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Finite Difference Modeling of SH-Wave Propagation in Multilayered Porous Crust

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ABSTRACT

The present article deals with the propagation of SH-waves in a multilayered porous media with Weiskopf type anisotropy. Using Biot's theory of porous medium, the problem has been formulated. The finite difference method has been used here to model the wave propagation problem and also to analyze the effect of porosity and anisotropic factors on the phase and group velocities. Three-dimensional diagram has been developed to describe the displacement of the SH wave propagation as a function of two variables x and z. Also, the relation has been developed between the incremental displacement and the time, which is shown graphically. The convergence and stability criteria of the finite difference method has been established i) to minimize the exponential growing of the error; ii) to make the finite difference method stable; and iii) to decide the valid range of numerical values of the parameters.

INTRODUCTION

The near surface of the earth consists of layers of different types of material properties overlying a half space of various types of rocks, underground water, oil and gases. So, the studies of the propagation of seismic waves will be of great interest to seismologist. Such investigations will help them to obtain knowledge not only of geological structure, but also about the rock structure of the earth. The knowledge of seismic waves will help in investigating the exploration of oil, underground water and gas accumulation. In recent years, efforts have been made in using seismic methods to characterize hydrocarbons reservoirs, to monitor reservoir production and to enhance oil recovery processes.

Modeling of seismic wave propagation, reflection and refraction plays a very important role in exploration of petroleum, civil engineering, earthquake disaster prevention and signal processing. A model of the earth's interior and surface geological structures may be assumed to be consisting of liquid-filled porous layers at which density and elastic modulii change discontinuously. Biot (1956) has established the theory of the propagation of elastic waves in a porous elastic solid saturated by a viscous fluid. Based on this theory, the problems of wave propagation in porous media have been discussed by Deresiewicz (1961), Chakraborty and Dey (1982), Kalyani and Kar (1986), Kar and Kalyani (1989). Considerable experimental work (Laughton, 1954) has also been performed to investigate the seismic properties of marine sediments. The theory of Wood (1941) and Nafe and Drake (1957) are of much importance in practice for the sediments.

The geophysical industry has been actively involved in the development and use of finite-difference methods for seismic modeling since last forty years. These methods are very efficiently introduced by many researchers into exploration studies to simulate seismic wave propagation and to seismic data. Various techniques including finite differences (Alterman & Karal 1968, Mufti 1985, Kelly et. al. 1976), finite element (Chen, 1984), Fourier or pseudo spectrum methods (Kosloff & Baysal 1982) and hybrid methods (Shtivelman 1985, Gazdag 1981) have been developed by many authors to explore wave propagation problems. Unfortunately, the finite–element method is computationally expensive and requires large amounts of computer memory. Among the various techniques available for seismic modeling, the finite-difference method is particularly versatile in studying seismic wave behavior and in obtaining fast and accurate solution of the same equation. The finite-difference scheme, based on the first-order velocity-stress hyperbolic system of elastic wave equation, is computationally less expensive and stable for all values of Poisson's ratio with small numerical dispersion. Most schemes for solving the wave propagation problem involve some sort of approximation but the finite difference method provides accurate and detailed predictions of the displacement of the wave propagation throughout the medium. On the contrary, analytical solutions at all the points of the medium are not possible. Keiswetter et al. (1996) in his paper presented entire computer program (FDMODEL) based on finite-difference techniques to approximate the solution of the two-dimensional acoustic, heterogeneous wave equation. This program uses explicit approximations of second-order accuracy for both the spatial and temporal sampling intervals, and energy-absorbing boundary conditions.

In the present work, Biot's theory of porous media has been used to formulate the problem. Also, finite–difference method is applied to calculate group and phase velocities of SH-wave propagation in a multilayered porous medium for different values of anisotropy and porosity parameters of the medium. The stability criteria are established for the finite difference approximation in time and space for existence of pure SH-wave propagation. It also minimizes the exponential growth of the error with time to make the finite difference scheme stable and convergent.

FORMULATION OF THE PROBLEM

Let us consider a liquid-saturated anisotropic porous crust consisting of (n-1) parallel layers overlying a half-space, as shown in Fig.1. The layers are numbered serially, the layer at the top being layer no.1 and the half space being layer no. n. The origin of a right-handed cartesian coordinate system (x, y, z) is considered at the free surface with the z-axis drawn into the half-space and the y-axis pointing positively from the plane of the paper towards the reader.

The equations of motion in a liquid-filled porous medium Biot (1956), are given by

$$\left.\begin{aligned}&\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial \tau_{xy}}{\partial y}+\frac{\partial \tau_{xz}}{\partial z}=\frac{\partial^2}{\partial t^2}\left(\rho_{11}u_x+\rho_{12}U_x\right)\\&\frac{\partial T}{\partial x}=\frac{\partial^2}{\partial t^2}\left(\rho_{12}u_x+\rho_{22}U_x\right)\end{aligned}\right\}\quad \ldots.(1)$$

where τ_{xx}, τ_{xy}, … are the components of the stress tensor and T, the force exerted by the fluid on the fraction of an area of the unit cross section of the aggregate is related to the pressure p of the fluid by

$$-T = \beta p,$$

where β is the porosity of the layer. Here u_x, u_y and u_z are the components of the displacement vector u of the solid and U_x, U_y and U_z is that of liquid. The coefficients ρ_{11}, ρ_{12}, ρ_{22} are the mass coefficients related to the mass of the solid ρ(s) and that of the liquid ρ(f), each measured per unit volume of the aggregate, by means of

$$\rho(s) = \rho_{11} + \rho_{12}\,,\ \rho(f) = \rho_{12} + \rho_{22}$$

and, moreover, obey the inequalities

$$\rho_{11} > 0,\ \rho_{22} > 0,\ \rho_{12} < 0$$

$$\rho_{11}\,\rho_{22} - \rho_{12}^{2} > 0$$

Also,

$$\rho(s) = (1\text{-}\beta)\,\rho_s \text{ and } \rho(f) = \beta\rho_f\,,$$

where ρ_s and ρ_f are the mass densities of the solid and the liquid, respectively; the mass density of the aggregate is given by

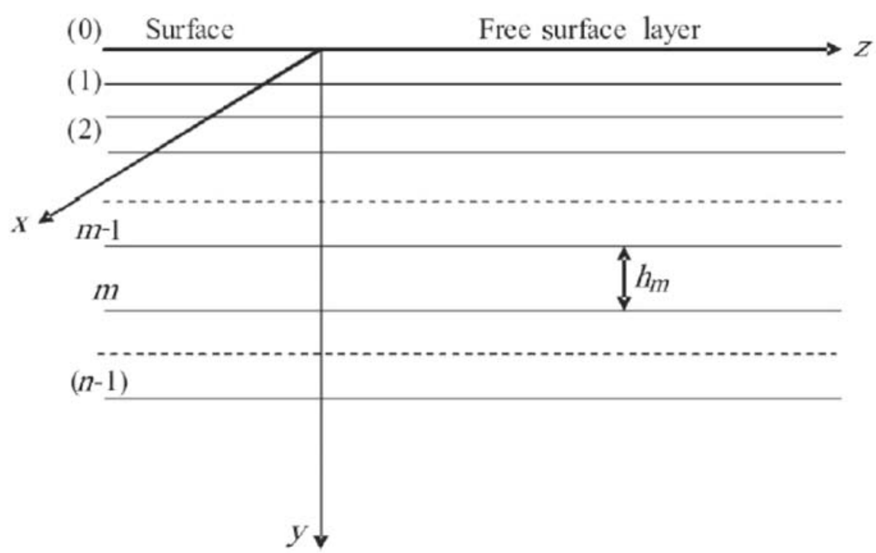

Figure 1. Geometry of the problem

$$\rho = \rho_{11} + 2\rho_{12} + \rho_{22}$$

The stress strain relations for the liquid filled porous medium are (Biot 1956, Weiskopf 1945) given by

$$\left.\begin{aligned} \tau_{xx} &= 2Ne_{xx} + Ae + Q\theta, \\ \tau_{yy} &= 2Ne_{yy} + Ae + Q\theta, \\ \tau_{zz} &= 2Ne_{zz} + Ae + Q\theta, \\ \tau_{xy} &= Ne_{xy} \\ \tau_{yz} &= Ge_{yz} \\ \tau_{zx} &= Ge_{zx} \end{aligned}\right\} \quad \ldots (2)$$

and

$$T = Q\,e + R\theta$$

where e = Div $\bar{u}$ and q = Div $\bar{U}$ and A, N correspond to the familiar Lame coefficients in the theory of elasticity and are positive. Moreover, the coefficient N represents the shear modulus of the material, the coefficient R is a measure of the pressure on the liquid while the total volume remains constant. Furthermore, the coefficient Q characterizes the coupling between the volume change of the solid and that of liquid.

For the propagation of SH-waves parallel to the x-axis and z-axis pointing downwards,

$$\begin{aligned} u_x &= 0 = u_z, & u_y &= v(x,z,t), \\ U_x &= 0 = U_z, & U_y &= V(x,z,t), \end{aligned} \quad \ldots (3)$$

Thus, the equation of motion in the mth layer is given by

$$N_m \frac{\partial^2 v_m}{\partial x^2} + G_m \frac{\partial^2 v_m}{\partial z^2} = d_m \frac{\partial^2 v_m}{\partial t^2} \quad \ldots (4)$$

in which

$$d_m = \rho_{11}^{(m)} - \frac{\rho_{12}^{2(m)}}{\rho_2^{(m)}}, \quad m = 1, 2, \ldots, n.$$

FINITE DIFFERENCE APPROACH

The finite difference is one of the most important methods to solve wave equation numerically. In finite difference scheme, the partial differential equation is replaced with a discrete approximation and then advancing the solution in time domain to get the accurate solution. The word "discrete", comes from the 15th Century Latin word *discretus,* is defined as a finite number of points in the domain. Increasing the number of mesh points in the domain, the accuracy of the numerical solutions can be increased. The mesh is the set of locations where the discrete solution is obtained and these points are also called nodes. The main idea of the finite–difference method is to replace partial derivatives with difference formulas that involve only the discrete values associated with positions on the mesh. Fig.1 represents a vertical section of a liquid-filled anisotropic porous crust consisting of (n-1) parallel layers overlying a half-space. For the development of a finite difference model, a finite rectangular portion of the medium is considered and it is discretized by introducing a grid on the xz plane with equal increments of Δx and Δz along the x and z-axes respectively. Also, Δt is the measure of discretization in time. By applying finite difference method, one can obtain an approximate solution for v (x, z, t) at a finite set of x, z and t. For the development of the method, time-space grid is taken as,

$x_m = m\Delta x$, m = 0,1,2, …,M

$z_n = n\Delta z$, n = 0,1,2, …, N

$t_l = l\Delta x$, l = 0,1, 2, …, L

Using the notation

$v^l_{m,n} = v(x_m, z_n, t_l)$

and applying Taylor series for the expansion of $v^l_{m+1,n}$ and $v^l_{m-1,n}$ respectively,

$$v^l_{m+1,n} = v^l_{m,n} + \Delta x \frac{\partial v}{\partial x} + \frac{\Delta x^2}{2}\frac{\partial^2 v}{\partial x^2} + \frac{(\Delta x)^3}{3!}\frac{\partial^3 v}{\partial x^3} + \ldots \quad ..(5)$$

and

$$v^l_{m-1,n} = v^l_{m,n} - \Delta x \frac{\partial v}{\partial x} + \frac{\Delta x^2}{2}\frac{\partial^2 v}{\partial x^2} - \frac{(\Delta x)^3}{3!}\frac{\partial^3 v}{\partial x^3} + \ldots \quad ..(6)$$

one obtains by subtracting (6) from (5):

$$v^l_{m+1,n} - v^l_{m-1,n} = 2\,\Delta x \frac{\partial v}{\partial x} + 2\frac{(\Delta x)^3}{3!}\frac{\partial^3 v}{\partial x^3} + \ldots \quad ..(7)$$

this gives

$$\frac{\partial v}{\partial x} = \frac{v^l_{m+1,n} - v^l_{m-1,n}}{2\Delta x} - \frac{(\Delta x)^2}{3!}\frac{\partial^3 v}{\partial x^3} + \ldots \quad ..(8)$$

This can also be expressed as

$$\frac{\partial v}{\partial x} = \frac{v^l_{m+1,n} - v^l_{m-1,n}}{2\Delta x} + O(\Delta x^2) \quad \ldots (9)$$

Assuming Δx small, central difference approximations of $\frac{\partial v}{\partial x}$ is formed as

$$\frac{\partial v}{\partial x} = \frac{v^{l}_{m+1,n} - v^{l}_{m-1,n}}{2\Delta x} \quad \ldots (10)$$

Instead of using the wave equation, which is a second order hyperbolic system, the elastodynamic equations are given by,

$$\left.\begin{aligned} d_m \frac{\partial^2 v_m}{\partial t^2} &= \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yz}}{\partial z} \\ \tau_{xy} &= N_m e_{xy} \\ \tau_{yz} &= G_m e_{yz} \end{aligned}\right\} \quad \ldots (11)$$

The above equations can be transformed into the following first-order hyperbolic system:

$$\left.\begin{aligned} \frac{\partial \dot{v}}{\partial t} &= \frac{1}{d_m}\left(\frac{\partial \alpha}{\partial x} + \frac{\partial \beta}{\partial z}\right) \\ \frac{\partial \alpha}{\partial t} &= N_m \frac{\partial \dot{v}}{\partial x} \\ \frac{\partial \beta}{\partial t} &= G_m \frac{\partial \dot{v}}{\partial z} \end{aligned}\right\} \quad \ldots (12)$$

The central finite-difference scheme developed in (10) is used to discretize the derivatives of these governing equations. Thus, the explicit numerical scheme, equivalent to the system (12), is given by

$$\left.\begin{aligned} \frac{\dot{v}^{l+1}_{m,n} - \dot{v}^{l-1}_{m,n}}{2\Delta t} &= \frac{1}{d_m}\left(\frac{\alpha^{l}_{m+1,n} - \alpha^{l}_{m-1,n}}{2\Delta x} + \frac{\beta^{l}_{m,n+1} - \beta^{l}_{m,n-1}}{2\Delta z}\right) \\ \frac{\alpha^{l+1}_{m,n} - \alpha^{l-1}_{m,n}}{2\Delta t} &= N_m\left(\frac{\dot{v}^{l}_{m+1,n} - \dot{v}^{l}_{m-1,n}}{2\Delta x}\right) \\ \frac{\beta^{l+1}_{m,n} - \beta^{l-1}_{m,n}}{2\Delta t} &= G_m\left(\frac{\dot{v}^{l}_{m,n+1} - \dot{v}^{l}_{m,n-1}}{2\Delta z}\right) \end{aligned}\right\} \quad \ldots (13)$$

where l is the index for time discretization, m for x-axis discretization, and n for z-axis discretization. Δt is the grid step in time, Δx and Δz are the grid steps for the x-axis and for the z-axis, respectively.

Initial and Boundary Conditions

Under the initial conditions both stress and velocity are zero everywhere in the medium at time t = 0 to make the medium in equilibrium (Virieux 1986). Boundary conditions considered here are the Neumann condition (stress-free conditions) and the Dirichlet condition (zero velocity or zero displacement conditions).

Stability Analysis

When the finite difference approximation is used to solve the equation of motion of seismic wave propagation in the time domain, the stability criteria must be satisfied and the finite difference scheme applied must be convergent and stable. By stability, one means that errors made at one stage of calculations do not cause increasingly large errors as the computations progress, but rather error dies out. Also by convergent one means that the results of the method approach the analytical results as Δt and Δx approach zero. Many authors (Cao & Greenhalgh 1998, Mitchell 1969) have developed stability for different finite difference approximations The stability condition obtained for the finite difference scheme (13), using the initial error in α, β and $\dot{v}$ at t = 0, is found to be

$$Sin(\omega \Delta t) = \left(C_1 \delta_1 Sin^2(k\Delta x) + C_2 \delta_2 Sin^2(t\Delta z)\right)^{1/2} \quad ..(14)$$

where,

$$C_1 = \frac{N_m}{d_m}, C_2 = \frac{G_m}{d_m}, \ \delta_1 = \left(\frac{\Delta t}{\Delta x}\right)^2, \ \delta_2 = \left(\frac{\Delta t}{\Delta z}\right)^2.$$

For the finite difference scheme (13) to be stable $|Sin(\omega \Delta t)|$ should be always less than or equal to 1. Consequently, ω will be real, and the error will not grow with time. Thus, the condition for stability is to make the time-mesh interval Δt smaller than or equal to $\frac{\Delta x}{\sqrt{C_1 + C_2}}$, where $\sqrt{C_1 + C_2}$ is the local wave velocity for $\Delta x = \Delta z$.

The stability condition (14) also gives the relation between frequency and wave number k to be satisfied by the solution. The phase and group velocities determined by (14) approach the correct local values if Δt, Δx and Δz are small. Also, for small Δt, Δx and Δz one can approximate $Sin\theta$ by θ and obtain, from (14),

$$\frac{\omega}{k} = \sqrt{C_1 + C_2} \quad \ldots (15)$$

It is important to know that how small Δx and Δz should be so that the above relation is approximately correct. The limit depends on the wavelength $\lambda = 2\pi/k$. Rewriting (14), the phase velocity is given by

$$\frac{\omega}{k} = \frac{\Delta x}{2\pi \Delta t}\frac{\lambda}{\Delta x} Sin^{-1}\left[\left\{(C_1 + C_2)\left(\frac{\Delta t}{\Delta y}\right)^2 Sin^2\left(\frac{2\pi \Delta y}{\lambda}\right)\right\}^{1/2}\right] \quad ..(16)$$

in which, k = r and $\Delta x = \Delta z$. The corresponding group velocity, the rate at which energy is transported, is given by

$$\frac{\partial \omega}{\partial k} = \frac{(C_1 + C_2)\dfrac{\Delta t}{\Delta x} Sin\left(\dfrac{4\pi\Delta x}{\lambda}\right)}{\left[1 - \left\{(C_1 + C_2)\left(\dfrac{\Delta t}{\Delta x}\right)^2 Sin^2\left(\dfrac{2\pi\Delta x}{\lambda}\right)\right\}^2\right]^{1/2}} \quad \ldots (17)$$

NUMERICAL RESULTS AND DISCUSSIONS

The numerical values of the phase velocities and group velocities have been computed from equations (16) and (17) respectively in non-dimensional form ω/k and δw/δk for different values of dispersion parameter Δx/λ for SH wave propagation in a layer overlying a half-space. Fig. 2 depicts the effect of variations of anisotropic parameter N/G on the phase velocity in

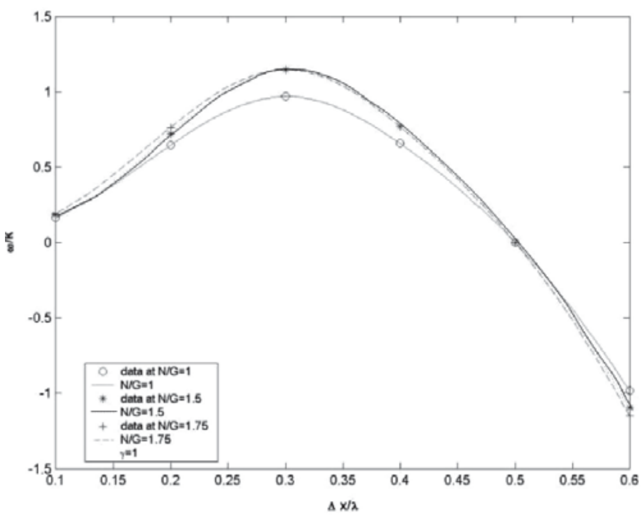

Figure 2. Variations of Phase Velocity with Dispersion Parameter when γ=1 and N/G=1, 1.5, 1.75 in Layer.

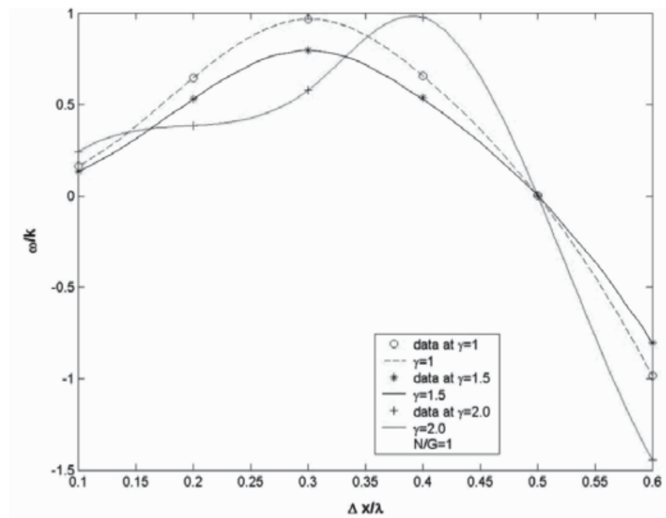

Figure 3. Variations of Phase Velocity with Dispersion Parameter when N/G=1 and γ=1 , 1.5, 2.0 in Layer.

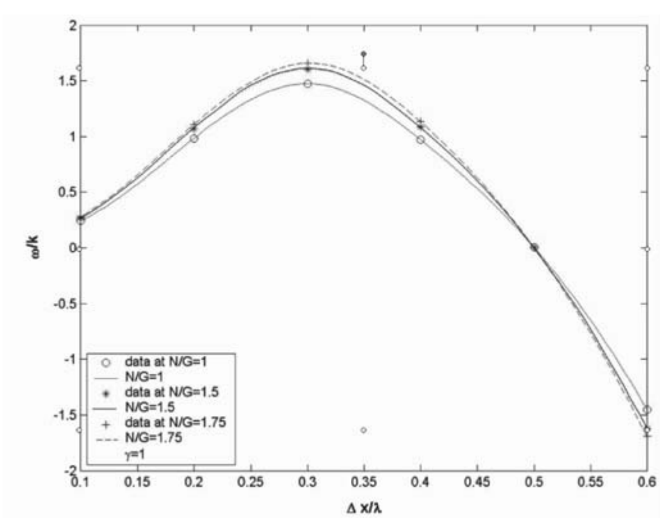

Figure 4. Variations of Phase Velocity with Dispersion Parameter when γ=1 and N/G=1 , 1.5, 1.75 in half-space.

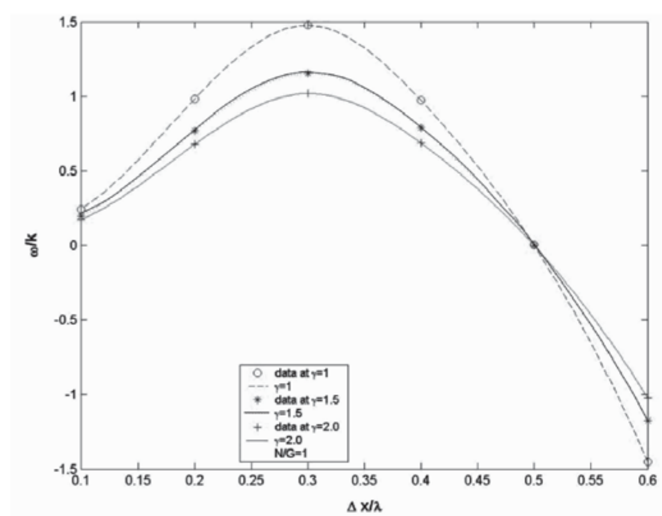

Figure 5. Variations of Phase Velocity with Dispersion Parameter when N/G=1 and γ=1, 1.5, 2.0 in half-space.

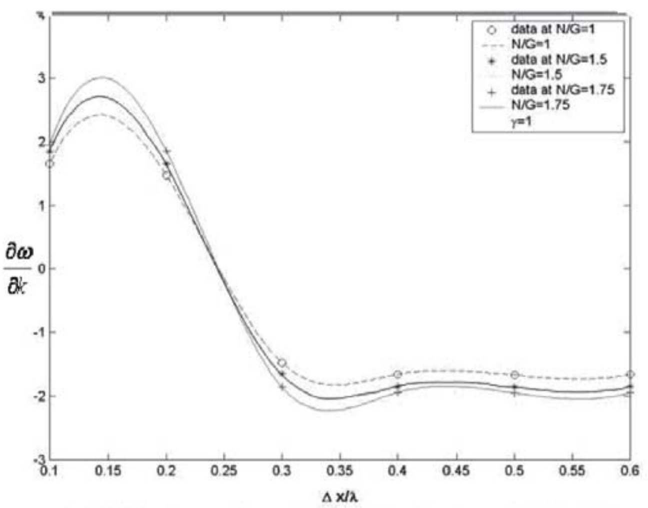

Figure 6. Variations of Group Velocity with Dispersion Parameter when γ=1 and N/G=1, 1.5, 1.75 in Layer.

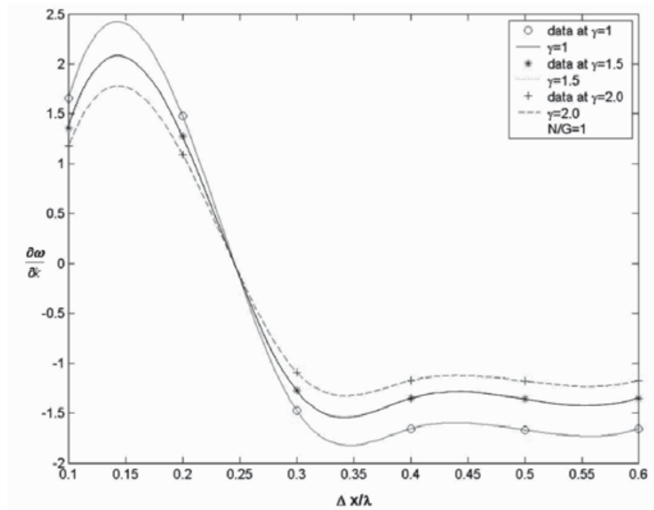

Figure 7. Variations of Group Velocity with Dispersion Parameter when N/G=1 and γ=1, 1.5, 2.0 in Layer.

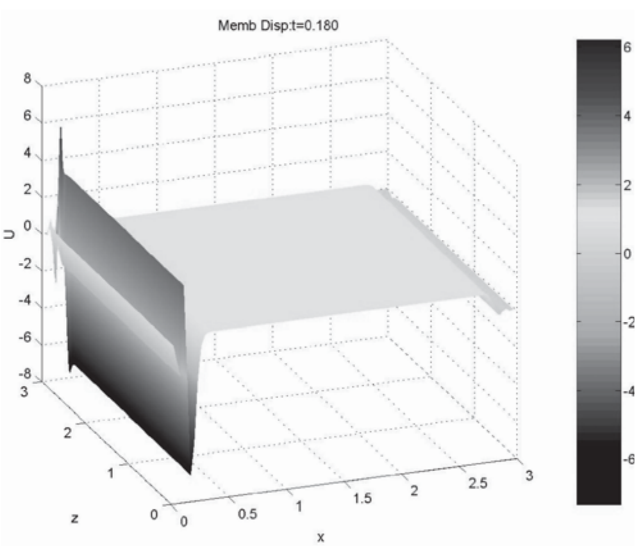

Figure 8. Showing displacement as a function of x and z

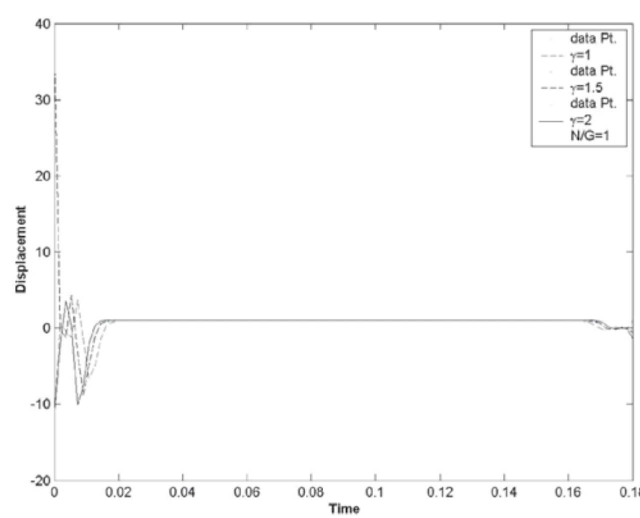

Figure 9. Showing displacement as a function of time

the layer with the increase in dispersion parameter Δx/λ, which indicates that the phase velocity increases with the increase in dispersion parameter and attains a maximum when the value of dispersion parameter Dx/l is nearer to 0.3 and thereafter decreases with the increase in the dispersion parameter for all values of N/G. From Fig. 3, it is observed that, the phase velocity in the layer first increases and attains its maximum for all values of porosity parameter γ (Kalyani et. al., 1986). On the other hand, the phase velocity also decreases with the increase in dispersion parameter for all values of porosity parameter γ. In Fig 4 the variations of phase velocity with dispersion parameter in the half space indicate that the phase velocity increases with the increase in dispersion parameter, and attains maximum and then decreases for all values of N/G. From fig. 5, it is observed that the phase velocity in the half space first increases attains maximum and then decreases with the increases in dispersion parameter for all values of porosity parameter. In the Figs.2-5, it is interesting to note that all the curves in the figures are intersecting at some point when the dispersion parameter is nearer to 0.5.

Figs. 6-7 show the variations of group velocity as a function of dispersion parameter for different values of anisotropic factor and porosity parameter. From these figures, it can be concluded that the group velocity in the layer depend not only on dispersion parameter but also on anisotropic factor N/G and porosity parameter γ. Fig. 8 is developed using the software MATLAB showing the three dimensional view of the displacement of the SH wave propagation as a function of two variables x and z. Fig.9 depicts the displacement as a function of time, which indicates that the curve is oscillating when the time is in between 0 and 0.02 for all values of porosity parameter.

CONCLUSIONS

The finite difference scheme is a straightforward and practical way of solving a number of pertinent seismological problems. The essence of this technique is to replace the differential equations and boundary conditions by simple finite difference approximations in such a way that an explicit, recursive set of equations is formed. The finite difference method offers a most direct path from the problem formulated in terms of basic equations, initial and boundary conditions to the digital computers, for solution with a minimum of analytical effort. The above findings can be used in the interpretation and simulation of geophysical data. Moreover, the same can be implemented in forecasting formation details.

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Dr. Amalendu Sinha (born on July 5, 1955) obtained M.Sc. in Applied Geology with First Class in 1976 and M.Sc.(Tech) First Class, in Mineral Exploration in 1977 and did his Ph.D. in Applied Geology in 1988 from Indian School of Mines, Dhanbad, a pioneer Institution in the field of Mining Sciences in India and abroad. Dr. Sinha joined CMRI in 1977 as Scientist 'B' and gradually elevated to the position of Scientist 'G' by virtue of his keenness, devotion and dedication to R&D in the areas of Geo-mechanics and Mining Technology.

His areas of research cover Development & Application of Geo-Mechanical Classification System for Support Design in Coal Mine Roadways; Evaluation of In-situ Stress Field for Stability Analysis; In-situ Stress Measurement in Underground Coal Mines and its Applications to Stability Analysis and Assessment of Ground Behaviour and Stability for Planning and Design of Non-coal Mines. He has coordinated and guided a number of R&D Projects, industry sponsored projects, grants-in-aid projects in the field of mining technology, geo-environment, coal-bed methane, blasting and explosive. In addition to these, he also completed successfully a good number of consultancy projects sponsored by the Industry.

Dr. Sinha has large number of research papers published in the journals of repute in India and abroad and presented in different National & International Conferences. He also edited a few proceedings and has some patents to his credit. Dr. Sinha has carved out a niche in the field of his areas of research and is well known scientist in the field of mining sciences in general and geo-mechanics in particular. Dr. Sinha is a member of Academic Council of Indian School of Mines, Dhanbad He also represents CMRI as a member in a number of committees constituted by different Government Organizations and Academic Institutions and Industries in the country. He has been elected as a Council Member of the prestigious institution 'The Mining, Geological & Metallurgical Institute of India' for the terms 2007-08, 2008-09 & 2009-10. Dr. Sinha became Acting Director on and from 29.7.2005 of erstwhile CMRI and after consolidation of both erstwhile CMRI and CFRI in their consolidated new entity as Central Institute of Mining and Fuel Research (CIMFR), he has taken over as Acting Director with effect from 04.5.2007. Dr. Sinha is member of the pioneer professional bodies like Mining Geological & Metallurgical Institute of India (MGMI), Indian Geo-technical Society (IGS), International Society of Rock Mechanics & Tunneling Technology, (ISRMTT) etc. He is a fellow of the Institution of Engineers (India) & Indian Geophysical Union. Dr .Sinha visited on deputation/assignment to various countries like USA, Germany, Czech Republic Iran and Canada. In November 12-13, 2007, he attended a Workshop on International Exchange of Experience in Underground Coal Gassification Technologies in Almaty, Kazakhstan organized by Department of Economic and Social Affairs, Division of Sustainable Development, United Nations, New York.