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# Deformation of an elastic layer coupling in different ways to a base due to a very long vertical strike-slip dislocation

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**Abstract.** The closed-form analytic expressions for the displacement and stresses at any point of an elastic layer lying over a base due to a very long vertical strike-slip dislocation are obtained. The interface between the layer and the base is assumed to be either 'smooth-rigid' or 'rough-rigid' or 'welded'. The variations of displacement and stresses with the horizontal distance from the fault for different types of coupling of the layer with the base have been studied. It is found that the displacement for 'welded interface' lies between the displacements due to 'smooth rigid' and 'rough-rigid' interfaces for different positions of the observer and different values of the ratio of rigidities of the layer and half-space.

**Keywords.** Subsurface deformation; vertical strike-slip fault; elastic layer.

## 1. Introduction

Steketee (1958a, b) used the theory of Volterra's dislocations to determine the three-dimensional static displacements and stresses in the earth due to a strike-slip fault with uniform slip. Maruyama (1966) derived the formulas for the displacement and stress fields of a two-dimensional Somigliana dislocation in a semi-infinite medium. The static deformation of a multilayered half-space due to seismic sources has been studied, amongst others, by Singh (1970), Sato and Matsu'ura (1973), Singh and Garg (1985) and Roth (1990).

Rybicki (1971) obtained the analytic expressions for the surface deformation of a semi-infinite elastic medium consisting of an elastic layer lying over an elastic half-space due to a very long vertical strike-slip fault lying in the layer using the method of images. Bonafede and Dragoni (1982) studied the effect of the stress concentration on a very long strike-slip fault situated in an elastic plate subject to basal shear stress.

The deformation at any point of the medium is useful to analyse the deformation field around mining tremors and drilling into the crust of the earth. In the present paper, we have calculated the deformation inside a layer lying over a base as a result of a very long vertical strike-slip fault in the layer. Different types of boundary conditions—namely, rough-rigid, smooth-rigid and welded—at the interface are considered and the resulting different deformations are compared numerically. The elastic layer represents the lithosphere and the welded case corresponds to the earth model consisting of the lithosphere overlying the asthenosphere.

The technique employed in the present paper consists of first finding the integral expressions for the displacement inside the layer from the corresponding integral expressions for an unbounded elastic medium, given by Singh (1985), by applying suitable boundary conditions at the boundaries of the layer and then evaluating the integrals analytically.

## 2. Theory

Let $(x, y, z)$ be the Cartesian coordinate system with $z$-axis vertically downwards. Let $(u, v, w)$ be the displacement components. We shall be considering the antiplane strain problem so that $v = w \equiv 0$ and $u = u(y, z)$ satisfies the equilibrium equation

$$(\partial^2 u/\partial y^2) + (\partial^2 u/\partial z^2) = 0 \tag{1}$$

for zero body forces. The non-zero strains and stresses are

$$e_{12} = \tfrac{1}{2}(\partial u/\partial y), \quad e_{13} = \tfrac{1}{2}(\partial u/\partial z) \tag{2}$$

$$\tau_{12} = \mu(\partial u/\partial y), \quad \tau_{13} = \mu(\partial u/\partial z) \tag{3}$$

$\mu$ being the rigidity of the elastic medium.

We assume that a line source parallel to $x$-axis intersects the $yz$-plane at the point $P(\alpha, \beta)$. The displacement $u_0$, parallel to the $x$-axis, due to the line source in an unbounded medium is given by Singh (1985)

$$u_0 = \int_0^\infty [A_0 \sin k(y-\alpha) + B_0 \cos k(y-\alpha)] \exp(-k|z-\beta|) \mathrm{d}k. \tag{4}$$

The source coefficients $A_0$ and $B_0$ for various single couples are given in table 1. These coefficients are independent of the variable of integration $k$. We note that the value of $B_0$ changes for $z \lessgtr \beta$. We write $B_0^1$ for $B_0$ when $z < \beta$. Then $B_0 = -B_0^1$ for $z > \beta$. The single couple [12] is a couple in the $xy$-plane with forces in the $x$-direction and with its arm in the $y$-direction. $F_{12}$ is the moment of the couple [12]. Similarly, [13] denotes a couple of moment $F_{13}$ in the $xz$-plane with forces in the $x$-direction and arm in the $z$-direction.

## 3. Formulation of the problem

Suppose that a horizontal layer of thickness $H$ and rigidity $\mu$ is lying over a half-space. The origin of the Cartesian coordinate system $(x, y, z)$ is placed at the upper boundary

**Table 1.** Source coefficients for various sources. The upper sign is for $z > \beta$ and the lower sign for $0 < z < \beta$.

| Source | $A_0$ | $B_0$ |
|---|---|---|
| Single couple [12] | $\frac{F_{12}}{2\pi\mu}$ | 0 |
| Single couple [13] | 0 | $\pm\frac{F_{13}}{2\pi\mu}$ |

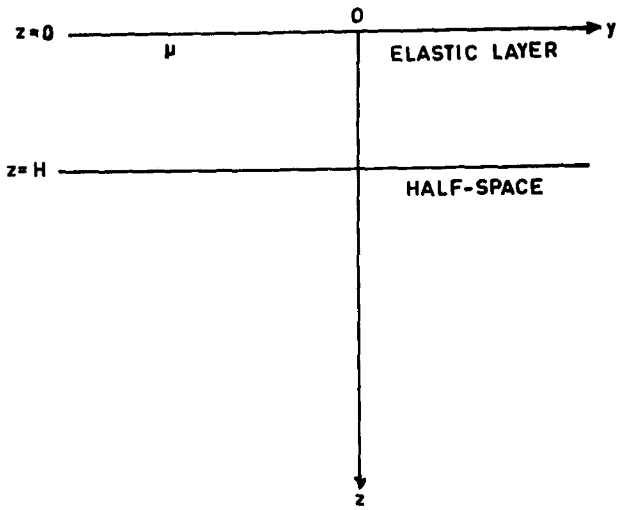


**Figure 1.** Section $x = 0$ of the model.

of the layer and $z$-axis is drawn vertically downwards so that the layer occupies the region $0 \leqslant z \leqslant H$. The region $z > H$ is the half-space as shown in figure 1.

We shall determine the deformation of the layer due to a very long strike-slip fault situated in the layer. The surface $z = 0$ is assumed to be traction-free. Therefore, the boundary condition, at $z = 0$, is

$$\tau_{13} = 0. \tag{5}$$

The interface $z = H$ between the layer and the half-space may be either 'welded' or 'smooth-rigid' or 'rough-rigid'.

When the interface is of the 'smooth-rigid' type, the boundary condition is (Small and Booker 1984)

$$\tau_{13}(z = H) = 0 \tag{6}$$

whereas for the 'rough-rigid' interface, the boundary condition is (Small and Booker 1984)

$$u(z = H) = 0. \tag{7}$$

When the interface is 'welded', the boundary conditions are

$$\begin{aligned} u(z = H-) &= u(z = H+) \\ \tau_{13}(z = H-) &= \tau_{13}(z = H+) \end{aligned} \tag{8}$$

and this case corresponds to the realistic earth model represented by a lithosphere overlying asthenosphere (Nur and Mavko 1974; Garg and Singh 1988).

We shall obtain the analytic expressions for the deformation of the layer corresponding to each type of contact between the half-space and the layer.

## 4. Solution of the problem

Suitable expression for the displacement, parallel to the $x$-axis and satisfying equation (1), at any point of the layer is

$$u = u_0 + \int_0^\infty [\{A \sin k(y-\alpha) + B \cos k(y-\alpha)\} \exp(-kz) + \{C \sin k(y-\alpha) + D \cos k(y-\alpha)\} \exp(kz)] \, dk \quad (9)$$

with $u_0$ given in (4). The stresses are

$$\tau_{12} = \mu \int_0^\infty [A_0 \cos k(y-\alpha) - B_0 \sin k(y-\alpha)] \exp(-k|z-\beta|) k \, dk + \mu \int_0^\infty [\{A \cos k(y-\alpha) - B \sin k(y-\alpha)\} \exp(-kz) + \{C \cos k(y-\alpha) - D \sin k(y-\alpha)\} \exp(kz)] k \, dk, \quad (10)$$

$$\tau_{13} = \mu \int_0^\infty [\mp \{A_0 \sin k(y-\alpha) + B_0 \cos k(y-\alpha)\}] \exp(-k|z-\beta|) k \, dk + \mu \int_0^\infty [\{-A \sin k(y-\alpha) - B \cos k(y-\alpha)\} \exp(-kz) + \{C \sin k(y-\alpha) + D \cos k(y-\alpha)\} \exp(kz)] k \, dk. \quad (11)$$

The traction-free boundary condition at the surface $z = 0$ yields

$$A_0 \exp(-k\beta) - A + C = 0$$
$$B_0^1 \exp(-k\beta) - B + D = 0 \quad (12)$$

### 4.1 *Smooth-rigid interface*

The boundary condition (6) gives

$$-A_0 \exp\{-k(H-\beta)\} - A \exp(-kH) + C \exp(kH) = 0$$
$$B_0^1 \exp\{-k(H-\beta)\} - B \exp(-kH) + D \exp(kH) = 0 \quad (13)$$

Equations (12) and (13) determine the values of the unknowns $A$, $B$, $C$ and $D$ for the 'smooth-rigid' interface. Substituting the values of $A$, $B$, etc., so obtained, in (9) the integral expression for the displacement is obtained. Expressing the denominator in the integrand as a power series and then evaluating the integrals analytically with the help of the standard transform integrals (Erdélyi 1954), the closed-form expression for the displacement is obtained as

$$u = A_0 \left[ \frac{y-\alpha}{(y-\alpha)^2 + (z-\beta)^2} \right] + B_0 \left[ \frac{|z-\beta|}{(y-\alpha)^2 + (z-\beta)^2} \right] + A_0 \left[ \frac{y-\alpha}{(y-\alpha)^2 + (z+\beta)^2} + \sum_{n=1}^{\infty} \left\{ \frac{y-\alpha}{(y-\alpha)^2 + (2nH + z + \beta)^2} \right. \right.$$

$$+\frac{y-\alpha}{(y-\alpha)^2+(2nH+z-\beta)^2}+\frac{y-\alpha}{(y-\alpha)^2+(2nH-z+\beta)^2}$$

$$+\frac{y-\alpha}{(y-\alpha)^2+(2nH-z-\beta)^2}\Bigg\}\Bigg]+B_0^1\Bigg[\frac{z+\beta}{(y-\alpha)^2+(z+\beta)^2}$$

$$+\sum_{n=1}^{\infty}\Bigg\{\frac{2nH+z+\beta}{(y-\alpha)^2+(2nH+z+\beta)^2}-\frac{2nH+z-\beta}{(y-\alpha)^2+(2nH+z-\beta)^2}$$

$$+\frac{2nH-z+\beta}{(y-\alpha)^2+(2nH-z+\beta)^2}-\frac{2nH-z-\beta}{(y-\alpha)^2+(2nH-z-\beta)^2}\Bigg\}\Bigg]. \tag{14}$$

## 4.2 *Rough-rigid interface*

As in section (4.1), the closed-form expression for the displacement $u$ is

$$u=A_0\Bigg[\frac{y-\alpha}{(y-\alpha)^2+(z-\beta)^2}\Bigg]+B_0\Bigg[\frac{|z-\beta|}{(y-\alpha)^2+(z-\beta)^2}\Bigg]$$

$$+A_0\Bigg[\frac{y-\alpha}{(y-\alpha)^2+(z+\beta)^2}+\sum_{n=1}^{\infty}(-1)^n\Bigg\{\frac{y-\alpha}{(y-\alpha)^2+(2nH+z+\beta)^2}$$

$$+\frac{y-\alpha}{(y-\alpha)^2+(2nH+z-\beta)^2}+\frac{y-\alpha}{(y-\alpha)^2+(2nH-z+\beta)^2}$$

$$+\frac{y-\alpha}{(y-\alpha)^2+(2nH-z-\beta)^2}\Bigg\}\Bigg]+B_0^1\Bigg[\frac{z+\beta}{(y-\alpha)^2+(z+\beta)^2}$$

$$+\sum_{n=1}^{\infty}(-1)^n\Bigg\{\frac{2nH+z+\beta}{(y-\alpha)^2+(2nH+z+\beta)^2}-\frac{2nH+z-\beta}{(y-\alpha)^2+(2nH+z-\beta)^2}$$

$$+\frac{2nH-z+\beta}{(y-\alpha)^2+(2nH-z+\beta)^2}-\frac{2nH-z-\beta}{(y-\alpha)^2+(2nH-z-\beta)^2}\Bigg\}\Bigg]. \tag{15}$$

## 4.3 *Welded interface*

Let $\mu_0$ be the rigidity of the half-space ($z \geqslant H$). The displacement $u$ in the region $z \geqslant H$ is of the type

$$u=\int_0^{\infty}[A_1\sin k(y-\alpha)+B_1\cos k(y-\alpha)]\exp(-kz)\,dk. \tag{16}$$

The shear stress $\tau_{13}$ is

$$\tau_{13}=\mu_0\int_0^{\infty}[A_1\sin k(y-\alpha)+B_1\cos k(y-\alpha)]\exp(-kz)\,k\,dk. \tag{17}$$

From equations (8), (9), (11), (12), (16), (17) and proceeding as in section (4.1), the displacement $u$ at any point of the layer is found to be

$$u=A_0\Bigg[\frac{y-\alpha}{(y-\alpha)^2+(z-\beta)^2}\Bigg]+B_0\Bigg[\frac{|z-\beta|}{(y-\alpha)^2+(z-\beta)^2}\Bigg]$$

$$+A_0\left[\frac{y-\alpha}{(y-\alpha)^2+(z+\beta)^2}+\sum_{n=1}^{\infty}R^n\left\{\frac{y-\alpha}{(y-\alpha)^2+(2nH+z+\beta)^2}\right.\right.$$

$$+\frac{y-\alpha}{(y-\alpha)^2+(2nH+z-\beta)^2}+\frac{y-\alpha}{(y-\alpha)^2+(2nH-z-\beta)^2}$$

$$\left.\left.+\frac{y-\alpha}{(y-\alpha)^2+(2nH-z+\beta)^2}\right\}\right]+B_0^1\left[\frac{z+\beta}{(y-\alpha)^2+(z+\beta)^2}\right.$$

$$+\sum_{n=1}^{\infty}R^n\left\{\frac{2nH+z+\beta}{(y-\alpha)^2+(2nH+z+\beta)^2}-\frac{2nH+z-\beta}{(y-\alpha)^2+(2nH+z-\beta)^2}\right.$$

$$\left.\left.+\frac{2nH-z+\beta}{(y-\alpha)^2+(2nH-z+\beta)^2}-\frac{2nH-z-\beta}{(y-\alpha)^2+(2nH-z-\beta)^2}\right\}\right] \tag{18}$$

where

$$R=(S-1)/(S+1), \quad S=(\mu/\mu_0). \tag{19}$$

We observe that the displacement due to the smooth rigid and rough-rigid interfaces can be obtained from that of welded interface by taking $R=1(\mu_0=0)$ and $R=-1$ $(\mu_0=\infty)$, respectively.

## 5. Vertical strike-slip dislocation

The single couple [12] is equivalent to a long vertical strike-slip line source such that (Maruyama 1966; Singh 1985)

$$F_{12}=\mu U_0\,\mathrm{d}\beta, \tag{20}$$

where $\Delta u=U_0$ is the slip. We shall be assuming that the slip is uniform, which makes the displacement discontinuous and the stress singular at the edge. This assumption has been made for mathematical convenience so that an analytic solution can be obtained.

Equations (14), (15), (18), (20) and table 1 determine the horizontal displacement $u$ at any point of the layer due to a long vertical strike-slip line source situated at the point $(\alpha,\beta)$ of the layer. The displacement at any point of the layer due to a long vertical strike-slip fault with finite vertical extent $0\leqslant\beta_1\leqslant\beta\leqslant\beta_2\leqslant H$ is obtained from the corresponding results for a long vertical line source on integrating with respect to $\beta$ from $\beta_1$ to $\beta_2$.

The results for the smooth-rigid interface can be obtained from the corresponding results for welded interface by taking $R=1$. On putting $R=-1$ in the expressions for the deformation field due to a welded interface, the deformation field for the rough-rigid interface can be obtained. The deformation field for the welded interface is given below:

$$u=\frac{U_0}{2\pi}\left[\tan^{-1}\left(\frac{z+\beta_2}{y-\alpha}\right)-\tan^{-1}\left(\frac{z+\beta_1}{y-\alpha}\right)-\tan^{-1}\left(\frac{z-\beta_2}{y-\alpha}\right)\right.$$

$$+\tan^{-1}\left(\frac{z-\beta_1}{y-\alpha}\right)+\sum_{n=1}^{\infty}R^n\left\{\tan^{-1}\left(\frac{2nH+z+\beta_2}{y-\alpha}\right)\right.$$

$$-\tan^{-1}\left(\frac{2nH+z+\beta_1}{y-\alpha}\right)-\tan^{-1}\left(\frac{2nH+z-\beta_2}{y-\alpha}\right)$$
$$+\tan^{-1}\left(\frac{2nH+z-\beta_1}{y-\alpha}\right)+\tan^{-1}\left(\frac{2nH-z+\beta_2}{y-\alpha}\right)$$
$$-\tan^{-1}\left(\frac{2nH-z+\beta_1}{y-\alpha}\right)-\tan^{-1}\left(\frac{2nH-z-\beta_2}{y-\alpha}\right)$$
$$+\tan^{-1}\left(\frac{2nH-z-\beta_1}{y-\alpha}\right)\Bigg\}\Bigg] \tag{21}$$

$$\tau_{12}=\frac{\mu U_0}{2\pi}\Bigg[\frac{z+\beta_1}{(y-\alpha)^2+(z+\beta_1)^2}-\frac{z+\beta_2}{(y-\alpha)^2+(z+\beta_2)^2}$$
$$+\frac{z-\beta_2}{(y-\alpha)^2+(z-\beta_2)^2}-\frac{z-\beta_1}{(y-\alpha)^2+(z-\beta_1)^2}$$
$$+\sum_{n=1}^{\infty}R^n\Bigg\{\frac{2nH+z+\beta_1}{(y-\alpha)^2+(2nH+z+\beta_1)^2}-\frac{2nH+z+\beta_2}{(y-\alpha)^2+(2nH+z+\beta_2)^2}$$
$$+\frac{2nH+z-\beta_2}{(y-\alpha)^2+(2nH+z-\beta_2)^2}-\frac{2nH+z-\beta_1}{(y-\alpha)^2+(2nH+z-\beta_1)^2}$$
$$-\frac{2nH-z+\beta_2}{(y-\alpha)^2+(2nH-z+\beta_2)^2}+\frac{2nH-z+\beta_1}{(y-\alpha)^2+(2nH-z+\beta_1)^2}$$
$$+\frac{2nH-z-\beta_2}{(y-\alpha)^2+(2nH-z-\beta_2)^2}-\frac{2nH-z-\beta_1}{(y-\alpha)^2+(2nH-z-\beta_1)^2}\Bigg\}\Bigg] \tag{22}$$

$$\tau_{13}=\frac{\mu U_0}{2\pi}\Bigg[\frac{y-\alpha}{(y-\alpha)^2+(z+\beta_2)^2}-\frac{y-\alpha}{(y-\alpha)^2+(z+\beta_1)^2}$$
$$-\frac{y-\alpha}{(y-\alpha)^2+(z-\beta_2)^2}+\frac{y-\alpha}{(y-\alpha)^2+(z-\beta_1)^2}$$
$$+\sum_{n=1}^{\infty}R^n\Bigg\{\frac{y-\alpha}{(y-\alpha)^2+(2nH+z+\beta_2)^2}-\frac{y-\alpha}{(y-\alpha)^2+(2nH+z+\beta_1)^2}$$
$$-\frac{y-\alpha}{(y-\alpha)^2+(2nH+z-\beta_2)^2}+\frac{y-\alpha}{(y-\alpha)^2+(2nH+z-\beta_1)^2}$$
$$-\frac{y-\alpha}{(y-\alpha)^2+(2nH-z+\beta_2)^2}+\frac{y-\alpha}{(y-\alpha)^2+(2nH-z+\beta_1)^2}$$
$$+\frac{y-\alpha}{(y-\alpha)^2+(2nH-z-\beta_2)^2}-\frac{y-\alpha}{(y-\alpha)^2+(2nH-z-\beta_1)^2}\Bigg\}\Bigg] \tag{23}$$

## 6. Numerical results

In this section, the variations of the displacement $u$ parallel to the fault and the stresses $\tau_{12}$ and $\tau_{13}$ with the horizontal distance $y$ from the fault for different types of the contact of the layer with the half-space have been studied numerically. The fault causing the deformation of the layer is a very long vertical strike-slip fault with finite vertical extent lying in the layer. For simplicity, $\alpha = 0$, $\beta_1 = H/4$ and $\beta_2 = 3H/4$ are taken so that the fault passes through the $z$-axis (figure 2).

Figures 3–5 exhibit the variation of the displacement $u$ with the horizontal distance

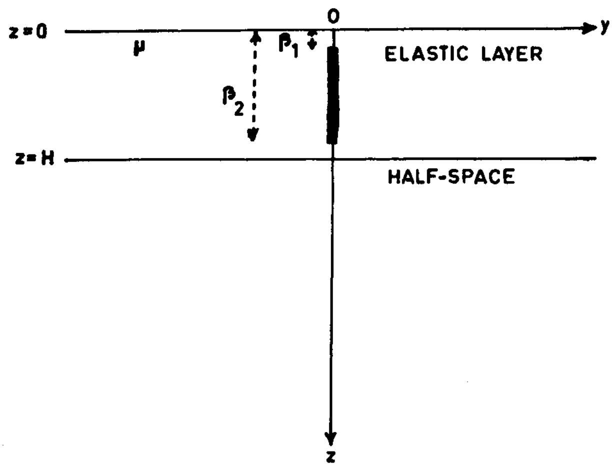


**Figure 2.** Section $x = 0$ of the model with finite vertical strike-slip fault ($0 \leqslant \beta_1 \leqslant z \leqslant \beta_2 \leqslant H$) in the elastic layer.

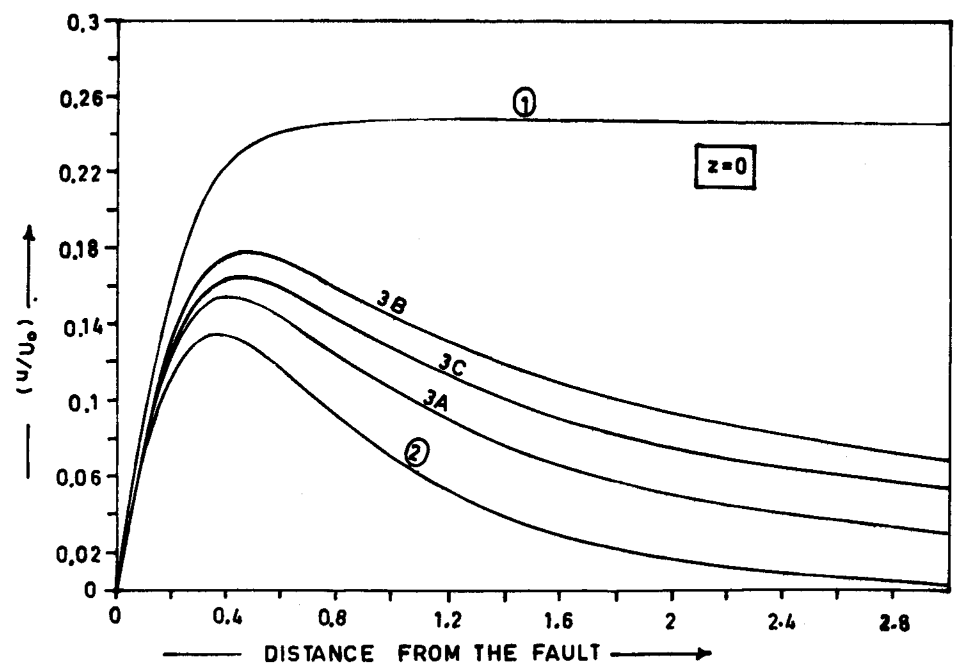


**Figure 3.** Variation of the dimensionless displacement $u/U_0$ with the dimensionless horizontal distance $y/H$ from a vertical strike-slip fault for $z = 0$. ① denotes that the curve is for a 'smooth-rigid' interface while ② for a 'rough-rigid' interface. 3A, 3B and 3C denote the curves for welded interface corresponding to the rigidity contrast $S = 0{\cdot}5$, $1{\cdot}5$ and 1, respectively.

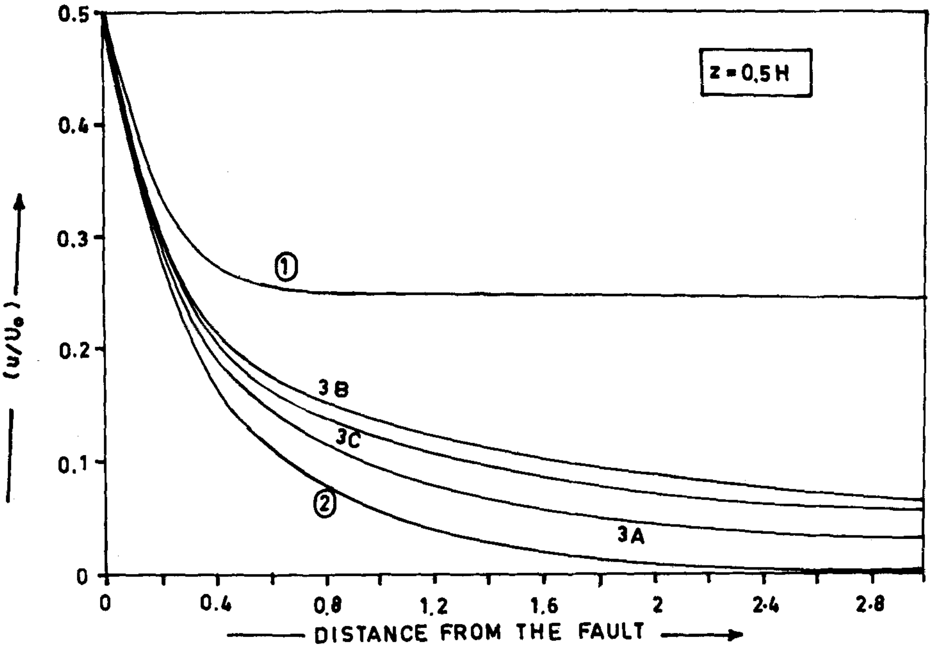


**Figure 4.** Variation of $u/U_0$ with $y/H$ for $z = 0{\cdot}5H$. Notation as in figure 3.

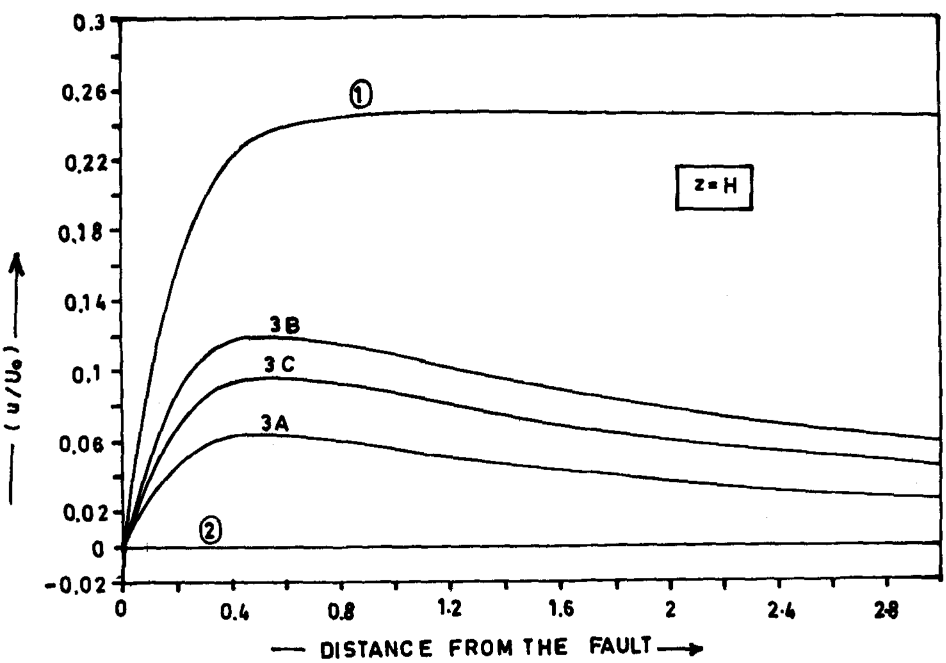


**Figure 5.** Variation of $u/U_0$ with $y/H$ for $z = H$. Notation as in figure 3.

from the fault for three different positions of the observer, namely, $z = 0$, $H/2$ and $H$. In each figure, curves corresponding to different types of the interface are drawn. For the welded contact, three values of the ratio of rigidities of the elastic layer and the elastic half-space are taken, namely, $S = 1/2$, 1 and 3/2. $S = 1/2$ implies that the elastic layer is of the low rigidity as compared to the rigidity of the elastic half-space while $S = 1$ means that the medium $(z \geqslant 0)$ is a uniform half-space. It is found that the displacement due to 'welded' contact lies between the displacements due to 'smooth-rigid' contact and 'rough-rigid' contact for different values of $S$.

The variation of the stress $\tau_{13}$ for two values of $z(z = H/2$ and $z = H)$ has been shown in figures 6–7. In each figure, curves corresponding to the three values of

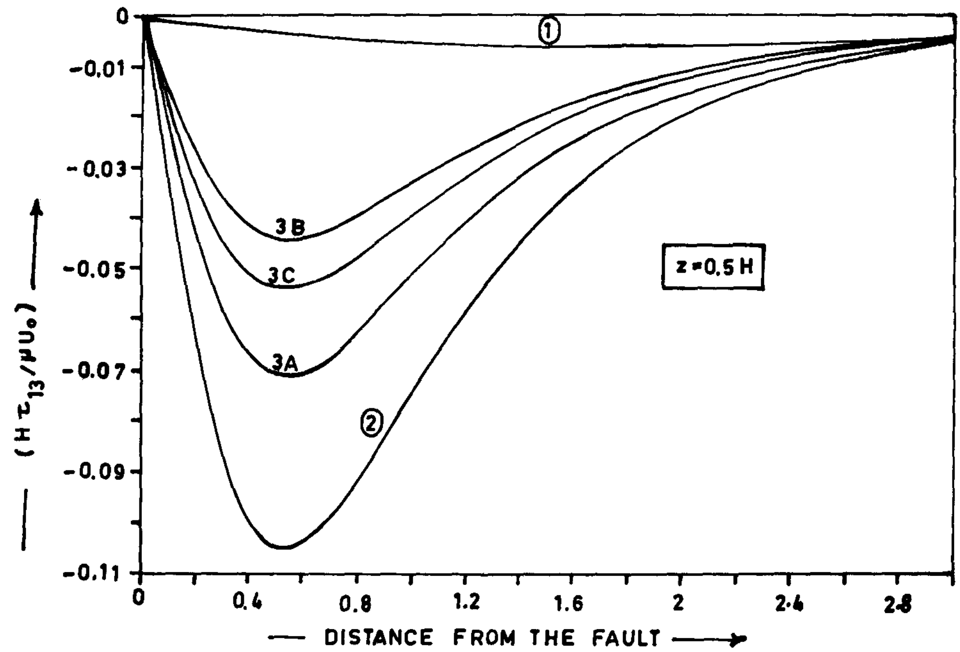


**Figure 6.** Variation of stress $H\tau_{13}/\mu U_0$ with $y/H$ for $z = 0{\cdot}5H$. Notation as in figure 3.

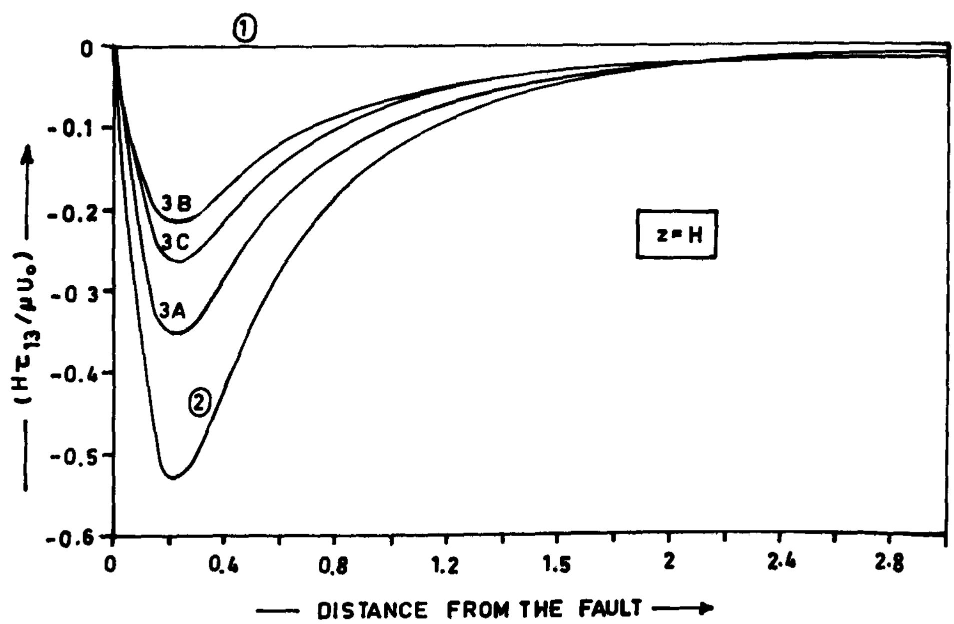


**Figure 7.** Variation of $H\tau_{13}/\mu U_0$ with $y/H$ for $z = H$. Notation as in figure 3.

$S(S = 1/2,\ 1$ and $3/2)$ for the welded interface have been drawn. In the interval, $0 \leqslant y \leqslant 2H$, the value of the stress due to welded interface lies between the corresponding values due to 'smooth-rigid' interface and 'rough-rigid' interface.

Figures 8–13 show the variation of the stress $\tau_{12}$ with the distance $y$. In these

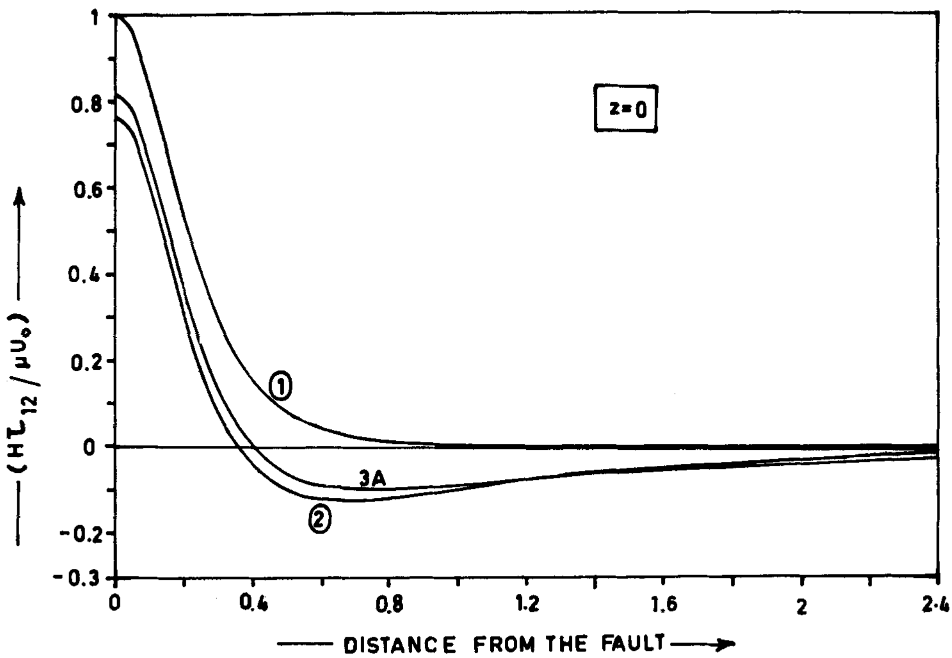


**Figure 8.** Variation of stress $H\tau_{12}/\mu U_0$ with $y/H$ for $z = 0$ and $S = 1/2$. Notation as in figure 3.

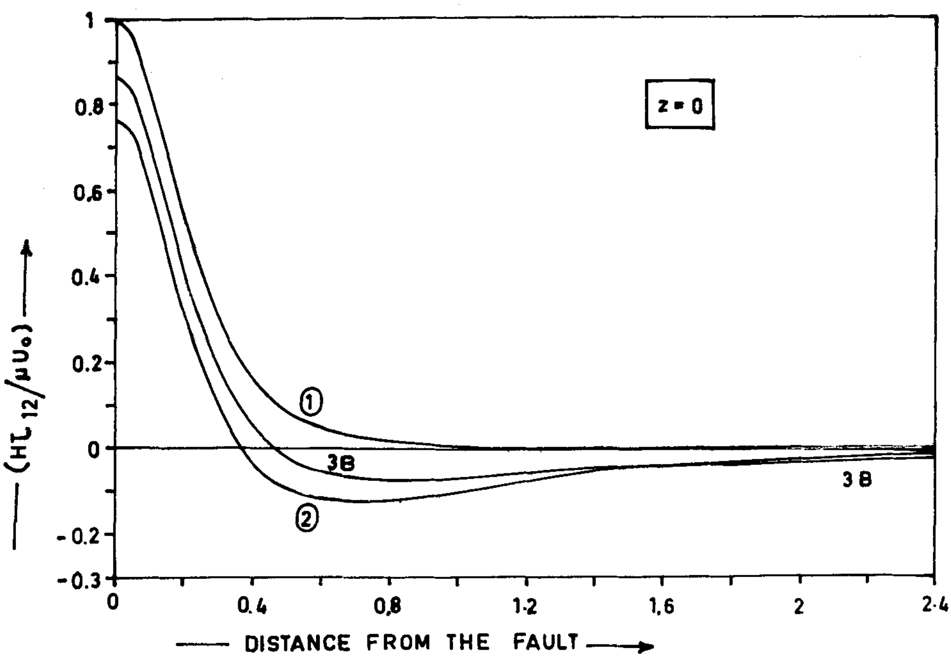


**Figure 9.** Variation of $H\tau_{12}/\mu U_0$ with $y/H$ for $z = 0$ and $S = 3/2$. Notation as in figure 3.

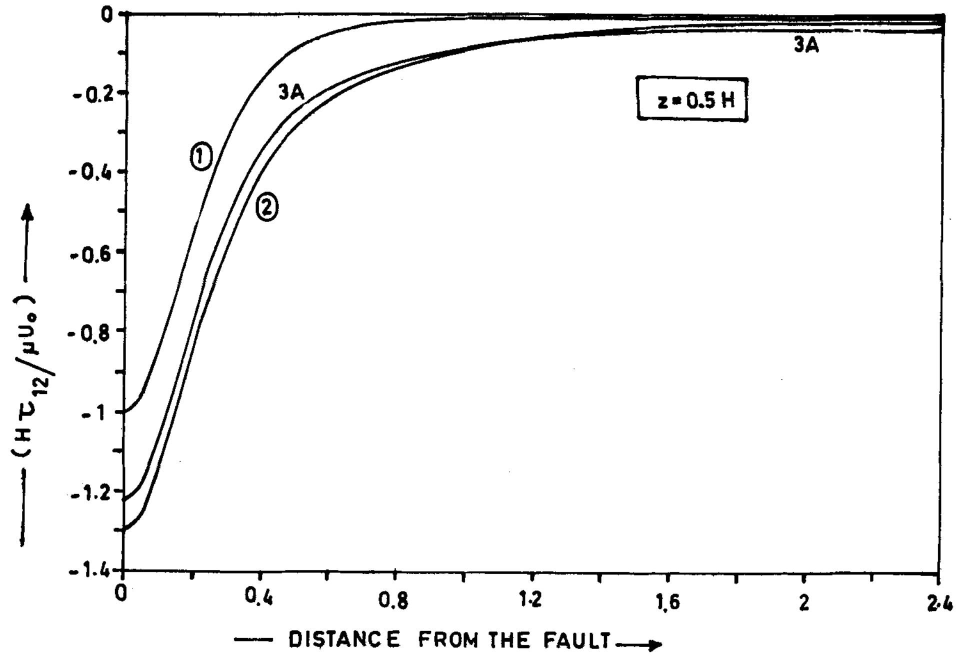


**Figure 10.** Variation of $H\tau_{12}/\mu U_0$ with $y/H$ for $z = 0{\cdot}5H$ and $S = 1/2$. Notation as in figure 3.

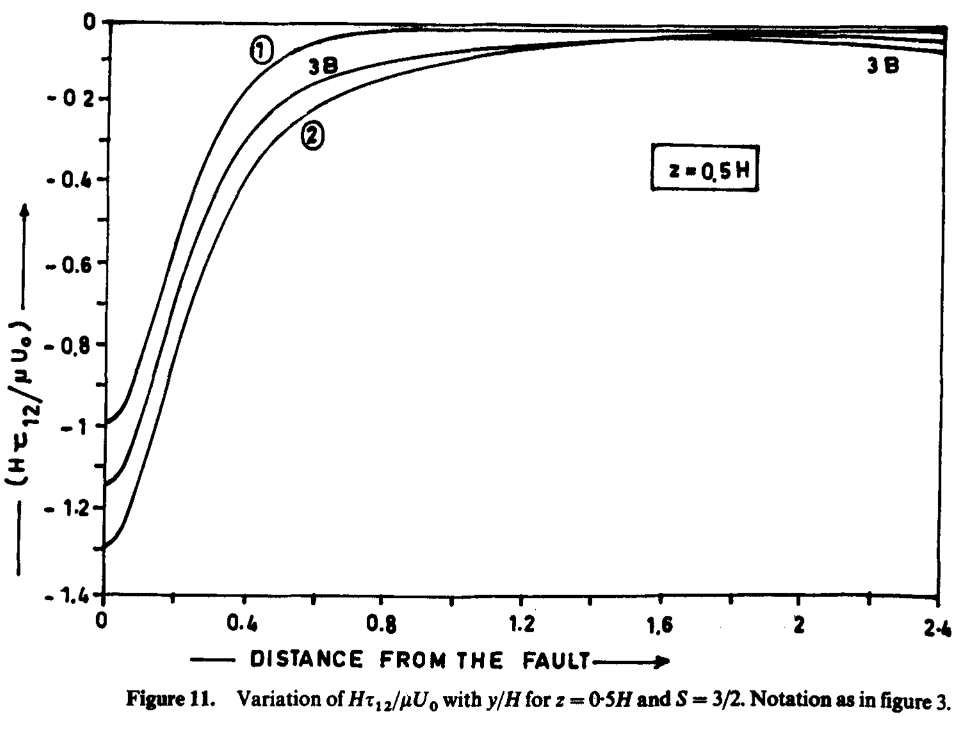


**Figure 11.** Variation of $H\tau_{12}/\mu U_0$ with $y/H$ for $z = 0{\cdot}5H$ and $S = 3/2$. Notation as in figure 3.

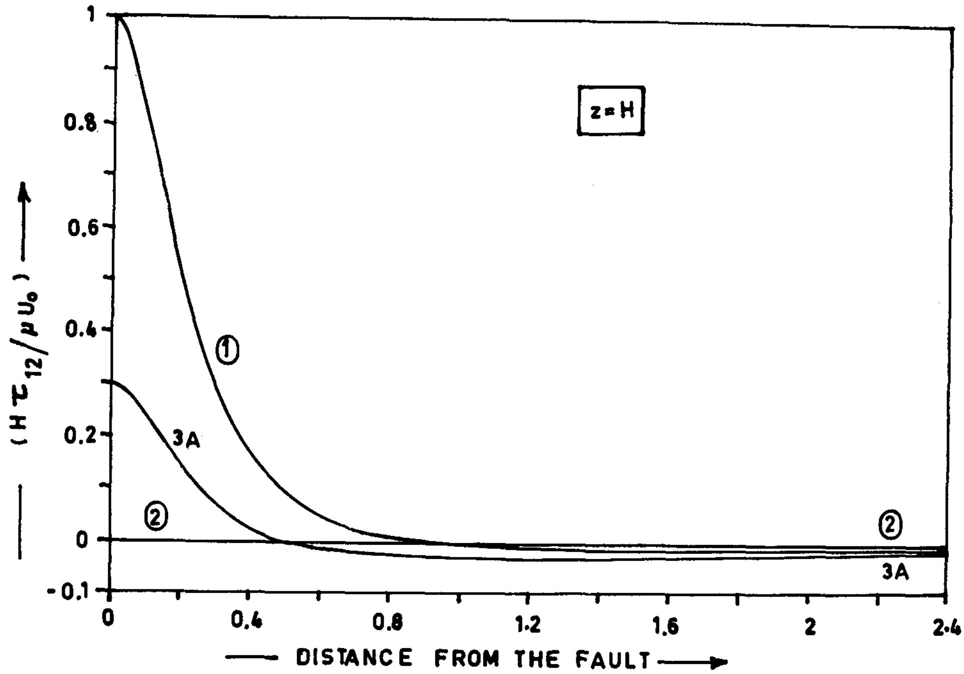


**Figure 12.** Variation of $H\tau_{12}/\mu U_0$ with $y/H$ for $z = H$ and $S = 1/2$. Notation as in figure 3.

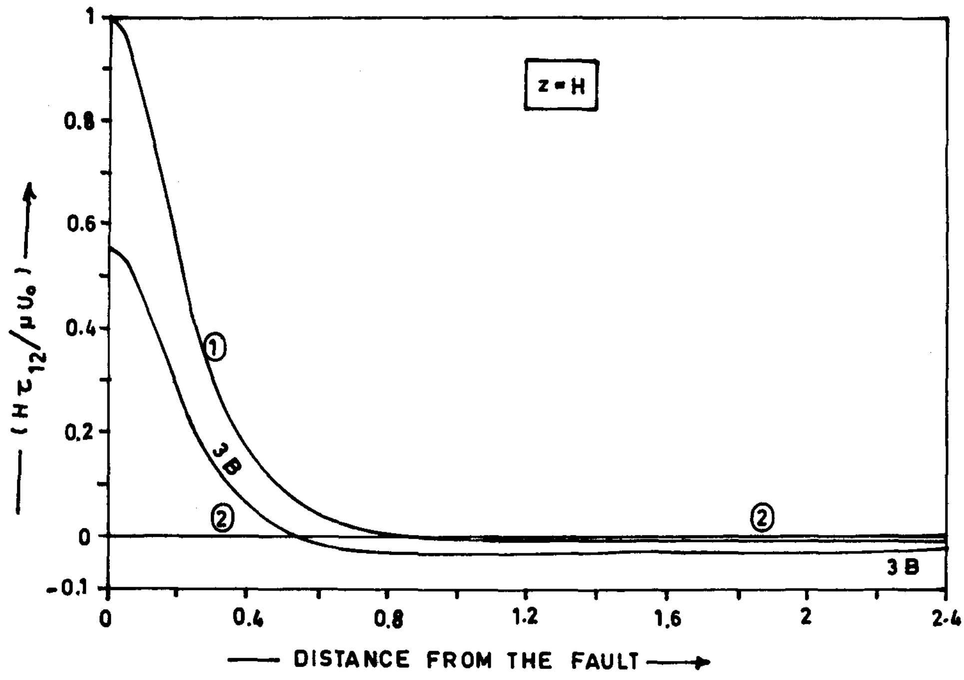


**Figure 13.** Variation of $H\tau_{12}/\mu U_0$ with $y/H$ for $z = H$ and $S = 3/2$. Notation as in figure 3.

figures, three locations of the observer at $z = 0$, $H/2$ and $H$ are considered. For the welded interface, two values of the ratio $S(S = 1/2$ and $S = 3/2)$ are considered. It is noted that the stress $\tau_{12}$ almost vanishes at the interface when the interface is of the 'rough-rigid' type.

## 7. Conclusions

Without using the method of images, analytic expressions for the displacement and stresses at any point of an elastic layer due to a very long vertical strike-slip fault in it are obtained in the present paper. Different cases arising out of the coupling of the lower boundary of the layer in different ways to a half-space are considered in detail. In engineering, elastic layer represents an elastic plate while in geophysics it represents a lithosphere. One type of the coupling of an elastic layer with an elastic half-space corresponds to the realistic earth model-lithosphere lying over an asthenosphere. Lastly, the influence of the different kinds of the interface upon the deformation field is studied numerically.

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