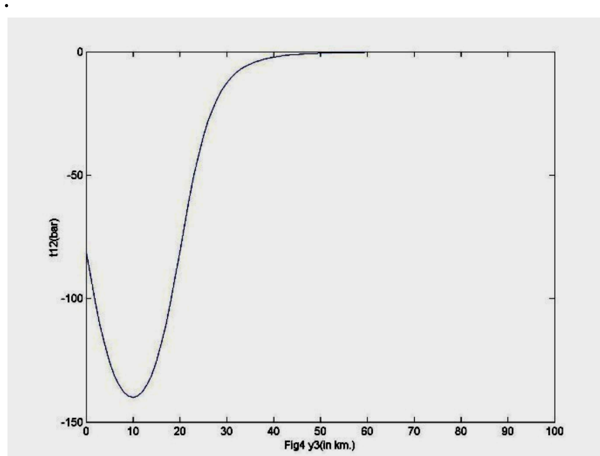

Fig4: Variation of shear stress t_{12} with y_3 for y_2 =10km and y_1 =10km. t_1=1year due to fault movement.

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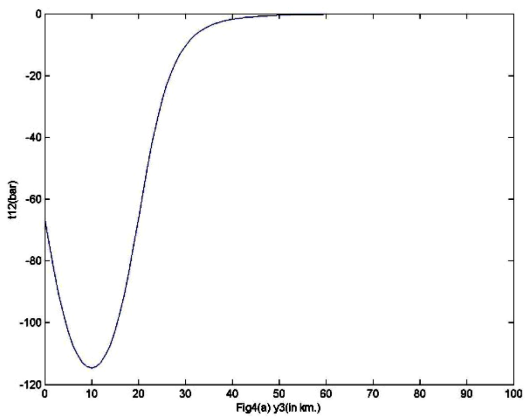

Fig4(a): Variation of shear stress t_{12} with y_3 for y_2 =-10km and y_1 =-10km. t_1=1year due to fault movement.

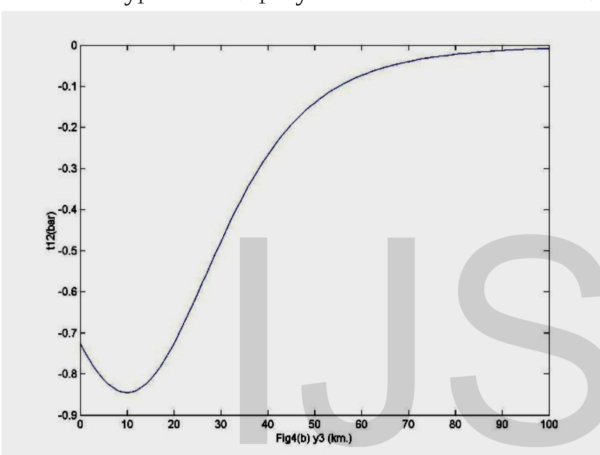

Fig 4(b): Variation of shear stress t_{12} with y_3 for y_2 =-30km and y_1 =-10km. t_1=1year due to fault movement

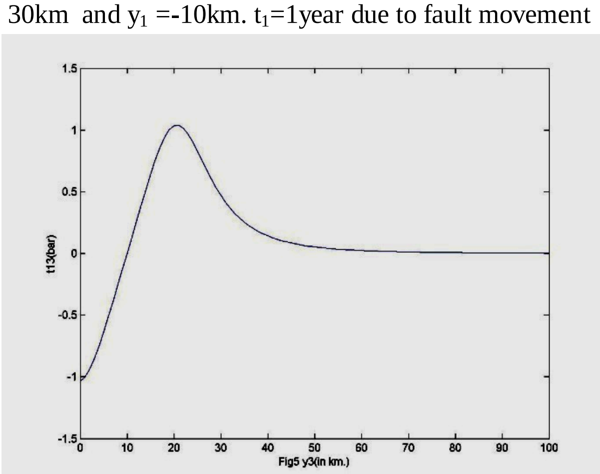

Fig5: Variation of shear stress t_{13} with y_3 for, y_1 =10km. and y_2 =10km. t_1=1year due to fault movement.

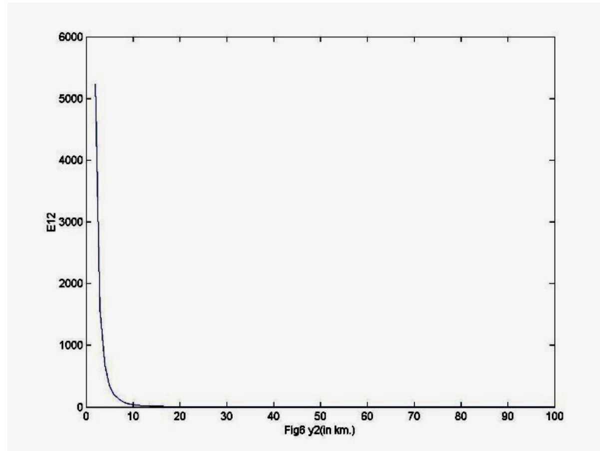

Fig6: Variation of strain $e_{12} \times 10^{10}$ for y_3=0km.t_1=1year with y_2 and y_1 =10km. due to fault movement.