Nature Of Stress-Strain Accumulation Due To A Reatangular Finite Fault In A Viscoelastic Layer Over A Viscoelastic Half-Space.

Subrata Kr. Debnath.

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 layer over a viscoelastic half space representing the lithosphere-asthenosphere system has been considered here. Stresses and strain 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 analytical 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-strain accumulation in the system, which in turn will be helpful in formulating an effective **earthquake prediction** programme.

Key words: - Aseismic period, Earthquake prediction**.** Finite fault, Mantle convection, Plate movements, Stress accumulation, Tectonic process, Viscoelastic layer.

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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 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 3 km. ice cover melted gradually leading and upliftment of the regions .Evidence of this upliftment has been discussed in the work of [10] , [27] , [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 [31] , [32] , [15] , [16] , [4] , [7] , [6] . Chinnery, M.A. and Dushan B. Jovanovich [5] 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 [24] , [25] , [22] , [30] , [2] , [23] , [17] , [18] , [19] , [20] , [8] , [28] , [25] , [10] , [29] , [12] , [9] . Paul Segall [26] has discussed various aspects of fault movement in his book. Ghosh, U and Sen, S [11] have discussed stress accumulation near buried fault in lithosphere-asthenosphere system. 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 a strike-slip fault of finite length situated in a viscoelastic layer over a viscoelastic half-space 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.

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2. Formulation:

We consider a strike-slip fault F of length 2L (L-finite) and width D situated in a viscoelastic layer of thickness H(say) over 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 fault is given by F : ($-L \le y_1 \le L$, $y_2 = 0$, $0 \le y_3 \le D$) as shown in fig1. Let (u^k_i), (τ^k_{ij}) and (e^k_{ij}) be the displacement, stress and strain components, i, j=1, 2, 3. And k=1 for the layer and k=2 for the half-space.

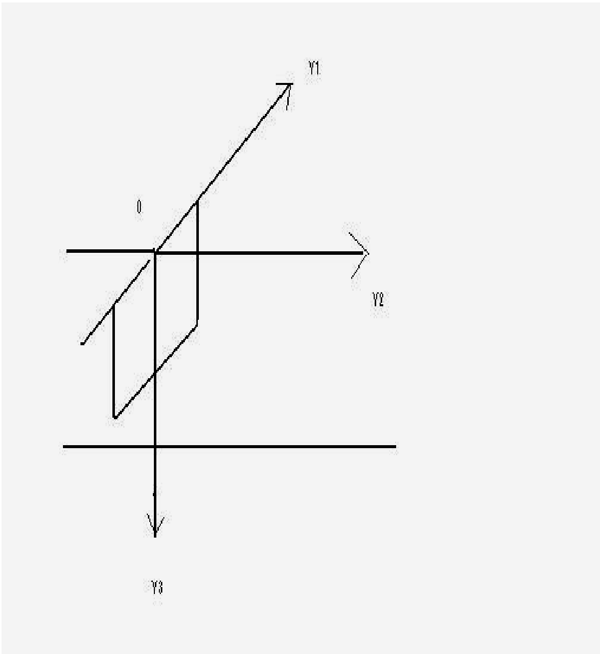


Fig 1:Section of the model by the plane y_1=0.

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

$$\left(\frac{1}{\eta_k}+\frac{1}{\mu_k}\frac{\partial}{\partial t}\right)\tau^k_{11}=\frac{\partial}{\partial t}(e^k_{11})=\frac{\partial}{\partial t}\left(\frac{\partial u^k_1}{\partial y_1}\right) \tag{1.1}$$

$$\left(\frac{1}{\eta_k}+\frac{1}{\mu_k}\frac{\partial}{\partial t}\right)\tau^k_{12}=\frac{\partial}{\partial t}(e^k{}_{12})=\left(\frac{1}{2}\right)\frac{\partial}{\partial t}\left(\frac{\partial u^k_1}{\partial y_2}+\frac{\partial u^k_2}{\partial y_1}\right) \tag{1.2}$$

$$\left(\frac{1}{\eta_k}+\frac{1}{\mu_k}\frac{\partial}{\partial t}\right)\tau^k_{13}=\frac{\partial}{\partial t}(e^k{}_{13})$$
$$=\left(\frac{1}{2}\right)\frac{\partial}{\partial t}\left(\frac{\partial u^k_1}{\partial y_3}+\frac{\partial u^k_3}{\partial y_1}\right) \tag{1.3}$$

$$\left(\frac{1}{\eta_k}+\frac{1}{\mu_k}\frac{\partial}{\partial t}\right)\tau^k{}_{22}=\frac{\partial}{\partial t}(e^k{}_{22})=\frac{\partial}{\partial t}\left(\frac{\partial u^k_2}{\partial y_2}\right) \tag{1.4}$$

$$\left(\frac{1}{\eta_k}+\frac{1}{\mu_k}\frac{\partial}{\partial t}\right)\tau^k{}_{23}=\frac{\partial}{\partial t}(e^k{}_{23})$$
$$=\left(\frac{1}{2}\right)\frac{\partial}{\partial t}\left(\frac{\partial u^k_2}{\partial y_3}+\frac{\partial u^k_3}{\partial y_2}\right) \tag{1.5}$$

$$\left(\frac{1}{\eta_k}+\frac{1}{\mu_k}\frac{\partial}{\partial t}\right)\tau^k{}_{33}=\frac{\partial}{\partial t}(e^k{}_{23})=\frac{\partial}{\partial t}\left(\frac{\partial u^k_3}{\partial y_3}\right) \tag{1.6}$$

k=1 for the layer and k=2 for the half-space.

where η_k is the effective viscosity and is the effective rigidity of the material.

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.

$$\frac{\partial}{\partial y_1}(\tau^k{}_{11})+\frac{\partial}{\partial y_2}(\tau^k{}_{12})+\frac{\partial}{\partial y_3}(\tau^k{}_{13})=0 \tag{1.7}$$

$$\frac{\partial}{\partial y_1}(\tau^k{}_{21})+\frac{\partial}{\partial y_2}(\tau^k{}_{22})+\frac{\partial}{\partial y_3}(\tau^k{}_{23})=0 \tag{1.8}$$

$$\frac{\partial}{\partial y_1}(\tau^k{}_{31})+\frac{\partial}{\partial y_2}(\tau^k{}_{32})+\frac{\partial}{\partial y_3}(\tau^k{}_{33})=0 \tag{1.9}$$

where ($-\infty<y_1<\infty$, $-\infty<y_2<\infty$, $0\le y_3\le H$, $t\ge 0$) for the layer and ($-\infty<y_1<\infty$, $-\infty<y_2<\infty$, $y_3\ge H$, $t\ge 0$) for the half-space.

Boundary conditions:

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

$$\lim_{y_1\to L-}\tau^1{}_{11}(y_1,y_2,y_3,t)=$$
$$\lim_{y_1\to L+}\tau^1{}_{11}(y_1,y_2,y_3,t)=\tau_L \text{ (say)},$$

$y_2 = 0$, $0\le y_3\le D$, $t\ge 0$ (1.10)

$$\lim_{y_1\to -L-}\tau^1{}_{11}(y_1,y_2,y_3,t)$$
$$=\lim_{y_1\to -L+}\tau^1{}_{11}(y_1,y_2,y_3,t)=\tau_{-L} \text{ (say)}$$

for $y_2 = 0$, $0 \le y_3 \le D$, $t \ge 0$ (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] .

$\tau^1{}_{12}(y_1,y_2,y_3,t)\to\tau_\infty(t)$ for

$$-\infty < y_1 < \infty, -\infty < y_2 < \infty, 0 \le y_3 \le H, t \ge 0 \quad (1.12)$$

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

$$\tau^1{}_{13}(y_1, y_2, y_3, t) = 0 \quad (1.13)$$

$$\tau^1{}_{23}(y_1, y_2, y_3, t) = 0 \quad (1.14)$$

$$\tau^1{}_{33}(y_1, y_2, y_3, t) = 0 \quad (1.15)$$

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

$$\tau^2{}_{13}(y_1, y_2, y_3, t) = 0 \quad (1.16)$$

$$\tau^2{}_{23}(y_1, y_2, y_3, t) = 0 \quad (1.17)$$

$$\tau^2{}_{33}(y_1, y_2, y_3, t) = 0 \quad (1.18)$$

$$\tau^2{}_{22}(y_1, y_2, y_3, t) = 0$$

as $-\infty < y_1 < \infty, -\infty < y_2 < \infty, y_3 \ge H, t \ge 0$ (1.19)

On the interface **,**

$$y_3 = H, (-\infty < y_1, y_2 < \infty, t \ge 0)$$

$$\tau^1{}_{13}(y_1, y_2, y_3, t) = \tau^2{}_{13}(y_1, y_2, y_3, t) \quad (1.20)$$

$$\tau^1{}_{23}(y_1, y_2, y_3, t) = \tau^2{}_{23}(y_1, y_2, y_3, t) \quad (1.21)$$

$$\tau^1{}_{33}(y_1, y_2, y_3, t) = \tau^1{}_{33}(y_1, y_2, y_3, t) \quad (1.22)$$

$$u_3^1(y_1,y_2,y_3,t)=u_3^2(y_1,y_2,y_3,t) \quad (1.23)$$

[where $\tau_\infty(t)$ is the shear stress maintained by tectonic forces which arises due to mantle convection and other tectonic phenomena] .

The initial conditions:

Let $(u^1{}_i)_0$, $(\tau^1{}_{ij})_0$ and $(e^1{}_{ij})_0$ i,j = 1,2,3 be the value of $(u^1{}_i)$, ($\tau^1{}_{ij}$) and ($e^1{}_{ij}$) at time t=0 which are functions of y_1,y_2,y_3 and satisfy the relations (1.1)-(1.23).

(3) Solutions before fault movement:

([31] , [32]).

The boundary value problem given by (1.1)-(1.23), can be solved (as shown in the Appendix-I) 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:

$$u^1{}_1(y_1, y_2, y_3, t) = (u^1{}_1)_0 + \left(\frac{\tau_L}{\mu_1}\right) y_1 t$$
$$+ (y_2/\mu_1)\left[(\tau_\infty(t) - \tau_\infty(0)) + \left(\frac{\mu_1}{\eta_1}\right)\int_0^t \tau_\infty(\tau) d\tau\right]$$

$$u^1{}_2(y_1, y_2, y_3, t) = (u^1{}_2)_0 + ((y_1 + y_2)/\mu_1) \times$$
$$\times\left[(\tau_\infty(t) - \tau_\infty(0)) + \left(\frac{\mu_1}{\eta_1}\right)\int_0^t \tau_\infty(\tau) d\tau\right]$$

$$u^1{}_3(y_1, y_2, y_3, t) = (u^1{}_3)_0$$

$$\tau^1{}_{11} = \left(\frac{\mu_1}{\eta_1}\right)\tau_L(1 - e^{-(\mu_1/\eta_1)t}) + (\tau^1{}_{11})_0 e^{-(\mu_1/\eta_1)t}$$

$$\tau^1{}_{12} = \tau_\infty(t) - \left[\tau_\infty(0) - (\tau^1{}_{12})_0\right] e^{-(\mu_1/\eta_1)t}$$

$$\tau^1{}_{13} = (\tau^1{}_{13})_0 e^{-(\mu_1/\eta_1)t} \quad \tau^1{}_{22} = (\tau^1{}_{22})_0 e^{-(\mu_1/\eta_1)t}$$

$$\tau^1{}_{23} = (\tau^1{}_{23})_0 e^{-(\mu_1/\eta_1)t} \quad \tau^1{}_{33} = (\tau^1{}_{33})_0 \quad \text{(A)}$$

From the above solution we find that $\tau^1{}_{12}$ increases with time and tends to $\tau_\infty(t)$ as t tends to ∞, while $\tau^1{}_{22}$, $\tau^1{}_{23}$ tends to zero, but $\tau^1{}_{33}$ retains the constant value $(\tau^1{}_{33})_0$. We assume that the geological conditions as well as the characteristic of the fault in such that when $\tau^1{}_{12}$ reaches some critical value, say $\tau_c < \tau_\infty(t)$ the fault F starts creeping. The magnitude of slip 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 ($y_1=\pm L$, y_2=0, $0 \le y_3 \le D$) along its length.

(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 fault.

$$(y_1 = \pm L, y_2 = 0, y_3 = D)$$

The function, $f(y_1, y_2)$ satisfy the above conditions.[we call it creep function]

(4) Solutions after fault movement:

([31] ,[32])

We assume that after a time T_1, the stress component $\tau^1{}_{12}$ (which is the main driving force for the strike-slip motion of the fault) exceeds the critical value τ_c, and the fault *F* starts creeping, characterized by a dislocation across the fault. We solve the resulting boundary value problem by modified Green's function method following [17] , [18] , [26] and correspondence principle (As shown in the Appendix 2) and get the solution for displacements, stresses and strain as :

$$u^1{}_1(y_1,y_2,y_3,t)=(u^1{}_1)_0+(\tau_L/\mu_1)y_1t+(y_2/\mu_1)$$

$$\left[(\tau_\infty(t)-\tau_\infty(0)+(\mu_1/\eta_1)\int_0^t \tau_\infty(\tau)d\tau\right]+H(t-T_1)/(2\times\pi)$$

$$\int_{-L}^{L}\int_0^D f(x_1,x_3)[(y_2/[(y_1-x_1)^2+(y_2-x_2)^2$$

$$+(y_3-x_3)^2]^{3/2}-(y_2/[(y_1+x_1)^2+$$

$$+(y_2-x_2)^2+(y_3-x_3)^2]^{3/2}]$$

$$-\sum_1^\infty (a/b)^m\{1+\sum_{r=1}^{m}\binom{m}{r}[b_1^r/(r-1)!]\,t^{(r-1)}e^{(-a_1t)}$$

[{(x2-y2)/[(y1-x1)^2+(x2–y2)^2+(x3-2mH–y3)^2] +(x2-y2)/[(y1-x1)^2+(x2–y2)^2+(x3-2mH+y3)^2] +(x2-y2)/[(y1-x1)^2+(x2–y2)^2+(x3+2mH+y3)^2] +(x2-y2)/[(y1-x1)^2+(x2–y2)^2+(x3+2mH-y3)^2] }□dx3dx1]

$$u^1{}_2(y_1,y_2,y_3,t)=(u^1{}_2)_0+((y_1+y_2)/\mu_1)\times$$

$$\times\left[(\tau_\infty(t)-\tau_\infty(0))+\left(\frac{\mu_1}{\eta_1}\right)\int_0^t \tau_\infty(\tau)d\tau\right]$$

$$u^1{}_3(y_1,y_2,y_3,t)=(u^1{}_3)_0$$

$$\tau^1{}_{11}(y_1,y_2,y_3,t)=(\mu_1/\eta)\tau_L(1-e^{(-\mu_1/\eta_1)t})+$$

$$+(\tau^1{}_{11})_0e^{(-\mu_1/\eta_1)t}+[H(t-T_1)/(2\times\pi)][u_1(t_1)-$$

$$-\mu_1/\eta_1\int_0^t u(\tau)e^{(-\mu_1/\eta_1)(t-\tau)}d\tau\Big]\times$$

$$\frac{\partial}{\partial y_1}\Big(\int\int_F f_1(x_1,x_3)\times$$

$$\frac{(y_2-x_2)}{\left[(y_1-x_1)^2+(y_2-x_2)^2+(y_3-x_3)^2\right]^{\frac{3}{2}}}$$

$$-\frac{(y_2-x_2)}{\left[(y_1+x_1)^2+(y_2-x_2)^2+(y_3-x_3)^2\right]^{3/2}}$$

$$-(1/4\pi)\sum_1^\infty (a/b)^m\{1+\sum_{r=1}^{m}\binom{m}{r}[b_1^r/(r-1)!]$$

$t^{(r-1)}e^{(-a_1t)}$

{(x2-y2)/[(y1-x1)^2+(x2–y2)^2+(x3-2mH–y3)^2] + (x2-y2)/[(y1-x1)^2+(x2–y2)^2+(x3-2mH+y3)^2] +(x2-y2)/[(y1-x1)^2+(x2–y2)^2+(x3+2mH+y3)^2] +(x2-y2)/[(y1-x1)^2+(x2–y2)^2+(x3+2mH-y3)^2] })dx3dx1)

$$\tau^1{}_{12}(y_1,y_2,y_3,t)=$$

$$\tau_\infty(t)-(\tau_\infty(0)-(\tau^1{}_{12})_0)e^{(-\mu_1/\eta_1)t}$$

$$+[H(t-T_1)/(2\times\pi)][u_1(t_1)$$

$$-\mu_1/\eta_1\int_0^t u(\tau)e^{(-\mu_1/\eta_1)(t-\tau)}d\tau]\times$$

$$\frac{\partial}{\partial y_2}\Big(\int\int_F f_1(x_1,x_3)\times$$

$$\frac{(y_2-x_2)}{\left[(y_1-x_1)^2+(y_2-x_2)^2+(y_3-x_3)^2\right]^{\frac{3}{2}}}$$

$$-\frac{(y_2-x_2)}{\left[(y_1+x_1)^2+(y_2-x_2)^2+(y_3-x_3)^2\right]^{3/2}}$$

$$-(1/4\pi)\sum_1^\infty (a/b)^m\{1+\sum_{r=1}^{m}\binom{m}{r}[b_1^r/(r-1)!]$$

$t^{(r-1)}e^{(-a_1t)}$ {(y2)/[(y1-x1)^2+(x2–y2)^2+(x3-2mH–y3)^2] +(y2)/[(y1-x1)^2+(x2–y2)^2+(x3-2mH+y3)^2] +(y2)/[(y1-x1)^2+(x2–y2)^2+(x3+2mH+y3)^2] +(y2)/[(y1-x1)^2+(x2–y2)^2+(x3+2mH-y3)^2]})

dx3dx1)

$$\tau^1{}_{23}=(\tau^1{}_{23})_0e^{-(\mu_1/\eta_1)t},\ \tau^1{}_{33}=(\tau^1{}_{33})_0$$

$$e^1{}_{12}(y_1,y_2,y_3,t)=\left(\frac{1}{2}\right)(e^1{}_{12})_0$$

$$+(1/\mu_1)[(\tau_\infty(t)-\tau_\infty(0))+(\mu_1/\eta_1)\int_0^t \tau_\infty(\tau)d\tau]$$

$$+H(t-T_1)/(2\times\pi)\int_{-L}^{L}\int_0^D f(x_1,x_3)[((y_2)(y_2-x_2))/$$

$$[(y_1-x_1)^2+(y_2-x_2)^2+(y_3-x_3)^2]^{5/2}$$

$$-(y_2)(y_2-x_2)/[(y_1+x_1)^2+(y_2-x_2)^2+$$

$$+(y_3-x_3)^2]^{5/2}]\times$$

$$\frac{\partial}{\partial y_2}\left(\int\int_F f_1(x_1,x_3)\times \frac{(y_2-x_2)}{\left[(y_1-x_1)^2+(y_2-x_2)^2+(y_3-x_3)^2\right]^{\frac{3}{2}}}\right.$$

$$-\frac{(y_2-x_2)}{\left[(y_1+x_1)^2+(y_2-x_2)^2+(y_3-x_3)^2\right]^{3/2}}$$

$$-(1/4\pi)\sum_{1}^{\infty}(a/b)^m\{1+\sum_{r=1}^{m}\binom{m}{r}[b_1^r/(r-1)!]$$

$t^{(r-1)}e^{(-a_1 t)}\{(y_2)/[(y_1-x_1)^2+(x_2-y_2)^2+(x_3-2mH-y_3)^2] +(y_2)/[(y_1-x_1)^2+(x_2-y_2)^2+(x_3-2mH+y_3)^2] +(y_2)/[(y_1-x_1)^2+(x_2-y_2)^2+(x_3+2mH+y_3)^2] +(y_2)/[(y_1-x_1)^2+(x_2-y_2)^2+(x_3+2mH-y_3)^2]\})$

$dx_3dx_1)$ (B).

3. Numerical computations:

Following [3] , [1] and the recent studies on rheological behaviour of crust and upper middle by[4] ,[16] ,the values of the model parameters are taken as:

$$\mu_1 = 3\times10^{11} dyne/cm^2, \eta_1 = 3\times10^{20}\, poise ..$$

$$\mu_2 = 3.5\times10^{11} dyne/cm^2, \eta_2 = 3.2\times10^{20}\, poise$$

D=Depth of the fault=10km.,[noting that the depth of all major earthquake faults are in between 10-15 km]

2L=Length of the fault=20km.(say).

$\tau_\infty(t)=2\times10^8$ 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.]

$(\tau^1{}_{12})_0 = 5\times10^7$ dyne/cm^2 (50 bars)
and $\tau_\infty(0)=0$

We take the function $f_1(x_1,x_3)=U\left(1-\frac{x_1^2}{L^2}\right)\left(1-\frac{3}{D_1^2}x_3^2+\frac{3}{D_1^3}x_3^3\right)$, with U = 1cm/year, satisfying the conditions stated in (C_1)–(C_3).

We now compute the following quantities:

$$U^1{}_1(y_1,y_2,y_3,t)=u^1{}_1(y_1,y_2,y_3,t)-(u^1{}_1)_0+ +(\tau_L/\mu_1)y_1t+y_2[(\tau_\infty(t)-\tau_\infty(0))/\mu_1)+ (\mu_1/\eta_1)\int_0^t \tau_\infty(\tau)d\tau \quad (2.1)$$

$$t^1{}_{11}(y_1,y_2,y_3,t)=\tau^1{}_{11}(y_1,y_2,y_3,t)- -(\mu_1/\eta_1)\tau_L(1-e^{(-\mu_1/\eta_1)t})+(\tau^1{}_{11})_0 e^{(-\mu_1/\eta_1)t} \quad (2.2)$$

$$t^1{}_{12}(y_1,y_2,y_3,t)=\tau^1{}_{12}(y_1,y_2,y_3,t)- \tau_\infty(t)-((\tau_\infty(0)-\tau^1{}_{12})_0)e^{(-\mu_1/\eta_1)t} \quad (2.3)$$

where $\tau^1{}_{11},\tau^1{}_{12}$ and $e^1{}_{11},e^1{}_{12}$ are given by (B).

4. Results and discussions.

(A) *Displacements ($U^1{}_1$) on the free surface y_3=0 due to the creeping movement across the fault:*

We first consider the displacement $U^1{}_1$ due to the movement of the fault for y_3=0.The expression for $U^1{}_1$ is given in (2.1). Figure2: shows the variation of $U^1{}_1$ against y_2 for some selective values of y_1 representing the distance of the point along the strike of the fault. It is found that,

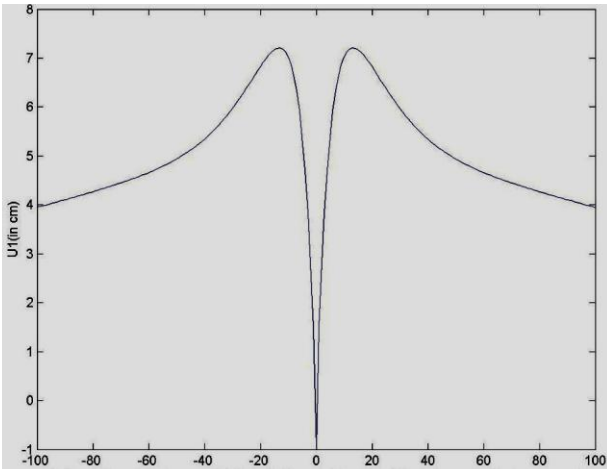
(i) $U^1{}_1$ is symmetric with respect to y_2 = 0;

(ii) For comparatively large values of y2 the magnitude of $U^1{}_1$ as expected becomes very small (10^{-2} cm); i.e. $|U^1{}_1|$ decreases as y_2 increases.

(iii) In each case for negative y_1, $U^1{}_1$ is the same for y_1>0.

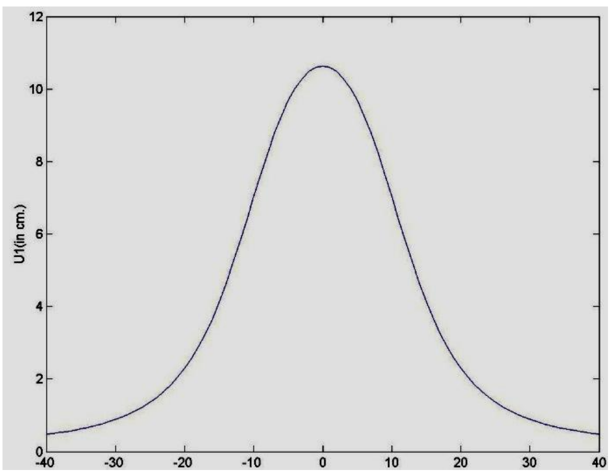
(iv) $|U^1{}_1| \to 0$ as $|y_1|$ increases.

(v) $|U^1{}_1|$ always remains bounded. It attains it's extreme at points which gradually drift away from y_1=0 with increase in y_2. The maximum magnitude of $U^1$1 is found to be of the order of 10.0 cm. one year after the commencement of the fault slip at points very close to the fault line on the free surface as is clear from the fig3. Thus the large observed displacement is well explained by our viscoelastic layered model.



y_2 (in km.)

Fig2: Variation of surface displacement U1with y_2 for y_3=0,y_1=5km,t_1=1year due to fault movement.



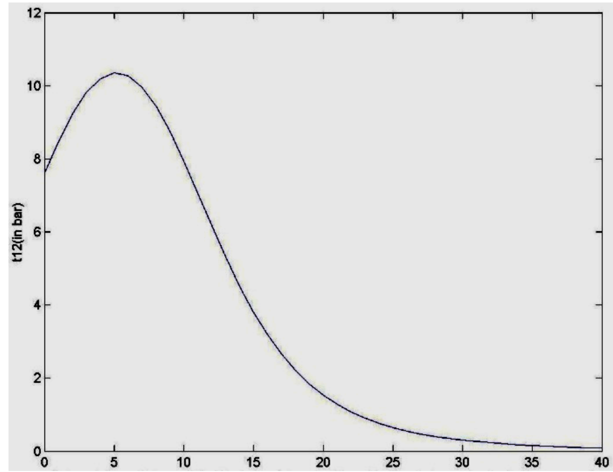
y_1 (in km.)

Fig3: Variation of surface displacement U1 with y_1 for y_2=10km,y_3=0,t_1=1year due to fault movement.

(B) *Spacial 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. In the fig4 it is observed that as we go down along the line y_1=10km,y_2=10km the accumulation of shear stress occurred with increasing depth with varying magnitude of accumulation. The magnitude of accumulation first increases up to a depth of about 7 km and there after decreases sharply up to a depth of about 22 km and after that the magnitude of stress accumulation is found to die out gradually as depth increases**.** It is also observed that the accumulation of stress pattern is the same for $y_1=\pm 10$km ,$y_2=\pm 10$km**.**

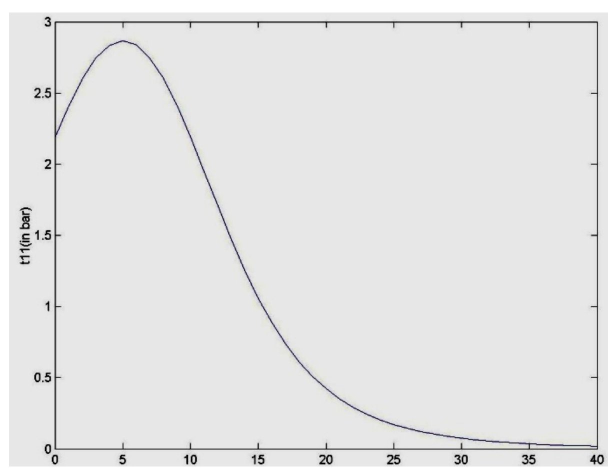


y_3 (in km.)

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

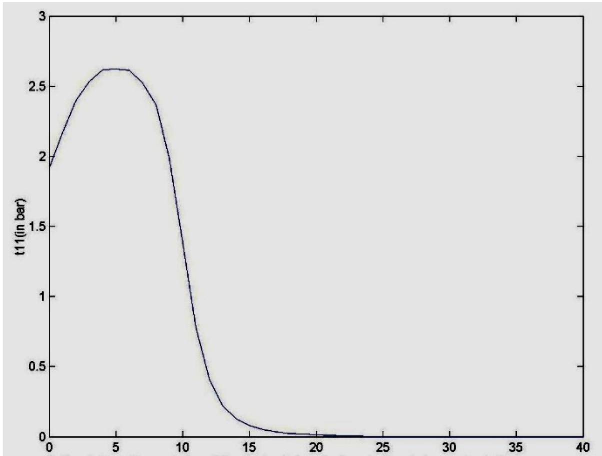
(ii) Variation of normal stress t_1:

Numerical computations show that as we move downwards with depth there are regions of stress accumulation. For points very close to the fault (y_1=1 km, y_2=1km.fig6) there are regions of stress accumulation with increasing depth. The maximum accumulation occurs very close to the free surface with y_3=6.5 km. Thereafter the rate of accumulation decreases sharply and ultimately decreases to zero at a depth of about 18 km. At points little bit away from the fault (y_1=10km, y_2=10km.) the nature of stress accumulation is similar to the above case but with much less magnitude. The accumulation ceased at a depth of about 36 km. from the free surface. Similar features have been observed along the verticals through the points (y_1= –10km, y_2=10km) and (y_1= –5km, y_2=5km;. In each cases the accumulation of stress t_{11} due to the fault movement tends to zero at a depth of about 50km. The maximum accumulation occurs at a depth of about 6 km from the free surfaces as the fig5 shows.



y_3(inkm.)

Fig5:Variation of normal stress t_{11} with depth y_3 for y_1=10km,y_2=10km and t_1=1 year due to fault movement.

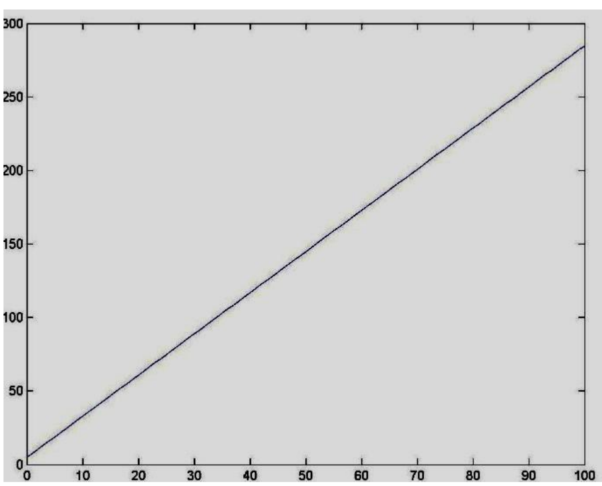


y_1(in km.)

Fig6: Variation of stress t_{11} with y_3 for y_2=1km,y_1=1km. t_1=1year due to fault movement.

(C)*Temporal variation of shear τ^1_{12} stress* :

Figure7 shows rate of shear stress τ^1_{12} accumulation/release at y_3=0km,y_1=10km and y_2=10km.It is observed that the rate of shear stress accumulation is linear represented by a straight line which does not pass through the origin, which is justified as the material is assumed to be linear viscoelastic of Maxwell type which carries memory**.**

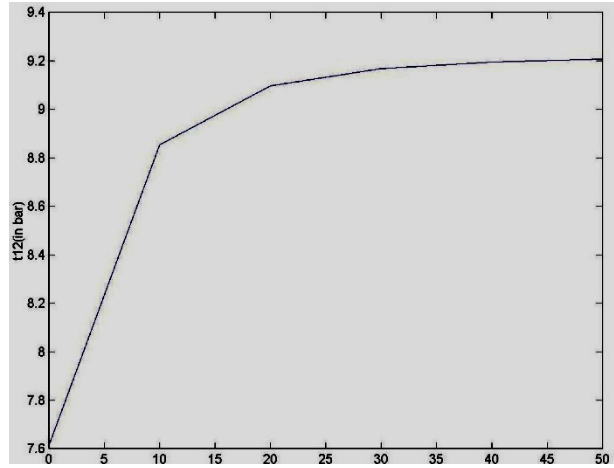


t(in year).

Fig7: Variation of shear stress t_{12} time t at y_3=0km,y_1=10km and y_2=10km.

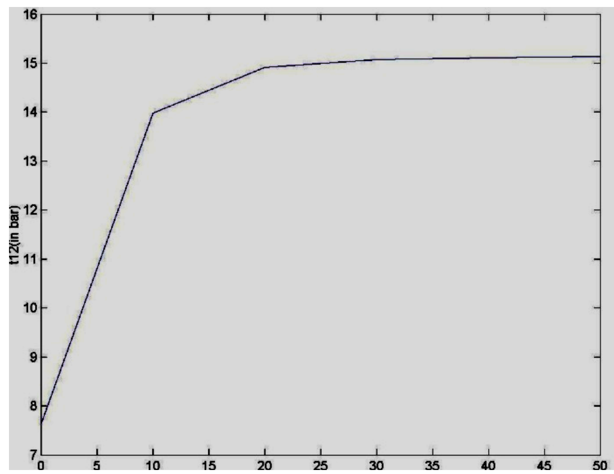
(D*) Effect of the length and width of the fault on shear stress accumulation/release*.

Fig8 shows the variation of shear stress t_{12} due to the variation of finite fault length. It is observed that as long as the length of the fault is less or equal to the width of the fault the shear stress t_{12} but when the length is greater than the width the change is slower. The similar phenomena is observed when the width is greater than the length but greater numerical value as is explained by the fig9.



L(in km.)

Fig8: Variation of shear stress t_{12} with the variation of the fault length L.



D(in km.)

Fig9: Variation of shear stress t_{12} with the variation of the fault width D.

5. APPENDIX-1.

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)-(1.23) with respect to time and we get,

$$\overline{\tau^1_{11}} = \frac{\left(p\frac{\partial \overline{u^1_1}}{\partial y_1}\right) - \left(\frac{\partial u^1_1}{\partial y_1}\right)_0}{\frac{1}{\eta_1} + \frac{p}{\mu_1}} + \frac{(\tau_{11})_0}{\frac{1}{\eta_1} + \frac{p}{\mu_1}} \qquad (3.1)$$

where, $\overline{\tau^1_{11}} = \int_0^\infty \tau^1_{11} e^{-pt} dt (p > 0$, Laplace transformation variable) and similar other equations. Also the stress equations of motions in Laplace transform domain as:

$$\frac{\partial}{\partial y_1}(\overline{\tau^1{}_{11}})+\frac{\partial}{\partial y_2}(\overline{\tau^1{}_{12}})+\frac{\partial}{\partial y_3}(\overline{\tau^1{}_{13}})=0 \quad (1.7a)$$

$$\frac{\partial}{\partial y_1}(\overline{\tau^1{}_{21}})+\frac{\partial}{\partial y_2}(\overline{\tau^1{}_{22}})+\frac{\partial}{\partial y_3}(\overline{\tau^1{}_{23}})=0 \quad (1.8a)$$

$$\frac{\partial}{\partial y_1}(\overline{\tau^1{}_{31}})+\frac{\partial}{\partial y_2}(\overline{\tau^1{}_{32}})+\frac{\partial}{\partial y_3}(\overline{\tau^1{}_{33}})=0 \quad (1.9a)$$

$$\lim_{y_1 \to L-} \tau^1{}_{11}(y_1, y_2, y_3, p) =$$

$$\lim_{y_1 \to L+} \overline{\tau^1{}_{11}}(y_1, y_2, y_3, p) = \tau_L \text{ (say)},$$

$y_2 = 0,\ 0 \le y_3 \le D$ (1.10a)

$$\lim_{y_1 \to -L-} \overline{\tau^1{}_{11}}(y_1, y_2, y_3, p) =$$

$$\lim_{y_1 \to -L+} \overline{\tau^1{}_{11}}(y_1, y_2, y_3, t) = \tau_{-L} \text{ (say)}$$

$y_2 = 0,\ 0 \le y_3 \le D$ (1.11a)

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

$\overline{\tau^1{}_{12}}(y_1, y_2, y_3, p) \to \tau_\infty(t)$ as

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

$$\overline{\tau^1{}_{13}}(y_1, y_2, y_3, p) = 0 \quad (1.13a)$$

$$\overline{\tau^1{}_{23}}(y_1, y_2, y_3, p) = 0 \quad (1.14a)$$

$$\overline{\tau^1{}_{33}}(y_1, y_2, y_3, p) = 0 \quad (1.15a)$$

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

$$\overline{\tau^1{}_{13}}(y_1, y_2, y_3, p) = 0 \quad (1.16a)$$

$$\overline{\tau^1{}_{23}}(y_1, y_2, y_3, p) = 0 \quad (1.17a)$$

$$\overline{\tau^1{}_{33}}(y_1, y_2, y_3, p) = 0 \quad (1.18a)$$

$\overline{\tau^1{}_{22}}(y_1, y_2, y_3, p) = 0$ 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).

$$\nabla^2(\overline{u^1{}_1}) = 0 \quad (3.2)$$

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

$$\text{Let, } \overline{u^1{}_1}(y_1, y_2, y_3, p) = \frac{(u^1{}_1)_0}{p} + A_1 y_1 + B_1 y_2 + C_1 y_3 \quad (3.3)$$

be the solution of (3.2).

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

$$A_1 = \frac{\tau_L}{\eta_1}\frac{1}{p^2} \quad (3.4)$$

$$B_1 = \frac{1}{p}\left[\left(\frac{1}{\eta_1} + \frac{p}{\mu_1}\right)\tau_\infty(p) - \frac{1}{\mu_1}\tau_\infty(0)\right] \quad (3.5)$$

and $C_1 = 0$ (3.6)

On taking inverse Laplace transformation, we get,

$$u^1{}_1(y_1, y_2, y_3, t) = (u^1{}_1)_0 + (\tau_L/\mu_1) y_1 t + (y_2/\mu_1) \times [(\tau_\infty(t) - \tau_\infty(0)) + (\mu_1/\eta_1)\int_0^t \tau_\infty(\tau) d\tau] \quad (3.7)$$

Similarly we can get the other components of the displacements.

The stress are given by,

$$\tau^1{}_{11} = (\mu_1/\eta_1)\tau_L(1 - e^{-(\mu_1/\eta_1)t}) + + (\tau^1{}_{11})_0 e^{-(\mu_1/\eta_1)t} \quad (3.8)$$

$$\tau^1{}_{12} = \tau_\infty(t) - [\tau_\infty(0) - (\tau^1{}_{12})_0] e^{-(\mu_1/\eta_1)t} \quad (3.9)$$

$$\tau^1{}_{13} = (\tau^1{}_{13})_0 e^{-(\mu_1/\eta_1)t} \quad (3.10)$$

$$\tau^1{}_{22} = (\tau^1{}_{22})_0 e^{-(\mu_1/\eta_1)t} \quad (3.11)$$

$$\tau^1{}_{23} = (\tau^1{}_{23})_0 e^{-(\mu_1/\eta_1)t} \quad (3.12)$$

$$\tau^1{}_{33} = (\tau^1{}_{33})_0 \quad (3.13)$$

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

$$e^1{}_{11}(y_1, y_2, y_3, t) = (e_{11})_0 + (\tau_L / \eta_1)t \qquad (3.14)$$

$$e^1{}_{12}(y_1, y_2, y_3, t) = (1/2)(e^1{}_{12})_0 + (1/\mu_1)(\tau_\infty(t) - \tau_\infty(0)) + (\mu_1/\eta_1)\int_0^t \tau_\infty(\tau)d\tau \qquad (3.15)$$

6. Appendix-II:

Solutions after the fault movement

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 starts creeping. Then we have an additional condition characterizing the dislocation in u_1 due to the creeping movement as:

$$\left[(u^1{}_1)\right]_F = u^1{}_1(t_1) f_1(y_1, y_3) H(t_1) \qquad (4.1)$$

where = The discontinuity of u_1^1 across F given by

$$\left[(u^1{}_1)\right]_F = \lim_{(y_2 \to 0+)} (u^1{}_1) - \lim_{(y_2 \to 0-)} (u^1{}_1) \qquad (4.2)$$

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

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

Taking Laplace transformation in (4.1), we get,

$$\left[(\overline{u^1{}_1})\right]_F = u_1(p) f_1(y_1, y_3) \qquad (4.3)$$

The fault creep commences across F after time T_1, clearly

$$\left[(u^1{}_1)\right]_F = 0$$

for $t_1 \le 0$, where $t_1 = t - T_1$, F is located in the region $(-L \le y_1 \le L, y_2 = 0, 0 \le y_3 \le D)$. We try to find the solution as :

$$u^1{}_1 = (u^1{}_1)_1 + (u^1{}_1)_2, u^1{}_2 = (u^1{}_2)_1 + (u^1{}_2)_2,$$
$$u^1{}_3 = (u^1{}_3)_1 + (u^1{}_3)_2,$$

$$\tau^1{}_{11} = (\tau^1{}_{11})_1 + (\tau^1{}_{11})_2, \tau^1{}_{12} = (\tau^1{}_{12})_1 + (\tau^1{}_{12})_2,$$

$$\tau^1{}_{13} = (\tau^1{}_{13})_1 + (\tau^1{}_{13})_2, \tau^1{}_{22} = (\tau^1{}_{22})_1 + (\tau^1{}_{22})_2,$$

$$\tau^1{}_{23} = (\tau^1{}_{23})_1 + (\tau^1{}_{23})_2, \tau^1{}_{33} = (\tau^1{}_{33})_1 + (\tau^1{}_{33})_2 \qquad (4.4)$$

where $(u^1{}_i)_1$, $(\tau^1{}_{ij})_1$, are continuous everywhere in the model and are given by (A); i,j=1,2,3. While the second part $(u^1{}_i)_2$, $(\tau^1{}_{ij})_2$ are obtained by solving modified boundary value problem as stated below. We note that $(u^1{}_2)_2$, $(u^1{}_3)_2$, are both continuous even after the fault creep, so that $[(u^1{}_2)]_2 = 0, [(u^1{}_3)]_2 = 0$, while $(u_1)_2$ satisfies the dislocation condition given by (4.2).

The resulting boundary value problem can now be stated as: $(u^1{}_1)_2$ satisfies 3D Laplace equation as

$$\nabla^2 (\overline{u^1{}_1})_2 = 0 \qquad (4.5)$$

where $(\overline{u^1{}_1})_2$ is the Laplace transformation of $(u_1)_2$ with respect to t, with the modified boundary condition.

$$\overline{\tau^1{}_{12}}(y_1, y_2, y_3, p) = 0 \text{ as } [y_2] \to \infty, -\infty < y_1 < \infty, y_3 \ge 0. \qquad (1.14b)$$

and the other boundary conditions are same as before.

We solve the above boundary value problem by modified Green's function method following[17] ,[18] , [26] , 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,

$$(\overline{u^1{}_1})_2(Q) = \int\int_F [(u^1{}_1)_2(P)] G(P,Q) dx_3 dx_1$$

$$= \int\int_F u^1{}_1(P) f_1(x_1, x_3) G(P,Q) dx_3 dx_1 \qquad (4.6)$$

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,

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

$$-(1/4\pi\bar{\mu}_1)\sum_1^\infty [(\bar{\mu}_1 - \bar{\mu}_2)/(\bar{\mu}_1 + \bar{\mu}_2)]^m \{1/[(y_1-x_1)^2+(x_2-y_2)^2+(x_3-2mH-y_3)^2] + 1/[(y_1-x_1)^2+(x_2-y_2)^2+(x_3-2mH+y_3)^2] + 1/[(y_1-x_1)^2+(x_2-y_2)^2+(x_3+2mH+y_3)^2]$$

$$+1/[(y_1-x_1)^2+(x_2-y_2)^2+(x_3+2mH-y_3)^2]\}, \text{where}, 0 \le y_3 \le H. \qquad (4.8)$$

Therefore,

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

$$-\frac{(y_2-x_2)}{\left[(y_1+x_1)^2+(y_2-x_2)^2+(y_3-x_3)^2\right]^{\frac{3}{2}}}$$

-(1/4πμ̄₁) $\sum_{1}^{\infty}$ [(μ̄₁ -μ̄₂)/(μ̄₁ +μ̄₂)] ^{m}{(x_2-y_2)/[(y_1-x_1)^2+(x_2–y_2)^2+(x_3-2mH–y_3)^2] + (x_2-y_2)/[(y_1-x_1)^2+(x_2–y_2)^2+(x_3-2mH+y_3)^2] +(x_2-y_2)/[(y_1-x_1)^2+(x_2–y_2)^2+(x_3+2mH+y_3)^2] +(x_2-y_2)/[(y_1-x_1)^2+(x_2–y_2)^2+(x_3+2mH-y_3)^2] }

$$(\overline{u_1})_2(Q)=\int\int_F u_1(P)\,f_1(x_1,x_3)\times$$

$$\times\frac{(y_2-x_2)}{\left[(y_1-x_1)^2+(y_2-x_2)^2+(y_3-x_3)^2\right]^{\frac{3}{2}}}$$

$$-\frac{(y_2-x_2)}{\left[(y_1+x_1)^2+(y_2-x_2)^2+(y_3-x_3)^2\right]^{\frac{3}{2}}}$$

-(1/4πμ̄₁) $\sum_{1}^{\infty}$ [(μ̄₁ -μ̄₂)/(μ̄₁ +μ̄₂)] ^{m}{(x_2-y_2)/[(y_1-x_1)^2+(x_2–y_2)^2+(x_3-2mH–y_3)^2] + (x_2-y_2)/[(y_1-x_1)^2+(x_2–y_2)^2+(x_3-2mH+y_3)^2] +(x_2-y_2)/[(y_1-x_1)^2+(x_2–y_2)^2+(x_3+2mH+y_3)^2] +(x_2-y_2)/[(y_1-x_1)^2+(x_2–y_2)^2+(x_3+2mH-y_3)^2] }□dx_3dx_1]

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

where,

$$\phi(y_1,y_2,y_3)=\int\int_F f_1(x_1,x_3)\times$$

$$\frac{(y_2-x_2)}{\left[(y_1-x_1)^2+(y_2-x_2)^2+(y_3-x_3)^2\right]^{\frac{3}{2}}}$$

$$-\frac{(y_2-x_2)}{\left[(y_1+x_1)^2+(y_2-x_2)^2+(y_3-x_3)^2\right]^{\frac{3}{2}}}$$

-(1/4πμ̄₁) $\sum_{1}^{\infty}$ [(μ̄₁ -μ̄₂)/(μ̄₁ +μ̄₂)] ^{m}{(x_2-y_2)/[(y_1-x_1)^2+(x_2–y_2)^2+(x_3-2mH–y_3)^2] + (x_2-y_2)/[(y_1-x_1)^2+(x_2–y_2)^2+(x_3-2mH+y_3)^2] +(x_2-y_2)/[(y_1-x_1)^2+(x_2-y_2)^2+(x_3+2mH+y_3)^2] +(x_2-y_2)/[(y_1-x_1)^2+(x_2–y_2)^2+(x_3+2mH-y_3)^2] }□dx_3dx_1] (4.10)

Taking inverse Laplace transformation,

$$(u^1{}_1)_2(Q)=u^1{}_1(t_1)\phi(y_1,y_2,y_3)H(t_1)$$

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,

$$(\overline{\tau^1{}_{11}})_2=\frac{p}{\frac{1}{\eta_1}+\frac{p}{\mu_1}}\left(\frac{\partial(\overline{u^1{}_1})_2}{\partial y_1}\right) \qquad (4.11)$$

and similar other equations. Now,

$$\frac{\partial(\overline{u^1{}_1})_2}{\partial y_1}=\overline{u^1{}_1}(p)\frac{\partial(\phi)}{\partial y_1}$$

$$=\overline{u^1{}_1}(p)\phi_1\ \text{(say)}$$

where,

$$\phi_1(y_1,y_2,y_3)=\frac{\partial}{\partial y_1}\Bigg(\int\int_F f_1(x_1,x_3)\times$$

$$\frac{(y_2-x_2)}{\left[(y_1-x_1)^2+(y_2-x_2)^2+(y_3-x_3)^2\right]^{\frac{3}{2}}}$$

$$-\frac{(y_2-x_2)}{\left[(y_1+x_1)^2+(y_2-x_2)^2+(y_3-x_3)^2\right]^{3/2}}$$

-(1/4πμ̄₁) $\sum_{1}^{\infty}$ [(μ̄₁ -μ̄₂)/(μ̄₁ +μ̄₂)] ^{m}{(x_2-y_2)/[(y_1-x_1)^2+(x_2–y_2)^2+(x_3-2mH–y_3)^2] + (x_2-y_2)/[(y_1-x_1)^2+(x_2–y_2)^2+(x_3-2mH+y_3)^2] +(x_2-y_2)/[(y_1-x_1)^2+(x_2–y_2)^2+(x_3+2mH+y_3)^2] +(x_2-y_2)/[(y_1-x_1)^2+(x_2–y_2)^2+(x_3+2mH-y_3)^2] }dx_3dx_1) (4.12)

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

$$(\tau^{1}{}_{11})_2 = H(t-T_1)/(2\times\pi)[u_1(t_1)-\mu_1/\eta_1$$

$$\int_0^t u(\tau)e^{(-\mu_1/\eta_1)(t-\tau)}d\tau]$$

$$\times\frac{\partial}{\partial y_1}\left(\int\int_F f_1(x_1,x_3)\times\right.$$

$$\frac{(y_2-x_2)}{\left[(y_1-x_1)^2+(y_2-x_2)^2+(y_3-x_3)^2\right]^{\frac{3}{2}}}$$

$$-\frac{(y_2-x_2)}{\left[(y_1+x_1)^2+(y_2-x_2)^2+(y_3-x_3)^2\right]^{3/2}}$$

$$-(1/4\pi\bar{\mu}_1)\sum[(\bar{\mu}_1-\bar{\mu}_2)/(\bar{\mu}_1+\bar{\mu}_2)]^m\{(x_2-y_2)/[(y_1-x_1)^2+(x_2-y_2)^2+(x_3-2mH-y_3)^2] + (x_2-y_2)/[(y_1-x_1)^2+(x_2-y_2)^2+(x_3-2mH+y_3)^2] +(x_2-y_2)/[(y_1-x_1)^2+(x_2-y_2)^2+(x_3+2mH+y_3)^2] +(x_2-y_2)/[(y_1-x_1)^2+(x_2-y_2)^2+(x_3+2mH-y_3)^2]\})\, dx_3dx_1) \qquad (4.13)$$

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

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