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DISPLACEMENTS AND STRESSES IN AN ANISOTROPIC MEDIUM DUE TO NON-UNIFORM SLIP ALONG A VERY LONG STRIKE-SLIP FAULT

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ABSTRACT

The problem of static deformation of a homogeneous, orthotropic elastic uniform half-space due to non-uniform slip along a vertical strike-slip fault of infinite length and finite width has been studied. Closed-form analytical expressions of displacements and stresses for different slip profiles – parabolic, linear, elliptic, and cubic are obtained. The results obtained here are the generalization of the results for an isotropic medium (Singh et al., 1994) in the sense that medium of the present work is orthotropic which is more realistic than isotropic and results for an isotropic case can be derived from our results. The variations of the horizontal displacements and stresses with distance from the fault due to various slip-profiles at the surface have been studied to examine the effect of anisotropy on the deformation. Numerically, it has been found that for parabolic, linear, and elliptic slip profiles, the surface displacements in magnitude for isotropic elastic medium are greater than that for an orthotropic elastic medium while in case of cubic slip, the surface displacements in magnitude for orthotropic elastic medium is greater than that for the isotropic medium.

KEYWORDS: Orthotropic, Non-uniform Slip, Strike-Slip

INTRODUCTION

Dislocation theory has proved to be a useful tool when applied to studies of ground deformation and stresses produced by faulting. On the basis of dislocation theory, several works deal with the mathematical treatment of static elastic residual fields. These have contributed to knowledge about the deformation of the Earth's crust associated with an earthquake (e.g., see Steketee (1958), Chinnery (1961, 1963), Maruyama (1964, 1966), and Press (1965)).

In the case of long faults, one is justified in using the two-dimensional (2-D) approximation which has simplified the algebra to a great extent. The static deformation of a semi-infinite elastic isotropic medium due to a very long strike-slip and a dip-slip fault has been studied by many researchers, e.g., by Kasahara (1960, 1964), Rybicki (1978, 1986), Savage (1980), and Mavko (1981). However, most of these studies assumed uniform slip profiles on the fault. The assumption of uniform slip makes the edges of the fault plane singular where the displacement is indeterminate and the stress is infinite. For this reason, uniform slip models cannot be used in the near field. There are a number of interesting phenomena that occur near the edge of the fault zone, e.g., vertical movements associated with strike-slip faulting. In order to study these phenomena, it is necessary to consider models of earthquake faulting with non-uniform slip on the fault. Yang and Toksöz (1981) used finite-element method to study the trapezoidal type of non-uniform slip on a strike-slip fault in an isotropic elastic half-space. Wang and Wu (1983) obtained a closed form analytical solution for displacement and stress fields due to a non-uniform slip along a strike-slip fault for the same model. Singh et al. (1994) obtained closed-form analytical expressions for displacements caused by a non-uniform slip on a long vertical strike-slip and dip-slip faults in a uniform isotropic elastic half-space.

The upper part of the Earth is anisotropic (Dziewonski and Anderson, 1981) and most of anisotropic media of interest in seismology have, at least approximately, a horizontal plane of symmetry. A plane of symmetry is a plane in which the elastic properties have reflection symmetry, and a medium with three mutually orthogonal planes of symmetry is known as orthorhombic. A large part of the Earth is recognized as having orthorhombic symmetry (Crampin, 1994). The orthorhombic symmetry of the upper mental is believed to be caused by orthorhombic crystals of olivine relative to the spreading centres (Hess, 1964). Orthorhombic symmetry is also expected to occur in sedimentary basins as a result of combination of vertical cracks with a horizontal axis of symmetry and a periodic thin-layer anisotropy with a vertical axis of symmetry (Bush and Crampin, 1987).

When one of the planes of symmetry in an orthorhombic is horizontal, the symmetry is termed as orthotropic symmetry (Crampin, 1989). Since the orientation of stress in the crust of the earth is usually orthotropic, most symmetry systems in the Earth's crust also have orthotropic orientations. The orthotropy symmetry is also exhibited by olivine and orthoyroxenes, the principal rock-forming minerals of deep crust and upper mantle.

Garg et al. (1996) obtained the representation of seismic sources causing antiplane strain deformation of an orthotropic medium. Recently, Garg et al. (2003) used an eigenvalue approach to study the plane strain problem of an infinite orthotropic elastic-medium due to two-dimensional sources.

In the present study, we have obtained closed-form analytical expressions of displacements and stresses caused by non-uniform slip on a long vertical strike-slip fault in an orthotropic elastic half-space. Four slip profiles, namely, parabolic, linear, elliptic, and cubic are considered. This paper is a continuation of previous paper (Garg et al., 1996) in the sense that we have taken the slip as non-uniform instead of uniform slip, and is generalization of the previous work for an isotropic medium (Singh et al., 1994) in the sense that the medium of the present paper is orthotropic which is a better approximation than isotropic case. The deformation at any point of the medium is useful to analyze the deformation field around mining tremors and drilling into the crust of the earth.

Most of the earthquakes on San Andreas fault are sufficiently long and shallow that a two-dimensional approximation may be used. The solution obtained here may find applications to model the lithospheric deformation associated with faulting.

In order to study the effect of orthotropy of an elastic medium in comparison with the isotropy, numerically, we compute the horizontal strike-slip displacements and stresses due to a very long vertical surface breaking fault for all different slip-profiles at the surface. For linear slip-profile the results are also compared at the depth. It is observed that the displacements and stresses for an orthotropic elastic medium differ significantly from the corresponding displacements and stresses for an isotropic elastic medium.

BASIC EQUATIONS

The equilibrium equations in the cartesian coordinate system (x_1, x_2, x_3) for zero body forces are

$$\frac{\partial \tau_{11}}{\partial x_1} + \frac{\partial \tau_{12}}{\partial x_2} + \frac{\partial \tau_{13}}{\partial x_3} = 0 \tag{1}$$

$$\frac{\partial \tau_{21}}{\partial x_1} + \frac{\partial \tau_{22}}{\partial x_2} + \frac{\partial \tau_{23}}{\partial x_3} = 0 \tag{2}$$

$$\frac{\partial \tau_{31}}{\partial x_1} + \frac{\partial \tau_{32}}{\partial x_2} + \frac{\partial \tau_{33}}{\partial x_3} = 0 \tag{3}$$

where τ_{ij} is the stress tensor. The strain-displacement relations are

$$e_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \qquad 1 \le i, j \le 3 \tag{4}$$

where $e_{ij}\,(i, j = 1,2,3)$ are the components of strain tensor and (u_1, u_2, u_3) are the displacement components.

For an orthotropic elastic medium, with the coordinate planes coinciding with the planes of symmetry and one plane of symmetry being horizontal, the stress-strain relations in matrix form are (Sokolnikoff, 1956)

$$\begin{bmatrix} \tau_{11} \\ \tau_{22} \\ \tau_{33} \\ \tau_{23} \\ \tau_{13} \\ \tau_{12} \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} & c_{13} & 0 & 0 & 0 \\ c_{12} & c_{22} & c_{23} & 0 & 0 & 0 \\ c_{13} & c_{23} & c_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{66} \end{bmatrix} \begin{bmatrix} e_{11} \\ e_{22} \\ e_{33} \\ 2e_{23} \\ 2e_{13} \\ 2e_{12} \end{bmatrix} \tag{5}$$

where the two-suffix quantities c_{ij} are elastic constants of the medium.

A transversely isotropic elastic medium, with x_3-axis coinciding with the axis of symmetry, is a particular case of an orthotropic elastic medium for which

$$c_{22} = c_{11},\ c_{23} = c_{13},\ c_{55} = c_{44},\ c_{66} = \frac{1}{2}\left(c_{11} - c_{12}\right) \tag{6}$$

and the number of independent elastic constants reduces from nine to five. When the medium is isotropic

$$\begin{aligned} c_{11} &= c_{22} = c_{33} = \lambda + 2\mu \\ c_{11} &= c_{13} = c_{23} = \lambda \\ c_{44} &= c_{55} = c_{66} = \mu \end{aligned} \tag{7}$$

where λ and μ are Lame's constants.

We consider antiplane strain problem in which the displacement vector is parallel to x_1-axis which is taken to be horizontal and $\partial / \partial x_1 = 0$ and $u_1 = u_1(x_2, x_3)$ is the only non-zero component of the displacement vector. In the following, we write u for u_1 and $(x,\ y,\ z)$ for (x_1, x_2, x_3). The non-zero stresses can be written as

$$\tau_{12} = c\alpha^2 \frac{\partial u}{\partial y},\ \tau_{13} = c\frac{\partial u}{\partial z} \tag{8}$$

where

$$c_{66} = c\alpha^2,\ c = c_{55} \tag{9}$$

The constants α and c are positive real numbers and depend upon elastic constants.

In case of an isotropic elastic medium

$$c = \mu \text{ and } \alpha = 1 \tag{10}$$

The equilibrium equations (Equations (2)-(3)) are identically satisfied for the antiplane strain deformation, and Equation (1) reduces to

$$\frac{\partial^2 u}{\partial y^2} + \frac{1}{\alpha^2}\frac{\partial^2 u}{\partial z^2} = 0 \tag{11}$$

FORMULATION AND SOLUTION OF THE PROBLEM

Consider a homogeneous orthotropic elastic half-space occupying the region $z \ge 0$. Suppose that there is a vertical strike-slip fault of infinite length $(-\infty < x < \infty)$ and of finite width $(0 \le z \le d)$ situated on the z-axis which is taken as vertically downwards (Figure 1). Let b denote the slip on the fault which is non-uniform, in general. Following Maruyama (1966) and Garg et al. (1996), the displacement at any point of the orthotropic elastic half-space due to non-uniform slip on the fault is given by

$$u = \frac{-\alpha y}{2\pi}\int_0^d b(h)\left[\frac{1}{y^2 + \alpha^2(z-h)^2} + \frac{1}{y^2 + \alpha^2(z+h)^2}\right]\mathrm{d}h \tag{12}$$

The closed-form analytical expressions of the displacements for various non-uniform slip-profiles are obtained from Equation (12).

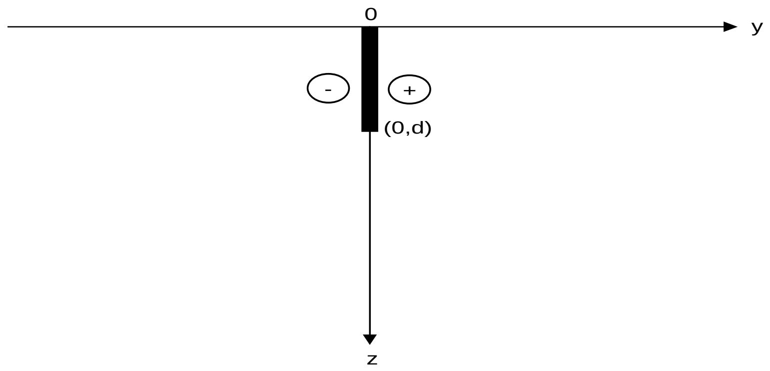

Fig. 1 $x = 0$ section of surface breaking, vertical long strike-slip fault in uniform half-space $z \geq 0$ (⊕ and Θ indicate the displacements in the positive *x*-direction and negative *x*-direction, respectively)

1. Uniform Slip

First we consider the case when the slip $b(h)$ is uniform slip. In this case, $b(h) = b_0$, and the displacement at any point (y, z) of an orthotropic half-space due to uniform slip on the fault becomes

$$U = \frac{-1}{2\pi}\left[\tan^{-1}\frac{\alpha(1-Z)}{Y} + \tan^{-1}\frac{\alpha(1+Z)}{Y}\right] \tag{13}$$

where

$$Y = \frac{y}{d}, \quad Z = \frac{z}{d} \tag{14}$$

are dimensionless distances and $U = u / b_0$ is dimensionless displacement in *x*-direction.

Using Equation (8), we get the following expressions for the stresses

$$\sigma_{12} = \frac{\alpha^3}{2\pi}\left[\frac{1-Z}{Y^2 + (1-Z)^2\alpha^2} + \frac{1+Z}{Y^2 + (1+Z)^2\alpha^2}\right] \tag{15}$$

$$\sigma_{13} = \frac{-\alpha}{2\pi}\left[\frac{Y}{Y^2 + (1+Z)\alpha^2} - \frac{Y}{Y^2 + (1-Z)\alpha^2}\right] \tag{16}$$

where

$$\sigma_{12} = \frac{\tau_{12} d}{b_0 c}, \quad \sigma_{13} = \frac{\tau_{13} d}{b_0 c} \tag{17}$$

are dimensionless stresses.

2. Parabolic Slip

Let the slip on the surface breaking fault vary according to

$$b(h) = b_0\left(1 - \frac{h^2}{d^2}\right), \qquad 0 \leq h \leq d \tag{18}$$

The closed-form expression for the displacement at any point of an orthotropic elastic half-space is obtained from Equations (12) and (18). We find

$$U=\frac{-1}{2\pi\alpha}\left[-2Y+YZ\log\left(\frac{Y^2+(1+Z)^2\alpha^2}{Y^2+(1-Z)^2\alpha^2}\right)+\right.$$
$$\left.\alpha\left\{1+\left(\frac{Y}{\alpha}\right)^2-Z^2\right\}\left\{\tan^{-1}\frac{(1-Z)\alpha}{Y}+\tan^{-1}\frac{(1+Z)\alpha}{Y}\right\}\right] \tag{19}$$

and the corresponding expressions for the stresses are

$$\sigma_{12}=\frac{-\alpha}{2\pi}\left[-2+Z\log\frac{Y^2+(1+Z)^2\alpha^2}{Y^2+(1-Z)^2\alpha^2}+2Y^2Z\left\{\frac{1}{Y^2+(1+Z)^2\alpha^2}-\frac{1}{Y^2+(1-Z)^2\alpha^2}\right\}\right.$$
$$+\frac{2Y}{\alpha}\left\{\tan^{-1}\frac{(1-Z)\alpha}{Y}+\tan^{-1}\frac{(1+Z)\alpha}{Y}\right\}-\alpha\left\{1+\left(\frac{Y}{\alpha}\right)^2-Z^2\right\}$$
$$\left.\times\left\{\frac{(1-Z)\alpha}{Y^2+(1-Z)^2\alpha^2}+\frac{(1+Z)\alpha}{Y^2+(1+Z)^2\alpha^2}\right\}\right] \tag{20}$$

$$\sigma_{13}=\frac{-1}{2\pi\alpha}\left[Y\log\frac{Y^2+(1+Z)^2\alpha^2}{Y^2+(1-Z)^2\alpha^2}+2YZ\left\{\frac{(1+Z)\alpha^2}{Y^2+(1+Z)^2\alpha^2}+\frac{(1-Z)\alpha^2}{Y^2+(1-Z)^2\alpha^2}\right\}\right.$$
$$-2\alpha Z\left\{\tan^{-1}\frac{(1-Z)\alpha}{Y}+\tan^{-1}\frac{(1+Z)\alpha}{Y}\right\}$$
$$\left.+\alpha^2Y\left\{1+\left(\frac{Y}{\alpha}\right)^2-Z^2\right\}\left\{\frac{1}{Y^2+(1+Z)^2\alpha^2}-\frac{1}{Y^2+(1-Z)^2\alpha^2}\right\}\right] \tag{21}$$

3. Linear Slip

Let the slip on the fault vary according to the law

$$b(h)=b_0\left(1-\frac{h}{d}\right),\qquad 0\le h\le d \tag{22}$$

The deformation at any point of an orthotropic elastic half-space is obtained as

$$U=\frac{-1}{2\pi\alpha}\left[\frac{-Y}{2}\log[(1-Z)^2\alpha^2+Y^2][(1+Z)^2\alpha^2+Y^2]\right.$$
$$\left.+Y\log(\alpha^2Z^2+Y^2)-2Z\alpha\tan^{-1}\frac{\alpha Z}{Y}+(1-Z)\alpha\tan^{-1}\frac{(1-Z)\alpha}{Y}+(1+Z)\alpha\tan^{-1}\frac{(1+Z)\alpha}{Y}\right] \tag{23}$$

$$\sigma_{12}=\frac{-\alpha}{2\pi}\left[2-\frac{1}{2}\log[(1-Z)^2\alpha^2+Y^2][(1+Z)^2\alpha^2+Y^2]-Y^2\left\{\frac{1}{Y^2+(1-Z)^2\alpha^2}\right.\right.$$
$$\left.\left.+\frac{1}{Y^2+(1+Z)^2\alpha^2}\right\}+\log(Y^2+\alpha^2Z^2)-\frac{(1-Z)^2\alpha^2}{Y^2+(1-Z)^2\alpha^2}-\frac{(1+Z)^2\alpha^2}{Y^2+(1+Z)^2\alpha^2}\right] \tag{24}$$

$$\sigma_{13}=\frac{-1}{2\pi\alpha}\left[\alpha\tan^{-1}\frac{(1+Z)\alpha}{Y}-2\alpha\tan^{-1}\frac{\alpha Z}{Y}-\alpha\tan^{-1}\frac{(1-Z)\alpha}{Y}\right] \tag{25}$$

4. Elliptic Slip

Let the slip on the surface breaking fault vary according to

$$b(h)=b_0\left(1-\frac{h^2}{d^2}\right)^{1/2},\qquad 0\le h\le d \tag{26}$$

The closed-form analytical expressions for the surface deformation due to elliptic slip are obtained as:

$$U = \frac{-1}{2\alpha}\left[-Y \pm (\alpha^2 + Y^2)^{1/2}\right] \tag{27}$$

$$\sigma_{12} = \frac{-\alpha}{2}\left[-1 \pm Y(\alpha^2 + Y^2)^{-1/2}\right] \tag{28}$$

The upper sign '+' is for $Y > 0$ and the lower sign '−' is for $Y < 0$.

5. Cubic Slip

For the cubic slip profile,

$$b(h) = b_0\left(1 - \frac{h^2}{d^2}\right)^{3/2}, \qquad 0 \le h \le d \tag{29}$$

The surface deformation is obtained as

$$U = \frac{-1}{2\alpha^2}\left[-Y\left(\frac{1}{2} + \alpha^2 + \frac{Y^2}{\alpha^2}\right) \pm \frac{1}{\alpha^2}(\alpha^2 + Y^2)^{3/2}\right] \tag{30}$$

$$\sigma_{12} = -\frac{1}{2}\left[-\frac{1}{2} - \alpha^2 - \frac{3Y^2}{\alpha^2} \pm \frac{3Y}{\alpha^2}(\alpha^2 + Y^2)^{1/2}\right] \tag{31}$$

The results for the corresponding problem for an isotropic medium can be obtained as a particular case from the above results on putting $\alpha = 1$, which coincide with the results obtained by Singh et al. (1994).

COMPARISON BETWEEN ANISOTROPIC AND ISOTROPIC RESULTS

In this section, we wish to examine the effect of the anisotropy on the deformation due to non-uniform slip along a vertical strike-slip fault of depth d. For this, we compare the results for an orthotropic elastic medium with isotropic elastic medium. For an orthotropic elastic medium, we assume $\alpha = 0.75$ and for an arbitrary isotropic medium, $\alpha = 1$.

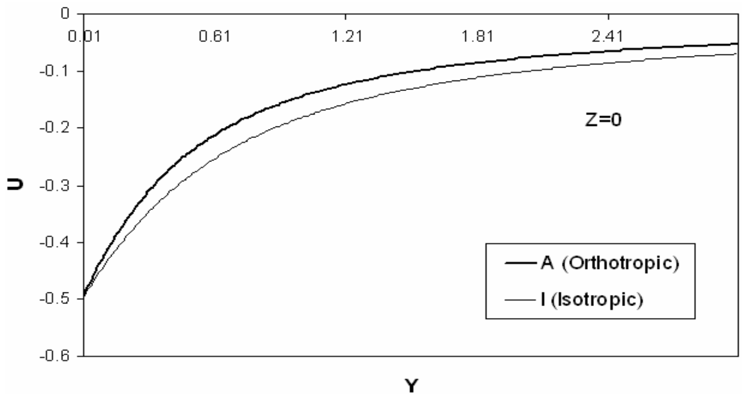

Fig. 2 Variation of dimensionless horizontal displacement $U = u/b_0$ for parabolic slip with the distance from the fault Y for orthotropic and isotropic elastic media on the surface $Z = 0$ (*A* denotes the curve for the orthotropic elastic medium and *I* for the isotropic elastic medium)

In Figures 2-5, the variation of horizontal dimensionless surface displacements U with the distance from the fault for different slip-profiles − parabolic, linear, elliptic and cubic have been shown. Figures 2-4 show that, for parabolic, linear and elliptic slips, the surface displacements in magnitude for isotropic medium is greater than that of orthotropic medium while Figure 5 shows that the surface displacements in magnitude, in case of cubic slip, for orthotropic medium is greater than that for the isotropic medium.

From these figures it is also found that, in case of parabolic, linear and elliptic slips, as we move away from the fault horizontally, the difference between the dimensionless horizontal surface displacements for an orthotropic medium and an isotropic medium decreases. In case of cubic slip, the difference between the displacements increases as we move away from the fault. The cubic slip profile provides the larger differences between the displacements for an orthotropic and an isotropic elastic medium.

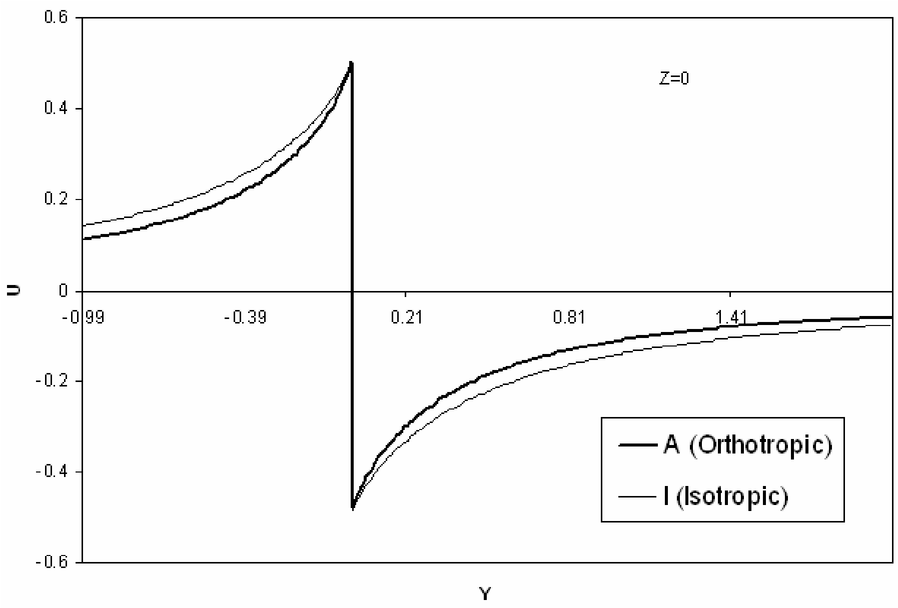

Fig. 3 Variation of U with Y for an orthotropic and isotropic elastic media on the surface $Z = 0$ for linear slip (notations as in Figure 2)

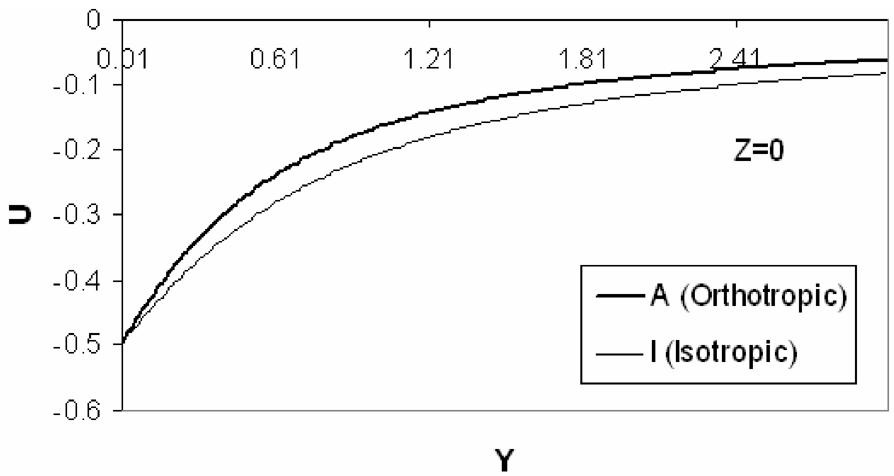

Fig. 4 Variation of U with Y for an orthotropic and isotropic elastic media on the surface $Z = 0$ for elliptic slip (notations as in Figure 2)

The variation of surface stress σ_{12} with the distance from the fault for different slip-profiles – parabolic and elliptic is shown in Figures 6-7. At the sub-surface level $z = d/2$ or $Z = 1/2$, the variation of the dimensionless stress σ_{12} and stress σ_{13} due to linear slip are shown in Figures 8-9. We note that the difference between deformations for the two types of elastic media increases with depth of the observation point. It is observed that deformation due to non-uniform slips – parabolic, linear, elliptic, and cubic for an orthotropic elastic medium differs significantly from the corresponding deformation for an isotropic elastic medium.

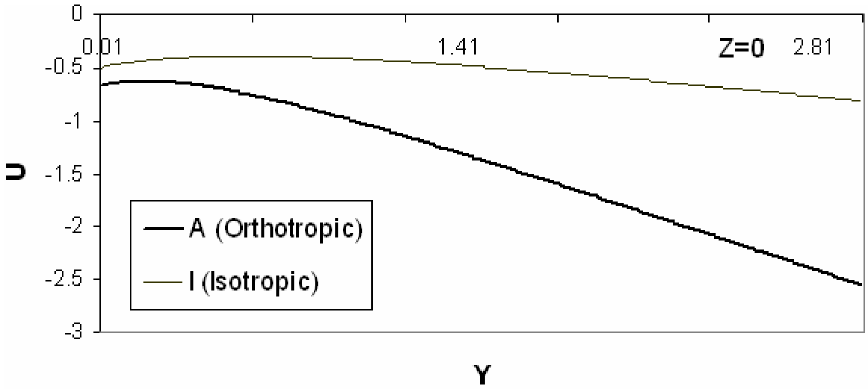

Fig. 5 Variation of U with Y for an orthotropic and isotropic elastic media on the surface $Z = 0$ for cubic slip (notations as in Figure 2)

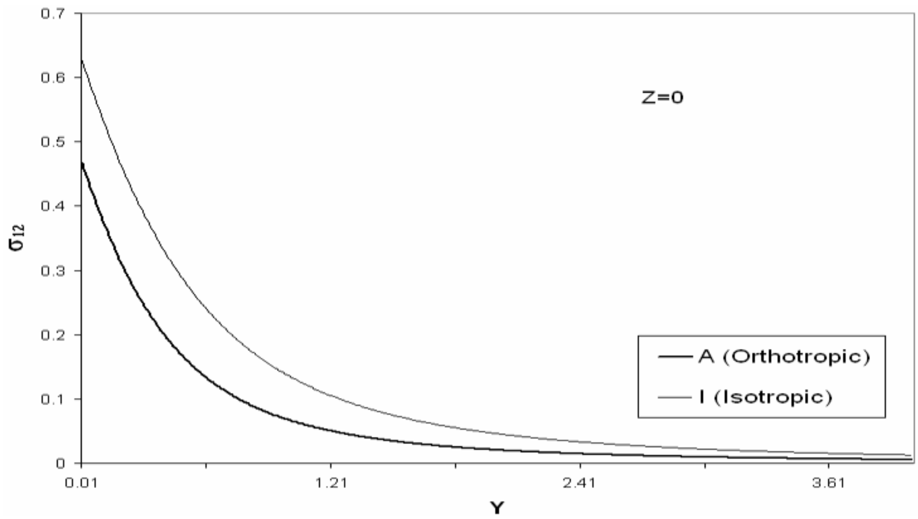

Fig. 6 Variation of dimensionless stress σ_{12} for parabolic slip with the distance Y for an orthotropic and isotropic elastic media at $Z = 0$ (notations as in Figure 2)

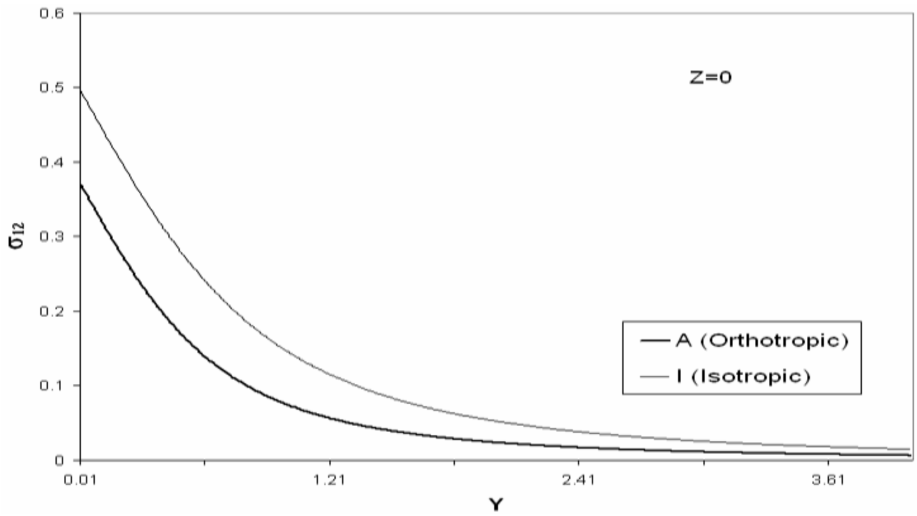

Fig. 7 Variation of σ_{12} with the distance Y for an orthotropic and isotropic elastic media at $Z = 0$ for elliptic slip (notations as in Figure 2)

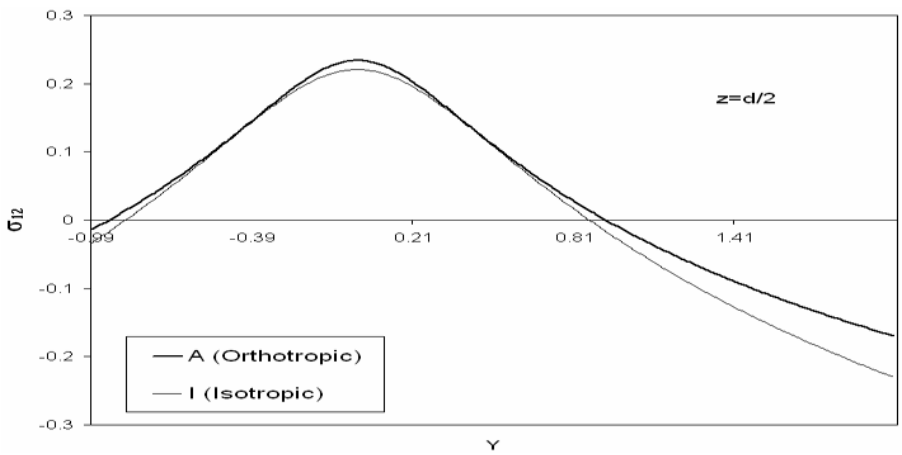

Fig. 8 Variation of σ_{12} for linear slip with the distance Y for an orthotropic and an isotropic elastic media at $z = d/2$ or $Z = 1/2$ (notations as in Figure 2)

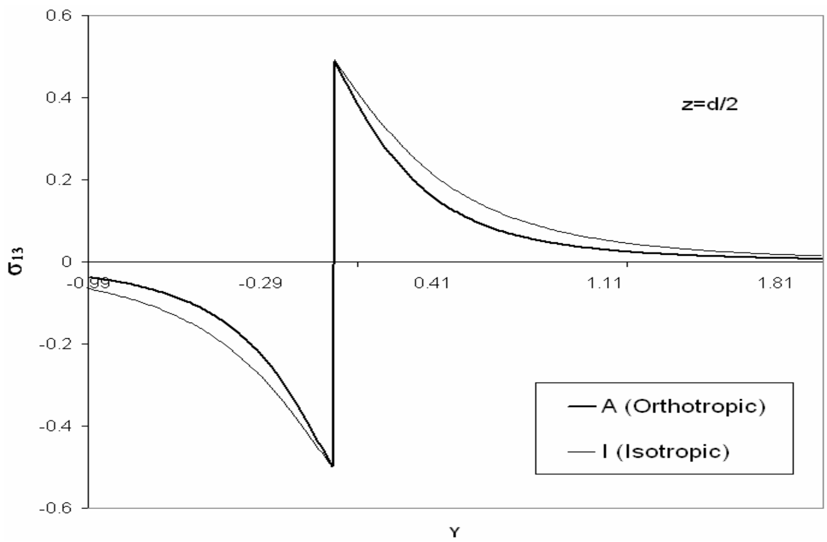

Fig. 9 Variation of σ_{13} for linear slip with the distance Y for an orthotropic and isotropic elastic media at $z = d/2$ (notations as in Figure 2)

DISCUSSION AND CONCLUSIONS

In the present paper we have obtained closed-form analytical expressions for static displacements and stresses at any point of a homogeneous orthotropic elastic half-space due to non-uniform slip-profiles − parabolic, linear, elliptic, and cubic along a very long vertical strike-slip fault. Numerically, it has been found that for parabolic, linear, and elliptic slips the surface displacements in magnitude for an isotropic medium are greater than that of an orthotropic medium while in case of cubic slip, the surface displacements in magnitude for an orthotropic medium are greater than that for an isotropic medium. It is also found that in case of parabolic, linear, and elliptic slip profiles as we move away from the fault horizontally, the difference between the surface displacements for an orthotropic medium and an isotropic medium decreases while in case of cubic slip the difference increases. The cubic slip distribution provides larger differences between the surface displacements for the orthotropic and isotropic medium.

For all slip profiles considered, the slip decreases from a value b_0 at the surface to zero at the depth d. If the surface slip b_0 and the fault depth d are assumed to be the same for all cases, then assuming the source potency as $\int_0^d b(h)\,\mathrm{d}h$ per unit length of the fault, is different for different profiles. This yields d_1

$=\frac{\pi}{4}d_2=\frac{2}{3}d_3=\frac{1}{2}d_4=\frac{3\pi}{16}d_5=d$ (say) where d_1 is the fault depth for the uniform slip model and d_2, d_3, d_4 and d_5 are, respectively, the fault depths for the elliptic, parabolic, linear, and cubic profiles.

To compare the deformation due to non-uniform slip profiles with the corresponding deformation due to uniform slip in the same elastic medium, the source potency should be same and it can be achieved by varying the fault depth d, keeping the surface-slip constant. In the present study we have compared the results of an orthotropic elastic medium with an isotropic elastic medium for different slip profiles with their respective source potencies.

The analytical solution obtained here is useful in modelling the lithospheric deformation associated with vertical strike-slip faulting in the earth. The results obtained in this paper are the generalization of the previous results for an isotropic medium (Singh et al., 1994) in the sense that the medium of the present work is orthotropic which is more realistic than isotropic. Although a 2-D model is simplification of the physical system, such models are useful in gaining insight into the relationship among various parameters. Moreover, there are faults, the most obvious being the San Andreas fault, which are sufficiently long and shallow that a 2-D approximation may be used. Static dislocation models are mainly applied to analyze the residual deformation of a medium caused by earthquake faults. Permanent surface deformations which occur as a result of faulting can be measured for geodetic surveys carried out before and after an earthquake.

The Palos Verdes fault is a long major strike-slip fault on the south-western edge of the Los Angles metropolitan area with its slip in the sediments (Olsen and Archuleta, 1996). It has been established that in a Palaeozoic type sedimentary rocks in Enola, Arkansas, USA, an earthquake source lies (Crampin, 1994). In the field, people have frequently encountered approximately equal spacing between the faults, i.e., uniform slip on the fault. While for normal faults and reverse faults it may have to do with the dominant wavelength of folding, the assumption of uniform slip makes the edges of the fault plane singular where the displacement is indeterminate and the stress is infinite. For this reason, uniform slip models cannot be used in the near field. The present paper may find applications in modelling crustal deformation due to non-uniform long vertical strike-slip faults.

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