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Propagation of love-type wave in a temperature dependent crustal Layer

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Abstract. The present study deals with the propagation of Love wave (a type of surface wave) in crustal layer having temperature dependent inhomogeneity. It is assumed that the inhomogeneity in the crustal layer arises due to linear temperature variation in rigidity and density. The upper boundary of the crustal layer is traction free. Numerical results for Love wave are discussed by plotting analytical curves between phase velocity against wave number and stress against depth in the presence of inhomogeneity and temperature parameters. The effects boundary condition on the Love wave propagation in the crustal layer is also analyzed. The results presented in this study would be useful for seismologists and geologists.

Keywords: love waves; temperature; elasticity; inhomogeneity

1. Introduction

The velocity of seismic waves depends on temperature, pressure, packing structure, mineral phase and composition of the media through which the seismic wave travel. These waves travel more quickly through high density medium (solid) than a liquid. Seismic waves are slowed down by anomalously hot areas. Molten areas slow down Love waves within the Earth. The mechanical properties of crustal rock change considerably with the change of temperature. This concept leads to some new ideas in mathematical modeling of thermoelastic behaviour of the Earth. The classical thermoelasticity fails to explain some important phenomena, large temperature variations, involved in the crustal layer. The formulations have been developed to explain realistic earth model in numerous studies by many authors, which involve the effect of crustal layer and surface topography. The Earth is inhomogeneous in nature constituting of very hard layers, therefore the boundary temperature plays a significant role in the propagation of seismic waves. These properties of crustal rock motivate us to present a model of propagation of Love-type surface wave in a crustal layer with temperature dependent inhomogeneity. The inhomogeneity of the crustal layer has been cosidered as $\mu = \mu_0\left(1+\varepsilon\Theta\right)$, $\rho = \rho_0\left(1+\varepsilon\Theta\right)$, where μ and ρ is the rigidity and mass density respectively, Θ is temperature, ε is constants having dimension that are inverse of temperature. It is assumed that the lower and upper boundary of crustal layer is kept at constant temperatures T_0 and T_1, respectively. The upper boundary of the crustal layer is assumed to be traction free. The rigidity and density varies linearly on temperature in the crustal layer. With this assumption, the layer tends to homogeneous behaviour at $T_0=T_1$.

The propagation of Love wave and thermal heating effects on solids has been discussed by many authors and researchers by considering various irregularities, inhomogeneities and boundaries of the Earth. Lokajíček *et al.* (2012) discussed the effect of temperature on phase velocities in granulate. Sun and Luo (2011) investigated propagation of waves in thermal dependent graded materials. Tillmann *et al.* (2008) studied temperature dependent properties of solid materials. Lee and Saravanos (1998) discussed the influence of temperature on piezoelectric materials. Emery and Fadale (1997) presented a note on the response of temperature and boundary conditions on materials. Deresiewicz (1962) introduced the concept of Love wave propagation in a crust which is homogeneous in nature overlying an inhomogeneous substratum. Manna *et al.* (2013) discussed Love wave propagation in hetrogeneous elastic half-space and piezoelectric layer. Du *et al.* (2008) discussed the influence of initial stress on piezoelectric layered structures loaded with viscous liquid under Love wave propagation. Kadian and Singh (2010) studied the influence of size of barrier on Love wave reflection. Gupta *et al.* (2013) purposed a mathematical model to study Love wave propagation in homogeneous and initially stressed hetrogeneous half-spaces. Kundu *et al.* (2013) discussed propagation of Love wave in porous rigid layer kept over prestressed half space. More recently, Chattaraj *et al.* (2013) discussed Love wave propagation in irregular prestressed anisotropic porous stratum. Madan *et al.* (2014) studied propagation of Love wave in saturated porous anisotropic layer. Presently, Abo-Dahad *et al.* (2016) discussed the rotational effects on Rayleigh, Love and Stonely waves propagating in

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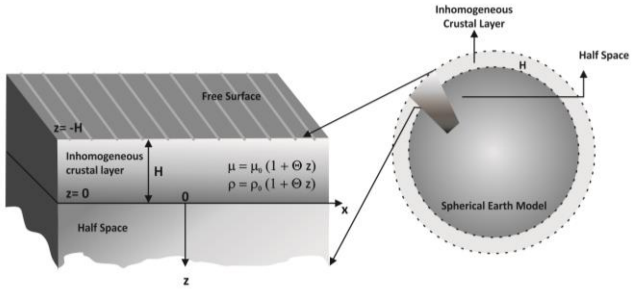

Fig. 1 Geometry of the problem

reinforced anisotropic general viscoelastic media of higher order.

2. Formulation of the problem

We consider an inhomogeneous crustal layer of finite thickness H. The z-axis is directed vertically downward and the x-axis is assumed to be in the direction of the propagation of the wave with velocity c. Let the lower and upper boundary of inhomogeneous crustal layer be kept at constant temperature T_1 and T_0. Let (x, y, z) represent the cartesian coordinate system such that the layer is located in the region $x \in R, 0 \le y \le H, z \in R$ where H>0 is constant thickness of the layer.

For Love waves, the displacement and body forces do not depend on y and if (u,v,w) denote the displacement components at any point $P(x,y,z)$ of the medium, then we have following displacement components in the y-axis only, assumed as

$$u = 0, \qquad w = 0, \qquad v = v(x,z,t) \tag{1}$$

The variations of rigidity and density in the layer are taken as

$$\mu = \mu_0(1+\varepsilon\Theta), \qquad \rho = \rho_0(1+\varepsilon\Theta) \tag{2}$$

where Θ is temperature, ε is inhomogeneous parameter of crustal layer and having dimension that are inverse of temperature, μ_0 and ρ_0 are constant values of rigidity (μ) and mass density (ρ)at the interface respectively. The variation of rigidity and mass density in the layer (Eq. (2)) on temperature agrees with the experimental results investigated by Schreiber *et al.* (1973).

3. Solution of the problem

Keeping in mind the above boundary conditions given during the formulation of the problem, the temperature distribution in the layer following geometry of the problem can be written as

$$\Theta(x,y) = \mathrm{A}_1 y + \mathrm{T}_0, \quad x \in R, \quad y \in \langle 0, H \rangle \tag{3}$$

where

$$\mathrm{A}_1 = \frac{\mathrm{T}_1 - \mathrm{T}_0}{H} \tag{4}$$

The anti-plane equation of motion is given by Love (1927)

$$\frac{\partial s_{xz}}{\partial x} + \frac{\partial s_{yz}}{\partial y} = \rho \frac{\partial^2 v}{\partial t^2} \tag{5}$$

and

$$s_{xy} = \mu\left(\frac{\partial v}{\partial x}\right), \quad s_{yz} = \mu\left(\frac{\partial v}{\partial z}\right) \tag{6}$$

where s_{xy} and s_{yz} are the incremental stress components and ρ is the density of the crustal layer.

Substituting Eq. (6), Eq. (2) and Eq. (3) into Eq. (5) yields

$$\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\mathrm{B}_1}{\mathrm{B}_0 + \mathrm{B}_1 y}\frac{\partial v}{\partial y} = \frac{\rho_0}{\mu_0}\frac{\partial^2 v}{\partial t^2} \tag{7}$$

where

$$\mathrm{B}_0 = 1 - \varepsilon \mathrm{T}_0, \quad \mathrm{B}_1 = -\varepsilon \mathrm{A}_1 \tag{8}$$

Denoting by

$$z = \mathrm{B}_0 + \mathrm{B}_1 y, \quad c_0^2 = \frac{\mu_0}{\rho_0} \tag{9}$$

Eq. (7) can be rewritten as

$$\frac{1}{\mathrm{B}_1^2}\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial z^2} + \frac{1}{z}\frac{\partial v}{\partial z} = \frac{1}{\mathrm{B}_1^2 c_0^2}\frac{\partial^2 v}{\partial t^2} \tag{10}$$

For propagation of Love wave as per geometry of the problem, we assume displacement given as

$$v = \zeta(z)\exp i(kx - \omega t) \tag{11}$$

where $i = \sqrt{-1}$, ω=kc, c is phase velocity and k is wave number and $\zeta(z)$ is the unknown amplitude of displacement.

Using Eq. (11) and Eq. (10), we get

$$\frac{d^2\zeta(z)}{dz^2} + \frac{1}{z}\frac{d\zeta(z)}{dz} + \left(\frac{\omega^2}{c_0^2} - k^2\right)\frac{1}{\mathrm{B}_1^2}\zeta(z) = 0 \tag{12}$$

The solution of Eq. (12) is

$$\zeta(z) = \mathrm{A}\ \mathrm{J}_0\left(\frac{iz}{\mathrm{B}_1}\sqrt{k^2 - \frac{\omega^2}{c_0^2}}\right) + \mathrm{B}\mathrm{Y}_0\left(\frac{iz}{\mathrm{B}_1}\sqrt{k^2 - \frac{\omega^2}{c_0^2}}\right) \tag{13}$$

where A and B are arbitrary constants, which are to be determined from adequate boundary conditions, $\mathrm{J}_0(\ )$ and $\mathrm{Y}_0(\ )$ are Bessel's functions.

We assume, the crystal layer is fixed to the rigid base and the upper boundary is free of loadings, this gives the following boundary conditions

$$v(x,0,\mathrm{t}) = 0,\ s_{yz}(x,H,\mathrm{t}) = 0,\ \ \mathrm{x}\in\mathrm{R},\ \ \mathrm{t}\in\mathrm{R} \quad (14)$$

Returning on the basis of Eq. (9) to the variable z_1 in $\zeta(z)$ given by Eq. (13) and using Eq. (11), Eq. (6), and Eq. (14), we get

$$\mathrm{A\,J}_0\left(\frac{i\mathrm{B}_0}{\mathrm{B}_1}\sqrt{k^2-\frac{\omega^2}{c_0^2}}\right)+\mathrm{BY}_0\left(\frac{i\mathrm{B}_0}{\mathrm{B}_1}\sqrt{k^2-\frac{\omega^2}{c_0^2}}\right)=0 \quad (15)$$

$$\mathrm{A\,J}_1\left(\frac{i(\mathrm{B}_0+\mathrm{B}_1H)}{\mathrm{B}_1}\sqrt{k^2-\frac{\omega^2}{c_0^2}}\right)+\mathrm{BY}_1\left(\frac{i(\mathrm{B}_0+\mathrm{B}_1H)}{\mathrm{B}_1}\sqrt{k^2-\frac{\omega^2}{c_0^2}}\right)=0 \quad (16)$$

Put $\frac{\mathrm{B}_0}{\mathrm{B}_1}=\beta^*H$ and $c=\frac{\omega}{k}$ in Eqs. (15) and (16), we have

$$\mathrm{A\,J}_0\left(i\beta^*kH\sqrt{1-\frac{c^2}{c_0^2}}\right)+\mathrm{BY}_0\left(i\beta^*kH\sqrt{1-\frac{c^2}{c_0^2}}\right)=0 \quad (17)$$

$$\mathrm{AJ}_1\left(i(1+\beta^*)kH\sqrt{1-\frac{c^2}{c_0^2}}\right)+\mathrm{BY}_1\left(i(1+\beta^*)kH\sqrt{1-\frac{c^2}{c_0^2}}\right)=0 \quad (18)$$

where J_v, Y_v, v=0; 1, are Bessel's functions of first and second kind.

Eliminating A and B from Eq. (17) and Eq. (18), we have

$$\begin{vmatrix} \mathrm{J}_0\left(i\beta^*kH\sqrt{1-\frac{c^2}{c_0^2}}\right) & \mathrm{Y}_0\left(i\beta^*kH\sqrt{1-\frac{c^2}{c_0^2}}\right) \\ \mathrm{J}_1\left(i(1+\beta^*)kH\sqrt{1-\frac{c^2}{c_0^2}}\right) & \mathrm{Y}_1\left(i(1+\beta^*)kH\sqrt{1-\frac{c^2}{c_0^2}}\right) \end{vmatrix}=0 \quad (19)$$

Solving Eq. (19), we have

$$\begin{aligned}&\mathrm{J}_0\left(i\beta^*kH\sqrt{1-\frac{c^2}{c_0^2}}\right)\mathrm{Y}_1\left(i(1+\beta^*)kH\sqrt{1-\frac{c^2}{c_0^2}}\right)+\\ &\mathrm{J}_1\left(i(1+\beta^*)kH\sqrt{1-\frac{c^2}{c_0^2}}\right)\mathrm{Y}_0\left(i\beta^*kH\sqrt{1-\frac{c^2}{c_0^2}}\right)=0\end{aligned} \quad (20)$$

Eq. (20) can be solved by using bisection method, for that we put $\psi=\sqrt{1-\frac{c^2}{c_0^2}}$ and $\chi=1-\psi$ we get

$$\begin{aligned}&\mathrm{J}_0\left(\beta^*ikH\sqrt{\chi}\right)\mathrm{Y}_1\left(i(1+\beta^*)kH\sqrt{\chi}\right)+\\ &\mathrm{J}_1\left((1+\beta^*)ikH\sqrt{\chi}\right)\mathrm{Y}_0\left(\beta^*ikH\sqrt{\chi}\right)=0\end{aligned} \quad (21)$$

The knowledge of phase velocity c (numerical analysis) allows us to calculate the displacement v, and stress components s_{xz} and s_{yz}, as a product of unknown constant B and well-defined coefficients. From Eqs. (17) and (18), it follows that

$$\mathrm{A}=-\mathrm{B}\frac{\mathrm{J}_0\left(i\beta^*kH\sqrt{1-\frac{c^2}{c_0^2}}\right)}{\mathrm{Y}_0\left(i\beta^*kH\sqrt{1-\frac{c^2}{c_0^2}}\right)} \quad (22)$$

and the displacement v given by Eqs. (11) and (13) can be written in the form

$$\frac{v(\breve{\mathrm{x}},\breve{\mathrm{y}},t)}{\mathrm{B}}=$$

$$\frac{-\mathrm{Y}_0\left(i\beta^*kH\sqrt{\chi}\right)\mathrm{J}_0\left(i(\breve{\mathrm{y}}+\beta^*)kH\sqrt{\chi}\right)+\mathrm{J}_0\left(i\beta^*kH\sqrt{\chi}\right)\mathrm{Y}_0\left(i(\breve{\mathrm{y}}+\beta^*)kH\sqrt{\chi}\right)}{\mathrm{J}_0\left(i\beta^*kH\sqrt{\chi}\right)\mathrm{Y}_0\left(i(1+\beta^*)kH\sqrt{\chi}\right)-\mathrm{Y}_0\left(i\beta^*kH\sqrt{\chi}\right)\mathrm{J}_0\left(i(1+\beta^*)kH\sqrt{\chi}\right)} \quad (23)$$

$$\exp i(k\,\breve{\mathrm{x}}-\omega t)$$

where

$$\beta^*=\frac{1}{H}\frac{\mathrm{B}_0}{\mathrm{B}_1},\ \ \breve{x}=\frac{x}{H},\ \ \breve{\mathrm{y}}=\frac{y}{H} \quad (24)$$

The stress components s_{xy} and s_{yz} can be obtained from Eqs. (6), (2), and (3).

4. Numerical analysis

To show the effects of inhomogeneity, stress and temperature on the Love wave propagation in crustal layer, we take following crustal parameters Gubbins (1990).

$$\mu_0=5.82\times10^{10}\,N/m^2,\ \rho_0=4500Kg/m^3.$$

Fig. 2 shows the distribution of dimensionless phase velocity $\frac{c^2}{c_0^2}$ against temperature T_1 for different value of dimensionless wave number kH=3,5,7,9 at T_0=273.15K having inhomogeneity factor ε=0.00075K^{-1}. It follows from this diagram, as T_1 (upper boundary temperature) $\rightarrow$ T_0 (lower boundary temperature), the ratio of phase velocity $\frac{c^2}{c_0^2}\rightarrow1$ which implies phase velocity c equals to the shear phase velocity c_0 for homogeneous space; it means that crustal layer is homogeneous in nature. Also, it is observed from this diagram, for the same difference of boundary temperatures, the dimensionless phase velocity $\frac{c^2}{c_0^2}$ increase remarkably along with increasing crustal layer thickness. Fig. 3 presents the variation of dimensionless phase velocity $\frac{c^2}{c_0^2}$ against dimensionless wave number kH for different value of upper boundary temperature T_1=273.15K, 373.15K, 473.15K, 573.15K, and T_0=273.15K. It is quite clear from Fig. 3, as dimensionless wave number *kH* approaches to 6 i.e., for significant thickness of layer; the phase velocity c tends to the shear phase velocity c_0. The phase velocity $\frac{c^2}{c_0^2}$ decreases with the decrease of dimensionless wave number *kH* at fixed ratio of boundary temperatures. Fig. 4 shows the variation of dimensionless phase velocity $\frac{c^2}{c_0^2}$ against dimensionless wave number *kH* for different value of inhomogeneous parameter ε=0.00009375K^{-1}, 0.0001875K^{-1}, 0.000375K^{-1} and 0.00075K^{-1} for T_1=473.15K and T_0=273.15K. It can be seen that for ε=0.00009375K^{-1} i.e., the smallest value of inhomogeneity factor, the ratio of phase velocity $\frac{c^2}{c_0^2} \to 1$ which implies phase velocity c equals to the shear phase velocity c_0 for homogeneous space; it means that crustal layer is homogeneous in nature. The distribution of amplitude of stress s_{yz} against function of dimensionless thickness of the layer $\breve{y}$ for different value of temperature T_1=273.15K, 373.15K, 473.15K, 573.15K at ε=0.000375K^{-1}, T_0=273.15K and kH=3 is shown in Fig. 5. In Fig. 6, the variation of amplitude of stress s_{yz} against dimensionless thickness of the layer $\breve{y}$ for different value of inhomogeneous parameter ε=0.00009375K^{-1}, 0.0001875K^{-1}, 0.000375K^{-1}, 0.00075K^{-1} at T_1=473.15K, T_0=273.15K and kH=3 is demonstrated. From the both Figs. 5-6, it is clear

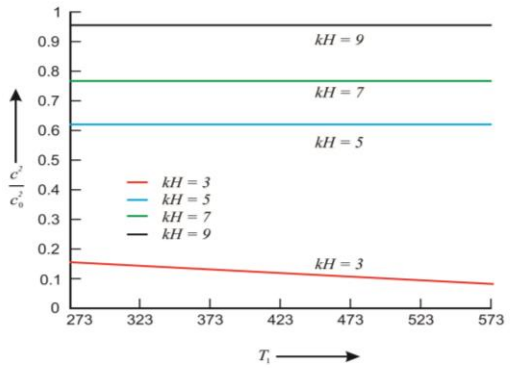

Fig. 2 Variation of dimensionless phase velocity $\frac{c^2}{c_0^2}$ against temperature T_1 for different value of dimensionless wave number *kH*

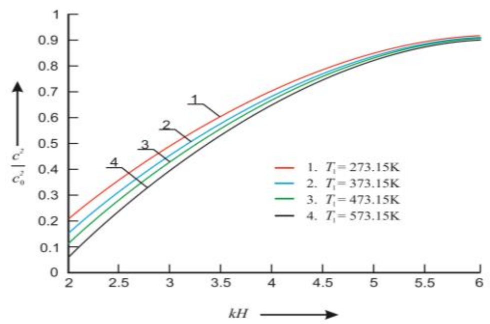

Fig. 3 Variation of dimensionless phase velocity $\frac{c^2}{c_0^2}$ against dimensionless wave number *kH* for different value of temperature T_1

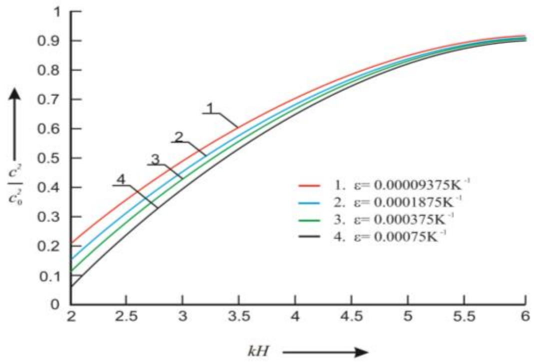

Fig. 4 Variation of dimensionless phase velocity $\frac{c^2}{c_0^2}$ against dimensionless wave number *kH* for different value of inhomogeneous parameter ε at T_1=473.15K and T_0=273.15K

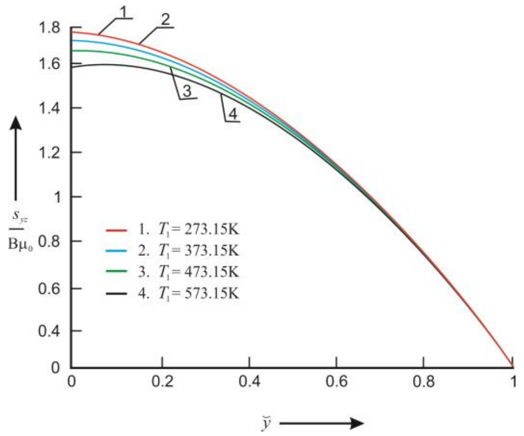

Fig. 5 Variation of amplitude of stress s_{yz} against dimensionless thickness of the layer $\breve{y}$ for different value of temperature T_1 at ε=0.000375K^{-1}, T_0=273.15K and kH=3

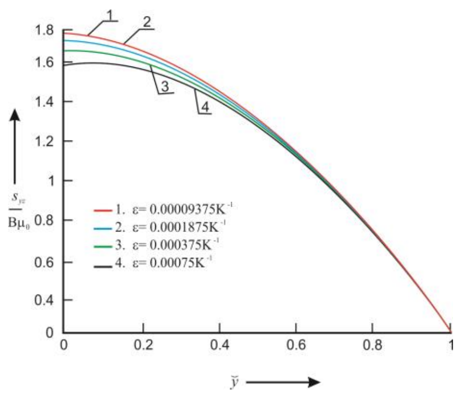

Fig. 6 Variation of amplitude of stress s_{yz} against dimensionless thickness of the layer $\breve{y}$ for different value of inhomogeneous parameter ε at T_1=473.15K^{-1}, T_0=273.15K and kH=3

the stress amplitude $\frac{s_{yz}}{\mathrm{B}\mu_0} \to 1$ for $\varepsilon \to 0$ or $\mathrm{T}_1 \to \mathrm{T}_0$ for homogeneous case. In both figures, the curves become linear for $\breve{y} > 6$.

5. Conclusions

In this model, we have taken crustal layer with linear variation of temperature in rigidity and mass density. Displacement of Love-type surface wave in this layer is derived by using simple mathematical techniques. From above numerical analysis, the following conclusions are made:

(1) The layer is assumed to be kept on constant temperatures T_0 and T_1 on the boundary ; and hence the thickness dependent properties of the layer are investigated

(2) For the same difference of boundary temperatures, the dimensionless phase velocity increases significantly along with increasing crustal layer thickness.

(3) The dimensionless phase velocity decreases with the decrease of dimensionless wave number *kH* at fixed ratio of boundary temperatures.

(4) It has been observed that for homogeneous crustal layer $\frac{c^2}{c_0^2} \to 1$ for ε=0.00009375K^{-1}.

(5) It is noted in case of homogeneous half-space, the stress amplitude $\frac{s_{yz}}{\mathrm{B}\mu_0} \to 1$ for $\mathrm{B} \to 0$ or $\mathrm{T}_1 \to \mathrm{T}_0$.

(6) In case A_1=0 and B_1=0, the Eq. (10) reduces to the equation for homogeneous layer.

(7) In the case of homogeneous crustal layer, the Love-type surface waves do not decay exponentially with thickness. This validates the solution discussed by Achenbach and Balogun (2010).

(8) It can be concluded from graphs that the inhomogeneity parameter, thickness of the layer and boundary temperatures have considerable effect on the phase velocity of Love wave.

Data and resources

No data were used in this paper. Some plots were made using the MATLAB software (Version 7.6.0.324 (R2008a), Trademark of Mathworks. Inc. U.S. Patent.

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