Aseismic Ground Deformation in a Viscoelastic Layer over Lying a Viscoelastic Half-Space Model of the Lithosphere-Asthenosphere System

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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. A long strike-slip fault in a viscoelastic layer over 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 two-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.

Keywords Viscoelastic Layered Model, Aseismic Period, Stress Accumulation, Mantle Convection, Plate Movements, Tectonic Process, And Earthquake Prediction

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.

A pioneering work involving static ground deformation in elastic media were initiated by ([8], [9]), ([21]), ([2]). Reference ([22]) has discussed various aspects of fault movement in his book. Reference ([5]) has discussed stress accumulation near buried fault in lithosphere-asthenosphere system.

In most of these studies the medium were taken to be elastic and/or viscoelastic, layered or otherwise. We now focus on some of the reasons of consideration of viscoelastic layer over viscoelastic half-space 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 3km. ice cover melted gradually leading to upliftment of the regions. Evidence of this uplift has been discussed in Fairbridge (1961), Schofield (1964), Chatthles (1975), if the Earth were perfectly elastic, this deformation would be managed after the removal of the load, but it did not happened, indicating that the Earth crust and upper mantle is not perfect elastic but rather viscoelastic in nature.

Therefore in the present case we consider a long strike-slip fault situated in a viscoelastic layer over a viscoelastic half-space which is surface breaking in nature. The medium is under the influence of tectonic forces due to mantle convection or some related phenomena. The fault undergoes
2. Formulation

We consider a long strike-slip fault F width D situated in a viscoelastic layer over a viscoelastic half space of linear Maxwell type.

We choose our rectangular Cartesian coordinates \((y_1, y_2, y_3)\) such that, the free surface is the plane \(y_3 = 0\) the fault \(F_1\) is in the plane \(y_2 = 0\), \(y_1\)-axis is perpendicular to plane of the fault and \(y_3\) axis pointing downwards as shown in the Fig: 1. Since our model is a viscoelastic layer of finite depth say \(H\), over a viscoelastic half space.

\[ \therefore \text{The interface is the plane } y_3 = H. \]

The half space is \(y_3 \geq H\).

\[ \text{(1.5)} \]

\[ \text{(1.6)} \]

\[ \therefore \text{The inertia term } \frac{\partial^2 u_1}{\partial t^2} \text{ is extremely small. Therefore, we neglect it.} \]

\[ \therefore \text{We have the stress equation of motion as} \]

\[ \frac{\partial}{\partial y_1} \left( \tau^1_{11} \right) + \frac{\partial}{\partial y_2} \left( \tau^1_{12} \right) + \frac{\partial}{\partial y_3} \left( \tau^1_{13} \right) = \rho \frac{\partial^2 u_1}{\partial t^2} \]

\[ \therefore \text{Since displacement, stress and strain are independent of } y_1 \text{ therefore the stress equation becomes,} \]

\[ \frac{\partial}{\partial y_2} \left( \tau^1_{12} \right) + \frac{\partial}{\partial y_3} \left( \tau^1_{13} \right) = \rho \frac{\partial^2 u_1}{\partial t^2} \]

\[ \rho = \text{average density of } M_1 \]

\[ \therefore \text{Since our observation is in the aseismic period while the order of displacement is } 10^{-4} \text{ c.g.s. unit or less.} \]

\[ \therefore \text{We have the constitutive equations (i.e., stress - strain relation) as, for the layer } M_1, \]

\[ \left( \begin{array}{c} \frac{1}{\eta_1} + \frac{1}{\mu_1} \frac{\partial}{\partial y_1} \\ \frac{1}{\eta_1} \end{array} \right) \tau_{12}' = \frac{\partial}{\partial t} \left( e_{12}' \right) = \frac{\partial}{\partial y_2} \left( \frac{\partial u_1}{\partial y_2} \right) \]

\[ \left( \begin{array}{c} \frac{1}{\eta_2} + \frac{1}{\mu_2} \frac{\partial}{\partial y_2} \\ \frac{1}{\eta_2} \end{array} \right) \tau_{13}' = \frac{\partial}{\partial t} \left( e_{13}' \right) = \frac{\partial}{\partial y_3} \left( \frac{\partial u_1}{\partial y_3} \right) \]

2.1. Constitutive Equations

For perfect elastic body we know as soon as the stress is removed. The strain also disappears but for viscoelastic body, the strain does not at once remove.

To incorporate the viscoelastic effects stress-strain relations of a slightly different form have been suggested.

We have the constitutive equations (i.e., stress - strain relation) as, for the layer \(M_1\),

\[ \left( \begin{array}{c} \frac{1}{\eta_1} + \frac{1}{\mu_1} \frac{\partial}{\partial y_1} \\ \frac{1}{\eta_1} \end{array} \right) \tau_{12}' = \frac{\partial}{\partial t} \left( e_{12}' \right) = \frac{\partial}{\partial y_2} \left( \frac{\partial u_1}{\partial y_2} \right) \]

\[ \left( \begin{array}{c} \frac{1}{\eta_2} + \frac{1}{\mu_2} \frac{\partial}{\partial y_2} \\ \frac{1}{\eta_2} \end{array} \right) \tau_{13}' = \frac{\partial}{\partial t} \left( e_{13}' \right) = \frac{\partial}{\partial y_3} \left( \frac{\partial u_1}{\partial y_3} \right) \]

For the half space \(M_2\)

\[ \left( \begin{array}{c} \frac{1}{\eta_1} + \frac{1}{\mu_1} \frac{\partial}{\partial y_1} \\ \frac{1}{\eta_1} \end{array} \right) \tau_{12}^2 = \frac{\partial}{\partial t} \left( e_{12}^2 \right) = \frac{\partial}{\partial y_2} \left( \frac{\partial u_2}{\partial y_2} \right) \]

\[ \left( \begin{array}{c} \frac{1}{\eta_2} + \frac{1}{\mu_2} \frac{\partial}{\partial y_2} \\ \frac{1}{\eta_2} \end{array} \right) \tau_{13}^2 = \frac{\partial}{\partial t} \left( e_{13}^2 \right) = \frac{\partial}{\partial y_3} \left( \frac{\partial u_2}{\partial y_3} \right) \]

\[ \therefore \text{we have the stress equation of motion as} \]

\[ \frac{\partial}{\partial y_1} \tau_{12}^1 + \frac{\partial}{\partial y_2} \tau_{12}^1 + \frac{\partial}{\partial y_3} \tau_{13}^1 = \rho \frac{\partial^2 u_1}{\partial t^2} \]

\[ \therefore \text{Since displacement, stress and strain are independent of } y_1 \text{ therefore the stress equation becomes,} \]

\[ \frac{\partial}{\partial y_2} \tau_{12}^1 + \frac{\partial}{\partial y_3} \tau_{13}^1 = \rho \frac{\partial^2 u_1}{\partial t^2} \]

\[ \rho = \text{average density of } M_1 \]

\[ \therefore \text{Since our observation is in the aseismic period while the order of displacement is } 10^{-4} \text{ c.g.s. unit or less.} \]

\[ \therefore \text{The inertial term } \frac{\partial^2 u_1}{\partial t^2} \text{ is extremely small. Therefore, we neglect it.} \]

\[ \text{Stress equation of motion for the layer } M_1 \text{ is} \]

\[ \frac{\partial}{\partial y_2} \left( \tau_{12}^1 \right) + \frac{\partial}{\partial y_3} \left( \tau_{13}^1 \right) = 0 \]

\[ \text{for} \ (-\infty < y_2 < \infty, 0 \leq y_3 \leq H, t \geq 0) \]

Similarly for the half space \(M_2\)

\[ \frac{\partial}{\partial y_2} \left( \tau_{12}^2 \right) + \frac{\partial}{\partial y_3} \left( \tau_{13}^2 \right) = 0 \]

\[ \text{for} \ (-\infty < y_2 < \infty, y_3 \geq H, t \geq 0) \]

Now differentiating partially (1) With respect to \(y_2\), (2) with respect to \(y_3\) and adding and using (5) we get, \(u_2 = 0\) for

\[ \therefore \text{we get, } u_2 = 0 \]

\[ \text{for} \ (-\infty < y_1 < \infty, 0 \leq y_3 \leq H, t \geq 0) \]

\[ \text{[by (1.3), (1.4), (1.6)]} \]

Since we are concentrating 2D problem in which the length of the fault is large compared to the depth of it.

We take displacement, stress, strain to be independent of \(y_1\) and dependent on \(y_2, y_3, t\) where ‘t’ is the time measured after the establishment of aseismic state.

Let the components of displacement, stress and strain in the layer \(M_1\) be \(u_1, \tau^1_{12}, \tau^1_{13}, e^1_{12}, e^1_{13}\) respectively and in the half space \(M_2\) be \(u_2, \tau^2_{12}, \tau^2_{13}, e^2_{12}, e^2_{13}\) respectively.

Since we are considering strike-slip movement only, we are not considering the other components of displacements, stresses, strains (\(u_2, u_3, \tau_{22}, \tau_{33}\), etc.)

In our model \(M_1\) is isotropic-homogeneous layer of rigidly modulus \(\mu_1\), effective viscosity \(\eta_1\) (say).\(M_2\) is another isotropic homogeneous half space of rigidity modulus \(\mu_2\) and effective viscosity \(\eta_2\) (say).
3. Solutions in Absence of Fault Creep

Solving the boundary value problem, (1.12)-(1.15) We get,

\[
\begin{align*}
\tau_1^{12} & = \tau_{\infty}(t) - \tau_{\infty}(0) + \left( \frac{\mu_1}{\eta_1} \right) \int_{0}^{t} \tau_{\infty}(\tau) d\tau \\
\tau_1^{13} & = \tau_{H} \left( 1 - e^{-\frac{\mu_1}{\eta_1}} \right) + \left( \frac{\mu_1}{\eta_1} \right) e^{-\frac{\mu_1}{\eta_1}} 
\end{align*}
\]

If we take \( \tau_{\infty}(t) = \text{constant} = \tau_{\infty} \) (say)

Then,

\[
\begin{align*}
u_t(y_1, y_2, t) & = \left( \frac{\mu_1}{\eta_1} \right) y_2 + \frac{y_2}{\eta_1} \tau_{\infty} t + y_3 \frac{\tau_{H} - t}{\eta_1} \\
\therefore \quad e^{12} & = \frac{\partial u_t}{\partial y_2} = \frac{\partial}{\partial y_2} \left( \frac{\mu_1}{\eta_1} \right) y_2 + \frac{\tau_{\infty}}{\eta_1} t \\
\therefore \quad \frac{d}{dt} (e^{12}) & = \frac{\tau_{\infty}}{\eta_1}
\end{align*}
\]

If we take \( \tau_{\infty} = 200 \text{ bars} = 200 \times 10^6 \text{ dynes/cm}^2 \) and \( \eta_1 = 1 \times 10^{21} \text{ poise} \) then, \( \tau_{\infty} = 2 \times 10^{-13} \text{ /sec} = 6 \times 10^{-6} \text{ / year} \)

which tally with the observational value which is order \( 10^{-6} \) to \( 10^{-7} \).

4. Displacements and Stresses after the Commencement of Fault Creep across the Fault \( F_1 :([24],[25]) \)

In our paper we are considering 1 creeping fault in the layer \( M_1 \).

If the creep commences across \( F \) at time \( t = T_1 \), then the relations (1.1) to (1.10) are satisfied and we have the following creeping conditions.

\[
[u_t]_{F_1} = u_1(t_1) f_1(y_3) H(t_1)
\]

Where \( F \) is the fault located in the region \( y_2 = 0, \theta \leq y_3 \leq D_1 \) and \( t_1 = t - T_1 \),

\[
[u_t]_{F_1} \text{ is the discontinuity in the displacement } u_1 \text{ across the fault } F_1.
\]

\[
(u_1)_{F_1} = \lim_{y_2 \to 0+} u_1 - \lim_{y_2 \to 0-} u_1 \quad (0 \leq y_3 \leq D_1)
\]

\[
[u_t]_{F_1} = 0 \text{ for } t_1 \leq 0 \text{ and } H(t_1) \text{ Heaviside unit step function.}
\]

\[
\frac{\partial}{\partial t} (u_t)_{F_1} = V_1(t_1) f_1(y_3) H(t_1)
\]

where

\[
V_1(t_1) = \frac{\partial}{\partial t} u_1(t_1) = \frac{\partial}{\partial t_1} u_1(t_1)
\]

Taking Laplace transformation of (3.1)

\[
[u_t]_{F_1} = u_1(p_1) f_1(y_3) \text{ for, } y_2 = 0, \delta \leq y_3 \leq D_1
\]

where \( u_1(p_1) \) is the Laplace transformation of \( u_1(t_1) \) with respect to \( t_1 \) and is given by

\[
u_1(p_1) = \int_{0}^{\infty} e^{-p_1 t} u_1(t_1) dt_1
\]

Now we try to find \( u_1, \tau_{12}^{-1}, \tau_{13}^{-1} \) in the form,

\[
\begin{align*}
u_1 & = (u_1)_{1} + (u_1)_{2} + (u_1)_{3} = (t_{12})_{1} + (t_{12})_{2} + (t_{13})_{1} \\
& = (t_{12})_{1} + (t_{13})_{2}
\end{align*}
\]

where \( (u_1)_{1}, (\tau_{12})_{1}, (\tau_{13})_{1} \) are continuous everywhere and are therefore given by (2.1), (2.1.1), (2.1.27).

We are only to find \( (u_1)_{2}, (\tau_{12})_{2}, (\tau_{13})_{2} \) which depend on the fault creep across \( F_1 \). The values of \( (u_1)_{2}, (\tau_{12})_{2}, (\tau_{13})_{2} \) are assumed to be zero for \( t \leq T_1 \).

We have the new constitutive equations

\[
\begin{align*}
\left( \frac{1}{\eta_1} + \frac{1}{\mu_1} \right) \tau_{12}^{12} & = \frac{\partial}{\partial t} (e^{12})_{2} = \frac{\partial}{\partial t} (u_1)_{2} \quad (3.4) \\
\left( \frac{1}{\eta_1} + \frac{1}{\mu_1} \right) \tau_{13}^{13} & = \frac{\partial}{\partial t} (e^{13})_{2} = \frac{\partial}{\partial t} (u_1)_{2} \quad (3.5)
\end{align*}
\]

Now stress equation of motion
\[ \frac{\partial}{\partial y_2} (\tau_{12})_2 + \frac{\partial}{\partial y_2} (\tau_{13})_2 = 0 \] (3.6) Proceeding as before, we get,
\[ \nabla^2 (u_{1})_2 = 0 \] (3.7) New set of boundary conditions
\[ (\tau_{13})_2 = 0, \quad y_3 = H (\infty < y_2 < \infty, \quad t_1 \geq 0) \] (3.8)
\[ (\tau_{12})_2 = 0, \quad (y_2, y_3) \rightarrow \infty (y_3 \geq 0, \quad t_1 \geq 0) \] (3.9) We are to solve (3.7) – (3.9).
We take Laplace Transformation of (3.7) – (3.9)
\[ \nabla^2 (u_{1})_2 = 0 \] (3.10),
where the Green’s function, then using
\[ (\tau_{12})_2 = \bar{\mu}_1 \frac{\partial (\bar{u}_1)}{\partial y_2} \] (3.12)
\[ (\tau_{13})_2 = \bar{\mu}_1 \frac{\partial (\bar{u}_1)}{\partial y_3} \] (3.13) We shall get (\bar{\tau}_{12})_2, (\bar{\tau}_{13})_2, finally, inverse Laplace Transform of which will give (u_{1})_2 (t_1, y_2, y_3).
Now let Q (y_1, y_2, y_3) be any point in the M_1 and P (x, x_2, x_3) be any point on F_1. The by modified Green’s function technique by (\bar{\eta}_2)([21]), to get (u_{1})_2 and then using
\[ (\bar{u}_1)_2 (Q) = \int_{F_1} \left[ \bar{u}_1 (P) G (P, Q) \right] dx_3 \] (3.14) where \( G (P, Q) \) is the G.F. and (\bar{u}_1)_2 (P) is the discontinuity in [(\bar{u}_1)_2] across \( F_1 \) and is given by
\[ [(\bar{u}_1)_2 (P)] = u_1 (P) \eta_1 (y_3) \] where \( \eta_1 \) = Laplace transformation variable.
Therefore we get, \( (\bar{u}_1)_2 (Q) = \int_{F_1} \bar{u}_1 (P) f_1 (x, x_2, x_3) dx_3 \) (3.15)
where the Green’s function,
\[ G (P, Q) = \bar{\mu}_1 (\bar{\partial}/\bar{\partial}x_3) G_0 (P, Q) \]
where, \( G_0 (P, Q) = (1/4\pi \bar{\mu}_1) \log[(x_2-y_2)^2+(x_3-y_3)^2]+\log[(x_2-y_2)^2+(x_3-y_3)^2]+\sum_{i=1}^{\infty} \left( \bar{\mu}_1 - \bar{\mu}_2 \right)/(\bar{\mu}_1 + \bar{\mu}_2) \]
\[ \right) \end{array} \] (3.16) \[ G (P, Q) = -(1/2 \times 3.142) \left[ \begin{array}{c} (y_2-x_2)^2+(y_3-x_3)^2 \\ (y_2-x_2)^2+(y_3-x_3)^2 \end{array} \right] + \frac{(y_2-x_2)^2+(y_3-x_3)^2}{(1/2\pi) \sum_{i=1}^{\infty} \left( \bar{\mu}_1 - \bar{\mu}_2 \right)/(\bar{\mu}_1 + \bar{\mu}_2)} \] (3.17) Thus we have,
\[ (\bar{u}_1)_2 (Q) = \int_{F_1} \bar{u}_1 (P) f_1 (x, x_2, x_3) \left[ \begin{array}{c} (y_2-x_2)^2+(y_3-x_3)^2 \\ (y_2-x_2)^2+(y_3-x_3)^2 \end{array} \right] + \frac{(y_2-x_2)^2+(y_3-x_3)^2}{(1/2\pi) \sum_{i=1}^{\infty} \left( \bar{\mu}_1 - \bar{\mu}_2 \right)/(\bar{\mu}_1 + \bar{\mu}_2)} \] (3.18) where \( f_3 (x_3) \) is creep function.
On the fault \( F_1, x_2 = 0 \)
Let,
\[ \phi (y_1, y_2, y_3) = \int_{0}^{\infty} f_3 (x_3) \left[ \begin{array}{c} (y_2-x_2)^2+(y_3-x_3)^2 \\ (y_2-x_2)^2+(y_3-x_3)^2 \end{array} \right] + \frac{(y_2-x_2)^2+(y_3-x_3)^2}{(1/2\pi) \sum_{i=1}^{\infty} \left( \bar{\mu}_1 - \bar{\mu}_2 \right)/(\bar{\mu}_1 + \bar{\mu}_2)} \] (3.19) Therefore we get,
\[ (\bar{\tau}_{12})_2 = \frac{\mu P}{P + \mu_1} \bar{u}_1 (P) / \eta_1 \] (3.20) \[ \int_{0}^{\infty} \int_{F_1} \bar{u}_1 (P) f_1 (x_3) \left[ \begin{array}{c} (y_2-x_2)^2+(y_3-x_3)^2 \\ (y_2-x_2)^2+(y_3-x_3)^2 \end{array} \right] + \frac{(y_2-x_2)^2+(y_3-x_3)^2}{(1/2\pi) \sum_{i=1}^{\infty} \left( \bar{\mu}_1 - \bar{\mu}_2 \right)/(\bar{\mu}_1 + \bar{\mu}_2)} \] (3.21) \[ \int_{F_1} \bar{u}_1 (P) f_1 (x_3) \left[ \begin{array}{c} (y_2-x_2)^2+(y_3-x_3)^2 \\ (y_2-x_2)^2+(y_3-x_3)^2 \end{array} \right] + \frac{(y_2-x_2)^2+(y_3-x_3)^2}{(1/2\pi) \sum_{i=1}^{\infty} \left( \bar{\mu}_1 - \bar{\mu}_2 \right)/(\bar{\mu}_1 + \bar{\mu}_2)} \] (3.22) Similarly we get,
\[ (\bar{\tau}_{12})_2 = \frac{\mu_1}{2\pi} \bar{u}_2 (y_2, y_3) \] (3.23)
5. Numerical Computations

Following [1] and recent studies on rheological behavior of crust and upper mantle by ([4],[7]) the values of the model parameters are taken as:

\[ \mu_1 = 3 \times 10^{11} \text{ dynes/cm}^2, \mu_2 = 2 \times 10^{11} \text{ dynes/cm}^2, \eta_1 = 2.10, \text{ and } \eta_2 = 3 \times 10^{11} \text{ poise}. \]

\[ D_1 = \text{Depth of the fault} = 40 \text{ km}, \text{nothing that the depth of all major earthquake faults is in between 10-35 km}. \]

\[ \tau_{\infty}(t) = \text{const.} \quad \tau_{\infty} = 2 \times 10^5 \text{ dynes/cm}^2 \quad \text{(200 bars)} \]

We take the creep function:

\[ f(x_j) = 1 - \frac{3}{D_1^2} x_j^2 + \frac{2}{D_1} x_j^3, \text{with} \]

\[ U = 1 \text{ cm/year}, \text{satisfying the conditions stated in } (C_1) - (C_2). \]

The rate of change of shear strain is:

\[ \partial \tau(t) = \nabla \tau \cdot \nabla \sigma + \nabla \cdot \tau \nabla \sigma, \]

\[ \text{with} \quad \text{max. shear strain} \text{ for } \text{the case of} \text{ earthquake} \text{ is } 2.1 \times 10^{-3}. \]

6. Discussions and Conclusions

(A) Variation of displacement due to the creep movement across the fault after \( t = 1 \text{ year}. \)

Equation (3.24) gives the displacement \( U \) at any point \((y_3,x_3,t)\) at any time \( t \), due to the fault movement across the fault F. Figure 2 shows the variation of displacement \( U \) with depth \( y_3 \) for \( y_3 = 8 \text{ km}, t = 1 \text{ year. It is observed that maximum displacement occurred at } y_3 = 0 \text{ and its magnitude is } 2.25 \text{ cm/year and it gradually decreases to zero at a depth about } 100 \text{ km from the free surface}. \)

We observe that the displacement has a discontinuity at \( y_3 = 0 \text{ km} \) and is antisymmetric about the fault plane.
Figure 2. shows the variation of displacement $U_1$ with depth $y_3$ for $y_2=8$km, $t_1=1$year due to fault movement.

Figure 3. shows the variation of surface displacement $U_1$ for $y_3=0$km and $t_1=1$year with $y_2$ due to the fault movement across the fault F.

(B) Rate of change of surface displacement before fault movement.

Equation (3.24) gives the displacement $u_1$ at any point $(y_2, y_3)$ at any time $t$, before the fault movement across the fault F. We have $\frac{\partial u_1}{\partial t}=y_2 \tau_1(t)/\eta_1$ which represents a straight line through the origin with slope $<<1$.

(C) Variation of stress $12(t_{12})$, which is the main driving force) due to the creep movement across the fault after $t_1=1$year.

Equation (3.25) gives the stress component $12$ at any point $(y_2, y_3)$ at any time $t$, due to the fault movement across the fault $F$.

Fig 4 shows the variation of stress $t_{12}$ with $y_3$ for $y_2=5$km, $t_1=1$year due to the fault movement across the fault $F$.

We observe that stress $12$ releases up to a depth about 20km and then begin to accumulate. The maximum accumulation occurred at a depth about 40km with a magnitude of about 0.39 bar per year but the rate of accumulation gradually decreases to zero at a depth of about 150km.

(D) Variation of surface shear strain $E_{12}$ with time $t$.

Equation (3.26) gives the rate of change of shear stress $t_{12}$.

Fig 5 shows the variation of stress $t_{12}$ with time $t$. It is observed that the graph is a straight line parallel to time axis, i.e. the rate of change of shear stress is constant.

(E) Variation of surface shear strain $E_{12}$ (say) for $t_1=1$ year for $y_3=0$km with $y_2$ due to the fault movement.

Equation (3.26) gives the variation of surface shear strain $E_{12}$ Fig 6 shows the variation of surface shear strain $E_{12}$ with $y_2$ for $y_3=0$km and $t=1$ year due to the fault movement. It is observed that the surface shear strain is maximum near $y_2=0$, its magnitude is $2*10^{-6}$ and gradually decreases as we go away from the fault.
Equation (3.27) gives the rate of change of shear strain $e_{12}$. Fig 7 shows the variation of stress $e_{12}$ with time $t$. It is observed that the graph is a straight line through the origin and its magnitude is of order $10^{-6}$ which well matched with the observational data.

$U_1$ is the component of displacement, $t_{12}$ is stress component and $E_{12}$ is the component of shear strain due to faults.
the fault movement]

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