



Research Article

# Static Stress Strain Analysis in a Laterally Inhomogeneous Lithosphere-Asthenosphere System

Debnath S.K.<sup>a\*</sup>, Dutta T.<sup>b</sup>, Ghosh U.<sup>c</sup>, and Biswas S.<sup>d</sup>

<sup>a</sup> Department of Basic Sciences and Humanities, Meghnad Saha Institute of Technology (A unit of Techno India Group), Under MAKAUT (Formerly known as West Bengal University of Technology) Nazirabad.P.O. Uchhepota, Via-Sonarpur, Kolkata-700150, W.B, India.

<sup>b</sup> Bengal Institute of Technology and Management Under MAKAUT, Sriniketan road, P.O Doranda, Santiniketan, Gopalnagar. W.B. Pin- 731236, India,

<sup>c</sup> Swami Niswambalananda Girls' College, Uttarpara, Hoogly, West Bengal, India,

<sup>d</sup> Purba banbania Bhagabati vidyamandir, P.O:Habra P.S:Ashokenagar North 24 Parganas pin :743263 W.B, India

\*Corresponding author (E-mail: : [subrata.debnath@msit.edu.in](mailto:subrata.debnath@msit.edu.in))

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## Abstract

Noting that the Real Earth being highly laterally inhomogeneous where, the rigidity of the material of the Earth gradually increases/decreases as we go apart from any earthquake fault. In the present paper the lithosphere- asthenosphere system is considered up to a depth of 200 km. from the free surface where rigidity is assumed to vary linearly with distance from the fault. We have tried to develop a mathematical model to investigate the effect of this variation of rigidity with distance on stress and strain accumulation/release in the lithosphere-asthenosphere system due to the movement across the long strike slip fault assumed to be situated vertically and surface breaking. The associated boundary value problem is numerically solved by finite difference method in presence of discontinuity and

a MATLAB program is developed. It is found that the continuous change of rigidity with distance from the fault has considerable effect on the nature of stress-strain accumulation /release in the system as compared to the elastic half-space and elastic layered model.

*Keywords: Intraplate earthquake, long strike slip fault, inhomogeneity, Mantle convection, Stress accumulation.*

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## 1 Introduction :

Large earthquakes within stable continental regions show that significant amounts of elastic strain can be released on geological structures far from plate boundary faults, where the vast majority of the Earth's seismic activity take place. The 1811-1812 New Madrid events in the Mississippi valley are classical examples of large intraplate earthquakes (e.g Nuttli,1963;Johnston ,1996;Hough et al.,2003),but the reason of such intraplate earthquake is not still clear. In our present paper we have tried to develop a mathematical model to investigate the possible reason of such intraplate earthquake and its spatial prediction.

In the layered model (vertical/horizontal) the rigidity or the viscosity of different layers were taken to be different with a suitable boundary condition at the interface. But the sudden changes of the parameters (rigidity/viscosity) were not well explained. And also, it is the experimental result that the rigidity of the Earth crust continuously changes as we go distance apart from any fault.(Rybicki.K and Kasahara . K ,1977).

In our paper we have considered an elastic half-space with continuously increasing/decreasing rigidity with distance from the fault and a long strike slip fault is considered to be situated in the medium. The fault is assumed to undergo a sudden slip when the stresses in the region exceed certain threshold value. The medium is under the influence of tectonic forces due to mantle convection or some related phenomena

Numerical computational works have been carried out with finite difference scheme in presence of discontinuity, suitable values of the model parameters and the nature of the stress and strain accumulation in the medium are obtained both before and after movement across the fault, following the observational data mentioned by (Chift, P., Lin, J. and Barcktiausen, U. 2002), (Karato Shun-Ichiro. 2010).

Associated MATLAB program is developed. The convergence and stability analysis of the associated finite difference scheme have also been done. Higher dimensional interpolation (Lagrange's Interpolation) and higher dimensional numerical differentiation are used for stress and strain calculation.

The solution shows a significant change both in quantitative and qualitative behavior in the nature of displacement, stress and strain field as compared to the elastic half-space and elastic layered model.

In our present paper we have shown that the continuous change of rigidity of the Earth material may be one of the possible reasons for intraplate earthquake. Also, spatial prediction of earthquake has been done.

In the earlier models, the Earth was represented by an elastic half-space (Chinnery, M.A. 1961; 1964; 1965), (Maruyama, T. 1964; 1966), (Rybicki, K. 1971), (Chinnery, M.A. et al., 1972), (Singh, S J. and Rosenman, M. 1974), (Matsu'ura, M. and Sato, R. 1975), (Rani, S. and Singh, S J. 1992), (Sen, S. et al. 1993), and/or elastic layer (Steketee, J A. 1958), (Segal, P. 2010), and/or elastic layer over viscoelastic half-space (Nur, A. and Mavko, G. 1974), (Mukhopadhyay, A. and Mukherjee, P. 1979), (Cohen, S.C. 1980), (Mukhopadhyay, A. et al. 1980), (Ghosh, U. et al. 1992), (Savage, J C. 1998), (Mondal, S. C. et al. 2018), (Kundu, P. et al. 2021), or viscoelastic layer over viscoelastic half-space (Debnath, S.K and Sen, S. 2013).

## 2 Formulation

We consider a long strike-slip surface breaking vertical fault  $F$ , width  $D$  situated in an elastic half space of linearly increasing/decreasing rigidity. A Cartesian coordinate system is used with a suitable point  $O$  on the strike of the fault as the origin, the strike of the fault along the  $X$  axis and  $Y$  axis is as shown in Figure 1, and  $Z$  axis pointing downwards, so that the fault is given by  $F : (y = 0, 0 \leq z \leq D)$ .

Let  $u$  be the displacement component along  $X$ -axis,  $\tau_{1j}, e_{1j}$ ,  $j = 2, 3$  be the stress and strain components associated with strike slip motion and  $\mu(y)$  is the effective rigidity which is a continuous function of distance  $y$  from the fault.

For an elastic medium the constitutive equations associated to long strike slip fault are taken as:

$$\tau_{12} = \mu(y)(e_{12}) = \mu(y) \frac{\partial u}{\partial y} \quad (1)$$

$$\tau_{13} = \mu(y)(e_{13}) = \mu(y) \frac{\partial u}{\partial z} \quad (2)$$

The stresses satisfy the following equations:(assuming quasi static deformation for which the inertia terms are neglected and the body forces do not change during the investigation).

$$\frac{\partial(\tau_{12})}{\partial y} + \frac{\partial(\tau_{13})}{\partial z} = 0 \quad (3)$$

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

$$\tau_{12}(y, z) = \tau_{\infty}(t), \text{ as } |y| = d, z \geq 0, t \geq 0 \quad (4)$$

, where  $d$  is sufficient large .

On the free surface,

$$z = 0, (-\infty < y < \infty, t \geq 0), \tau_{13}(y, z) = 0 \quad (5)$$

Also, as

$$z \rightarrow \infty, (-\infty < y < \infty, t \geq 0), \tau_{13}(y, z) = 0 \quad (6)$$

[where  $\tau_{\infty}(t)$  is the shear stress maintained by mantle convection and other tectonic phenomena].

### 3 (A) Solutions in the absence of any fault dislocation:

Using equations (1) & (2) in (3), we get the boundary value problem

$$\nabla^2 u + \frac{k_F}{1 \pm k_F |y|} \frac{\partial u}{\partial y} = 0 \quad (7)$$

where  $\mu(y) = \mu_F(1 \pm k_F |y|)$  is the rigidity on the fault and  $k_F=0.0016/\text{km}$ .(the value of  $k_F$  is estimated by least square method),  $\mu_F = 3 \times 10^{10} \text{ newton/m}^2$

We solve the boundary value problem (7) with the boundary conditions (4) to (6) by finite difference method.

We have the finite difference scheme as

$$\left(\frac{2}{h^2} + \frac{2}{k^2} + \frac{1}{h} \cdot \frac{k_F}{1 \pm k_F |y_i|}\right) u_{i,j} = \frac{1}{h^2} u_{i-1,j} + \frac{1}{k^2} (u_{i,j+1} + u_{i,j-1}) + \left(\frac{1}{h^2} + \frac{1}{h} \cdot \frac{k_F}{1 \pm k_F |y_i|}\right) u_{i+1,j} \quad (8)$$

$y_i = ih$  ,  $i = 0, \pm 1, \pm 2, \pm 3, \dots, \pm 300$   $z_j = jk$  ,  $j = 0, 1, 2, 3, 4, \dots, 600$   
where  $h$ =step length along Y axis and  $k$ =step length along Z axis.

**Boundary conditions before dislocation:**

$$u_{i+1,j} - u_{i,j} = \frac{\tau_\infty(t)}{\mu_F(1 \pm k_F |y_i|)} \quad (9)$$

for  $i = \pm 300$  ,  $j = 0, 1, 2, 3, \dots, 600$

$$u_{i,j+1} - u_{i,j} = 0 \quad (10)$$

for  $i = 0, \pm 1, \pm 2, \dots, \pm 300$  ,  $j = 0, 600$

using the boundary conditions (9) & (10) in finite difference scheme (8) we get the modified finite difference scheme as

$$\left(1 + \frac{h^2}{k^2}\right) u_{i,j} - \frac{h^2}{k^2} u_{i,j-1} - u_{i-1,j} = \left(1 + \frac{hk_F}{1 \pm k_F |y_i|}\right) \frac{\tau_\infty(t)}{\mu_F(1 \pm k_F |y_i|)} \quad (11)$$

From the numerical solution we find that  $\tau_{12}$  increases with time and tends to  $\tau_\infty(t)$  as  $t$  tends to  $\infty$  , while  $\tau_{13}$  tends to zero.

### 3. (B) Solutions after the movements across the fault (dislocation):

We assume that after a time  $T_1$  the stress component  $\tau_{12}$  (which is the main driving force for the strike-slip motion of the fault) exceeds the critical value  $\tau_c$ , the fault F starts slipping. Then we have an additional condition characterizing the dislocation in  $u$  due to the slipping movement as:

$$[(u)]_F = \nabla U f(z) H(t_1) \quad (12)$$

where,  $H(t_1)$  is the Heaviside function,  $t_1 = t - T_1$  ,  $\nabla U$  (slip across the fault) is constant,  $f(z)$  is the slip function which satisfies (A) and  $[(u)]_F$  = the discontinuity

of  $u$  across  $F$  given by

$$[(u)]_F = \lim_{(y \rightarrow 0+)}(u) - \lim_{(y \rightarrow 0-)}(u) \quad (13)$$

$y = 0, (0 \leq z \leq D)$ .

We assume that the geological conditions as well as the characteristic of the fault is such that when the stress-component  $\tau_{12}$  reaches some critical value, say  $\tau_c < \tau_\infty(t)$  then the fault  $F$  starts slipping.

For bounded stress and strains, the slip function should satisfy the following conditions as discussed in (Mukhopadhyay, A. et al. 1980).

( $C_1$ ) Its value will be maximum on the free surface.

( $C_2$ ) The magnitude of the slip will decrease with  $z$  as we move downwards and ultimately tends to zero near the lower edge of the fault. ( $y = 0, z = D$ ). The slip function  $f(z)$  should satisfy the above conditions. We try to find the solution as,

$$u = (u)_1 + (u)_2$$

$$\tau_{12} = (\tau_{12})_1 + (\tau_{12})_2$$

$$\tau_{13} = (\tau_{13})_1 + (\tau_{13})_2$$

$$e_{12} = (e_{12})_1 + (e_{12})_2$$

$$e_{13} = (e_{13})_1 + (e_{13})_2$$

where  $(u)_1, (\tau_{12})_1, (\tau_{13})_1, (e_{12})_1, (e_{13})_1$  respectively are displacement, stress, strain before the fault dislocation satisfying equations (1) to (6) and  $(u)_2, (\tau_{12})_2, (\tau_{13})_2, (e_{12})_2, (e_{13})_2$  respectively are displacement, stress, strain after the fault dislocation satisfying the modified boundary value problem.

The resulting boundary value problem can now be stated as:  $(u)_2$  satisfies 2D Laplace equation

$$\nabla^2(u)_2 + \frac{k_F}{1 \pm k_F |y|} \frac{\partial(u)_2}{\partial y} = 0 \quad (14)$$

With modified boundary conditions (12) & (13) and the other boundary conditions remains the same as before. We solve the resulting boundary value problem by finite difference method (finite difference method in presence of discontinuity)

and get the modified finite difference scheme as :

$$\left(\frac{2}{h^2} + \frac{2}{k^2} + \frac{1}{h} \cdot \frac{k_F}{1 \pm k_F |y_i|}\right)(u)_{2i,j} = \frac{1}{h^2}(u)_{2i-1,j} + \frac{1}{k^2}(u)_{2i,j+1} + (u)_{2i,j-1} + \left(\frac{1}{h^2} + \frac{1}{h} \cdot \frac{k_F}{1 \pm k_F |y_i|}\right)(u)_{2i+1,j} \quad (15)$$

$y_i = ih$  for  $i = 0, \pm 1, \pm 2, \pm 3, \dots, \pm 300$   $z_j = jk$  for  $j = 0, 1, 2, 3, 4, \dots, 600$

$$(u)_{2i+1,j} - (u)_{2i,j} = 0 \quad (16)$$

for  $i = \pm 300, j = 0, 1, 2, 3, \dots, 600$

$$(u)_{2i,j+1} - (u)_{2i,j} = 0 \quad (17)$$

for  $i = 0, \pm 1, \pm 2, \dots, \pm 300, j = 0, 600$

$$(u)_{2i,j+1} - (u)_{2i,j} = \nabla U f(z_j) \quad (18)$$

for  $i = 0, j = 0, 1, 2, \dots, 10$

Using the boundary conditions (16) to (18) in (15), we get

$$(u)_{2i,j} = \frac{1}{\left(1 + \frac{h^2}{k^2}\right)} \left[ \frac{h^2}{k^2} \nabla U f(z_j) + (u)_{2i-1,j} + \frac{h^2}{k^2} (u)_{2i,j-1} \right] \quad (19)$$

### 3. (C) Convergence and Stability Analysis:

For the linear partial differential equation

$f_1 u_{y_2 y_2} + f_2 u_{y_3 y_3} + f_3 u_{y_2} + f_4 u_{y_3} + f_5 u = f_6$  in a region R,

The difference scheme will be of the form

$$\begin{aligned} &\beta_0 u((y_2)_i, (y_3)_j) + \beta_1 u((y_2)_i + h_1, (y_3)_j) + \beta_2 u((y_2)_i, (y_3)_j + h_2) \\ &+ \beta_3 u((y_2)_i - h_3, (y_3)_j) + \beta_4 u((y_2)_i, (y_3)_j - h_4) = (f_6)_{ij} \end{aligned} \quad (20)$$

here  $f_1, f_2, f_3, f_4, f_5$ , and  $f_6$  are continuous functions of  $y_2$  and  $y_3$  and following (Jain, M, K. et.al. 1994), we get coefficient values as:

$$\begin{aligned}\beta_0 &= (f_6)_{i,j} - \left[ \frac{1}{h_1 h_3} \{2(f_1)_{i,j} + (h_3 - h_1)(f_3)_{i,j}\} + \frac{1}{h_2 h_4} \{2(f_2)_{i,j} + (h_4 - h_2)(f_4)_{i,j}\} \right], \\ \beta_1 &= \frac{2(f_1)_{i,j} + h_3(f_3)_{i,j}}{h_1(h_1 + h_3)}, \quad \beta_2 = \frac{2(f_2)_{i,j} + h_4(f_4)_{i,j}}{h_2(h_2 + h_4)}, \\ \beta_3 &= \frac{2(f_1)_{i,j} - h_1(f_3)_{i,j}}{h_1(h_1 + h_3)}, \quad \beta_4 = \frac{2(f_2)_{i,j} - h_2(f_4)_{i,j}}{h_2(h_2 + h_4)}.\end{aligned}$$

By applying difference scheme (8) at all the nodal points in the region R, we get a system of algebraic equations with the same number of equations as the number of unknowns and this system of equations can be written in the matrix form

$$\mathbf{AX} = \mathbf{B} \quad (21)$$

Under the following conditions

$$2(f_1)_{i,j} > \max[h_3|(f_3)_{i,j}|, h_1|(f_3)_{i,j}|], \quad 2(f_2)_{i,j} > \max[h_2|(f_4)_{i,j}|, h_4|(f_4)_{i,j}|]. \quad (22)$$

We have

$$\beta_0 < 0 \quad \text{and} \quad |\beta_0| > \beta_1 + \beta_2 + \beta_3 + \beta_4 \quad (23)$$

i.e. off-diagonal terms of A are positive, diagonal elements are negative and A is diagonally dominant. Thus, the matrix A is irreducible and by these properties we assume the convergence of system of equations.

In our problem the linear partial differential equation is given by (7) i.e.  $f_1 = f_2 = 1$ ,  $f_4 = f_5 = f_6 = 0$ , and  $f_3 = \frac{kF}{(1 \pm kF|y|)}$  for a square network with  $(h = k)$ . So, the condition (22) is satisfied for all values of  $(y)$  when  $(k_F = 0.0016/\text{km})$

It is important to note for the elliptic equation method of support operators (which we use for the finite difference scheme) that automatically gives us a stable finite- difference schemes (Shashkov. M. 1996).

## 4 Numerical Computations:

Following (Aki, K and Richards, P G. 1980) and recent studies on rheological behavior of crust and upper mantle by (Karato Shun-Ichiro 2010), (Matsu'ura, M. and Sato, R. 1975) the values of the model parameters are taken as:  $\mu_F =$

$3 \times 10^{10} \text{ N/m}^2$   $D = \text{Depth of the fault} = 10 \text{ km.}$ , [nothing that the depth of almost all major earthquake faults is in between 10-15 km]  $\tau_\infty(t) = \text{constant} = \tau_\infty = 2 \times 10^7 \text{ N/m}^2 (200 \text{ bars})$ , [post seismic observations reveal that in most of the cases, stress released in major earthquake are of the order of 200 bars or less, in extreme cases, it may be 400 bars. We assume  $\tau_c = 2.5 \times 10^7 \text{ N/m}^2$  (250 bars).

We take the slip function  $f(x_3) = (1 - \frac{3}{D^2}x_3^2 + \frac{2}{D^3}x_3^3)$ , with  $\nabla U = 0.00001 \text{ km}$ , satisfying the conditions stated in  $(C_1) - (C_2)$ .

#### **MATLAB program:**

[1] **Initialize parameters:**  $i_{\min} = -300$ ,  $i_{\max} = 300$ ,  $j_{\min} = 0$ ,  $j_{\max} = 600$   
 Grid steps:  $h = 1$  (x-direction),  $k = 1$  (y-direction) Grid sizes:  $N_x = i_{\max} - i_{\min} + 1$ ,  $N_y = j_{\max} - j_{\min} + 1$  Initialize  $U(i, j) = 0$  for all  $i, j$  Define grid points:  $x_i = \text{linspace}(i_{\min}, i_{\max}, N_x)$   $y_j = \text{linspace}(j_{\min}, j_{\max}, N_y)$  Precompute constant:  $r = \frac{h^2}{k^2}$   
 $i = 2 : N_x$   $j = 2 : N_y$  Compute source term:

$$\text{source\_term} = \left( 1 + h \frac{0.0016}{1 + 0.0016x_i(i)} \right) \frac{2 \times 10^8}{3 \times 10^{11}} (1 + 0.0016x_i(i))$$

Update solution using finite difference scheme:

$$U(i, j) = \frac{r U(i, j-1) + U(i-1, j) + \text{source\_term}}{1 + r}$$

Display the computed  $U(i, j)$  matrix

## **5 . Results and Discussion/Conclusion:**

### **Spatial variation before movement across the Fault:**

i. **Variation of surface shear strain:** Figure2 shows that magnitude of the free surface shear strain is of order  $10^{-7}$  which well agrees with the observational data (Segal, P. 2010). Therefore, lateral inhomogeneous model of the Earth is agreeing with observed ground deformation.

ii. **Variation of displacement with distance from the fault:** The Figure3 shows the symmetric/anti-symmetric nature of displacement with respect to fault  $y=0$  remain unaltered, but qualitative and quantitative changes occur i.e, as we go distance from the fault the displacement gradually increases .

iii. **Causes of intraplate strike-slip Earthquake:** The reason of intraplate strike-slip earthquake was not clear to the seismologist. From the Figure 4, it

is observed that as we move away from the fault, the shear stress continues to accumulate at the greater distance. We thus may conclude that the continuous variation of rigidity with distance from the fault may be a possible reason of such Earthquake.

iv. **Spatial prediction of intraplate Earthquake:** From Figure 4, assuming the value of critical stress  $\tau_c = 200$  bar, we see that at a point distance apart from the fault for example  $y = 50$  km. the accumulated shear stress exceeds  $\tau_c$  at a depth  $z = 10$  km (approx.) which is in good proximity with the observational data (Hough et al., 2003).

**Spatial variation after movement across the Fault:**

v. **Variation of shear strain with distance:** Figure 5 shows that magnitude of the free surface shear strain is of order  $10^{-6}$  which well agrees with the observational data (Segal, P. 2010). It is also observed that the shear strain increases with depth and attains its maximum nearer to the bottom of the fault and also increases with the distance from the fault.

vi. **Variation of displacement with distance from the fault:** The Figure 6 shows the symmetric nature of displacement with respect to fault  $y = 0$  remain unaltered, but qualitative and quantitative changes occur i.e., as we go distance from the fault the displacement gradually increases. Figure 8, Figure 9, shows the surface displacement after earthquake in the elastic two layered model (Rybicki, K. 1971). It is observed that the displacement is anti-symmetric with respect to the fault and is of magnitude of few centimeters whereas in our model the surface displacement is symmetric - a qualitative change is observed. Also, in our model the displacement is of order few millimeters. Therefore, a quantitative change is also observed in our model.

vii. **Variation of shear stress with distance:** From the Figure 7 it is observed that after the occurrence of intraplate strike slip earthquake the shear stress accumulation pattern drastically changes. While the shear stress was accumulating at the greater distance from the fault before fault movement, but after the fault movement it is accumulating at a greater rate at the nearer of the fault, which indicates that the occurrence of the intraplate earthquakes enhances the possibility of occurrence of the interplate earthquakes.

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