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Study of Normal Static Stresses under an Excitation in Poroelastic Flat Slabs

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Abstract

Biot's theory of Poroelasticity is employed to investigate normal static stresses under an excitation in an infinite Poroelastic slabs of arbitrary thickness. The radial normal static stress is obtained, and in the neighborhood of the center, the same is investigated. It is seen that poroelastic parameters have greater influence over radial normal static stress. Numerical data is presented graphically and then discussed.

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Keywords: Biot's theory, Normal static stresses Poroelasticity Flat Slabs

Introduction:

When the body forces act on a solid, the state of solid which is at rest gives static stress and strains. When the large static stress acts on a solid, one can neglect the effect of body forces (Mott, 1971). The static stress caused by large externally impressed surface forces is assumed to give effects much larger than the effect of gravity. The examples of externally impressed forces are ferroelectric, piezoelectric materials which have large static stress produced in them by some external agency, such as a battery or a coil (Mott, 1971). Elastic motion of an isotropic medium in the presence of body forces and static stresses is investigated (Mott, 1971). In the said paper, Mott derived the equations of motion in an elastic medium in the presence of body forces and static stresses. Further, elastic waveguide propagation in an infinite isotropic solid cylinder that is subjected to a static axial stress and strain is given in the paper (Mott, 1973). In the said paper, the effect of static axial stress and strain upon the velocity of the lowest-order flexural mode in solid circular cylinders is discussed and it has been proved that flexural waves in cylinders and transverse waves in stretched strings are of the same nature. on the other hand, flat slabs are most commonly used in structures such as railway stations, bus stations, exhibition halls, and large structures, like, high towers, telecom masts, etc. Such structures when exposed to natural turbulent wind are susceptible to wind induced excitation phenomena. In an earlier study (Davids & Kumar 1957),

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wave propagation in elastic flat slabs under excitation is carried out and even compared with experimental data. As these structures are poroelastic in nature,hence they are to be investigated using the theory of poroelasticity. The theory of poroelastic media originates from the requirements of particular problems of Geophysics such as the problems of seismic waves. Waves of axial symmetry in poroelastic cylindrical structures are studied in cylindrical co-ordinate system wherein boundaries go with radial coordinate (Malla Reddy & Tajuddin 2000, Tajuddin & S.A. Shah 2007, Tajuddin & S.A. Shah 2006, and Tajuddin & Narayan Reddy 2005) in the frame work (Biot 1956). Wave propagation in poroelastic flat slabs wherein boundaries go with the azimuthally coordinate is studied in the paper (Malla Reddy & Tajuddin 2006). In the said analysis, the frequency equation is investigated for a pervious boundary and an impervious boundary and realized the fact that the nature of boundary and mass coupling parameter influence wave propagation. Flexural vibrations of poroelastic solids in the presence of static stresses are studied (Rajitha, et.al). In the said analysis the three dimensional vibrations in a poroelastic solid that is subjected to static stresses are investigated. The effects of normal stress under an excitation in poroelastic flat slabs are studied (Sandhya Rani, et.al). In the present paper authors investigated the effect of normal static stresses under an excitation in poroelastic flat slabs in the framework of Biot theory (1956).

The rest of the paper is organized as follows. First, the problem is formulated and the boundary conditions are prescribed in section 2. Then in section 3, waves under line source excitation is investigated. The non-dimensionalisation as well as numerical results are discussed in section 4. Finally, concluding remarks are given in section5.

Nomenclature

(r,θ,z)	Cylindrical polar coordinates
u	Solid displacement
U	Liquid displacement
e	Dilation of solid
$\in$	Dilation of liquid
∇^2	Laplace operator in cylindrical polar coordinate
b	Dissipation
σ_{ij}	Stresses
s	Liquid pressure
A, N, Q, R	Poroelastic constant

2. The Boundary Value Problem

Consider an infinite poroelastic slab of thickness '*2a*' excited along a line coinciding with the z-axis in cylindrical polar coordinate system (r,θ,z). Let the slab be homogeneous and isotropic. The equations of motion of a poroelastic solid (Biot 1956) in presence of dissipation (*b*) which in terms of displacement vectors are:

$$N\nabla^2\vec{u} + \nabla[(A+N)e + Q\in] = \frac{\partial^2}{\partial t^2}\left(\rho_{11}\vec{u} + \rho_{12}\vec{U}\right) + b\frac{\partial}{\partial t}\left(\vec{u} - \vec{U}\right),$$

$$\nabla[Qe + R\in] = \frac{\partial^2}{\partial t^2}\left(\rho_{12}\vec{u} + \rho_{22}\vec{U}\right) - b\frac{\partial}{\partial t}\left(\vec{u} - \vec{U}\right). \tag{1}$$

In (1), *P (=A+2N), N, Q, R* are all poroelastic constants, ∇^2 is the Laplacian operator; and ρ_{ij} are mass coefficients, e and $\in$ are solid dilatation and fluid dilatation, respectively.

The equations of motion in terms of potential functions 'ϕ's and 'ψ' s are

$$P\nabla^2\phi_1 + Q\nabla^2\phi_2 = (\rho_{11}\ddot{\phi}_1 + \rho_{12}\ddot{\phi}_2) + b(\dot{\phi}_1 - \dot{\phi}_2)$$

$$
\begin{aligned}
&Q\nabla^2\phi_1 + R\nabla^2\phi_2 = (\rho_{12}\ddot{\phi}_1 + \rho_{22}\ddot{\phi}_2) - b(\dot{\phi}_1 - \dot{\phi}_2)\\
&N\nabla^2\psi_1 + Q\nabla^2\phi_2 = (\rho_{11}\ddot{\psi}_1 + \rho_{12}\ddot{\psi}_2) + b(\dot{\psi}_1 - \dot{\psi}_2)\\
&0 = (\rho_{12}\ddot{\psi}_1 + \rho_{22}\ddot{\psi}_2) - b(\dot{\psi}_1 - \dot{\psi}_2)
\end{aligned} \tag{2}
$$

A 'dot' over quantity stands for differentiation with respect to time t.
Consider the displacement decomposition

$$
u_r = \frac{\partial\phi_1}{\partial r} + \frac{\partial^2\psi_1}{\partial z\partial r}, \quad u_z = \frac{\partial\phi_1}{\partial z} - \frac{\partial^2\psi_1}{\partial r^2} - \frac{1}{r}\frac{\partial\psi_1}{\partial r}
$$

$$
U_r = \frac{\partial\phi_2}{\partial r} + \frac{\partial^2\psi_2}{\partial z\partial r}, \quad U_z = \frac{\partial\phi_2}{\partial z} - \frac{\partial^2\psi_2}{\partial r^2} - \frac{1}{r}\frac{\partial\psi_2}{\partial r} \tag{3}
$$

where u_r , u_z and U_r, U_z are components of displacements of solid and liquid phases in radial and azimuthally directions, respectively Then the solid and liquid dilatations are $e = \nabla^2\phi_1$ and $\varepsilon = \nabla^2\phi_2$ respectively. The solid displacement components $(u_{r,} 0, u_z)$ are functions of *r, z* and *t* (That is the problem here is plane strain that is independent of θ) which can readily be evaluated from the field equations (Biot 1956) representing steady state harmonic vibrations presented in the following matrix notation.

$$
\begin{bmatrix} \dfrac{u_r}{-J_1(\gamma r)} \\ \dfrac{u_z}{-J_0(\gamma r)} \end{bmatrix} = \begin{bmatrix} \gamma\cos(h_1 z) & \gamma\cos(h_2 z) & \gamma\cos(kz) \\ h_1\sin(h_1 z) & h_2\sin(h_2 z) & -\gamma^2\sin(kz) \end{bmatrix} \begin{bmatrix} A_1 \\ B_1 \\ C_1 \end{bmatrix} e^{ipt} \tag{4}
$$

where *p* is the frequency of wave, γ is the wave number, A_1, B_1, C_1 are all constants. $J_n(x)$ is Bessel function of first kind of order *n* and

$$
\alpha_i = h_i = (p^2 V_i^{-2} - \gamma^2)^{1/2},\ i = 1,2, \quad \alpha_3 = (p^2 V_3^{-2} - \gamma^2)^{1/2} \ . \tag{5}
$$

In equation (4), $V_i\ (i = 1,2,3)$ are dilatational wave velocities of first and second kind, and shear wave velocity, respectively. Using these displacements into stress-displacement relations (Biot 1956), the relevant static stresses σ'_{ij} (Mott 1971) and liquid pressure (*s*) are obtained as follows:

$$
\begin{aligned}
\sigma'_{zz} = &-(A_1 D_1\cos(h_1 z) + B_1 D_1\cos(h_2 z) + C_1(-2N\gamma^2 k\cos(kz))J_0(\gamma r)\,e^{ipt}\\
&-(2NA_1^{\,2}h_1^{\,2}\gamma^2\sin^2(h_1 z) + A_1B_1 4N\gamma^2 h_1 h_2\sin(h_1 z)\sin(h_2 z) + A_1C_1 N\gamma^2 h_1\sin(h_1 z)\sin(kz)(k^2 - 3\gamma^2) +\\
&B_1C_1 N\gamma^2 h_2\sin(kz)\sin(h_2 z)(k^2 - 3\gamma^2) + B_1^{\,2}2N\gamma^2 h_2^{\,2}\sin^2(h_2 z) +\\
&C_1^{\,2}N\gamma^2\sin^2(kz)(k^2 - \gamma^2))(J_1(\gamma r))^2 e^{2ipt}
\end{aligned} \tag{6}
$$

$$\sigma'_{zr} = (A_1 2Nh_1\gamma\sin(h_1 z) + B_1 2Nh_2\gamma\sin(h_2 z) + C_1\gamma\sin(kz)(k^2-\gamma^2))J_1(\gamma r)e^{ipt}$$
$$+(A_1^{\,2}h_1\gamma D_1\cos(h_1 z)\sin(h_1 z) + A_1B_1(\gamma h_1 D_2\sin(h_1 z)\cos(h_2 z) + \gamma h_2 D_1\cos(h_1 z)\sin(h_2 z)) +$$
$$A_1C_1(-2N\gamma^3 h_1 k\cos(kz)\sin(h_1 z) + \gamma k D_1) + B_1C_1(-2N\gamma^3 h_2 k\cos(kz)\sin(h_2 z) +$$
$$\gamma k D_2\cos(h_2 z)\sin(kz)) + B_1^{\,2}(\gamma h_2 D_2\cos(h_2 z)\sin(h_2 z)) +$$
$$C_1^{\,2}(-2N\gamma^3 k^2\cos(kz)\sin(kz)))J_0(\gamma r)J_1(\gamma r)e^{2ipt} \tag{7}$$

$$s = -(A_1 D_3\cos(h_1 z) + B_1 D_4\cos(h_2 z))J_0(\gamma r)e^{ipt}, \tag{8}$$

where

$$D_1 = 2Nh_1^{\,2} + (A+Q\delta_1)(r^2+h_1^{\,2})$$
$$D_2 = 2Nh_2^{\,2} + (A+Q\delta_2)(r^2+h_2^{\,2})$$
$$D_3 = (Q+R\delta_1)(r^2+h_1^{\,2})$$
$$D_4 = (Q+R\delta_2)(r^2+h_2^{\,2})$$

$$\delta_i = \sqrt{\frac{m_{11}V_i^{\,2}-P}{m_{22}V_i^{\,2}-R}}, \quad (i=1,2)$$
$$m_{11} = \rho_{11} - ibp^{-1}, \quad m_{12} = \rho_{12} + ibp^{-1}, \quad m_{22} = \rho_{22} - ibp^{-1} \tag{9}$$

The boundary condition that the front and back surfaces $z = a$ and $z = -a$ for a pervious surface and an impervious surface to be stress free are

$$\sigma'_{zz} + s = 0,\ \sigma'_{rz} = 0,\ s = 0 \qquad \text{(Pervious surface)}$$
$$\sigma'_{zz} + s = 0,\ \sigma'_{rz} = 0,\ \frac{\partial s}{\partial z} = 0 \qquad \text{(Impervious surface)} \tag{10}$$

Equations (6) and (10) together give a system of three homogeneous equations for the constants A_1, B_1, C_1 each for a pervious surface and an impervious surface. In order to obtain a nontrivial solution of this system, the coefficient matrix must be singular. This leads to a frequency equation for both pervious and impervious surfaces.

3. The Excitation

This section presents the conditions under which a wave represented by radial and azimuthally displacement components can be generated. Since the boundaries are static stress free, there can be no excitation from the faces of slab. The only remaining source for the wave which must be radially symmetric can be a line corresponding to the axis of cylindrical coordinate system. It is interesting to see how these free boundaries are affecting the static stress components σ'_{rz} and σ'_{rr} pertaining to radial coordinate.

3.1 Pervious surface

Because of the boundary conditions, arbitrary constants A_1, B_1, C_1 are no longer independent but are connected as follows:

From, the third boundary condition, we have $\dfrac{A_1}{B_1} = \dfrac{-D_4\cos(\alpha_2 a)}{D_3\cos(\alpha_1 a)}$ (11)

Substituting (11) in the first boundary condition, we obtain

$$\frac{C_1}{B_1}=[\frac{(-D_4\cos(\alpha_2 a))}{D_3}(D_1+D_3)J_0(\gamma r)+(D_2+D_4)\cos(\alpha_2 a)J_0(\gamma r)+ (D_5\sin(\alpha_1 a)+D_6\sin(\alpha_2 a)+D_7\sin(ka))]/(D_8\cos(ka)-D_9\sin(ka))$$

(12)

where

$$D_5=A_1 2N\gamma^2 h_1(2h_2\sin(h_2 z)-\frac{D_4\cos(h_2 z)}{D_3\cos(h_1 z)}h_1\sin(h_1 z))(J_1(\gamma r))^2 e^{ipt}$$

$$D_6=B_1 2N\gamma^2 h_2\sin(h_2 z)(J_1(\gamma r))^2 e^{ipt}$$

$$D_7=N\gamma^2(h_2\sin(h_2 z)(k^2-3\gamma^2)-\frac{D_4\cos(h_2 z)}{D_3\cos(h_1 z)}h_1\sin(h_1 z)(k^2-3\gamma^2))(J_1(\gamma r))^2 e^{ipt}$$

$$D_8=2N\gamma^2 kJ_0(\gamma r)$$

$$D_9=C_1 N\gamma^2(k^2-\gamma^2)\sin(kz)J_1(\gamma r)e^{ipt},$$

Substituting (12) and (13) in the expression for $\sigma'_{rr}+s$ we obtain

$$\sigma'_{rr}+s=-(B_1[\left(\frac{-D_4\cos(\alpha_2 a)}{D_3\cos(\alpha_1 a)}\right)D_{10}\cos(\alpha_1 a)+D_{11}\cos(\alpha_2 a))+\{\left(\frac{-D_4\cos(\alpha_2 a)}{D_3\cos(\alpha_1 a)}\right)(D_1+D_3)\cos(\alpha_1 a)+ (D_2+D_4)\cos(\alpha_2 a)+(D_5\sin(\alpha_1 a)+D_6\sin(\alpha_2 a)+D_7\sin(ka))\}/((D_8\cos(ka)-D_9\sin(ka))2N\gamma^2 k)])e^{ipt} \quad (13)$$

Similar expressions can be obtained for σ'_{rz} . The case of axial excitation can be dealt with the case $r\to 0$ in the expressions for $\sigma'_{rr}+s$ and σ'_{rz} . Their values in this case are

$\sigma'_{rz}=0$ and $\sigma'_{rr}+s=B_1 F_1 e^{ipt}$

where

$$F_1=[\left(\frac{-D_4\cos(\alpha_2 a)}{D_3\cos(\alpha_1 a)}\right)D_{10}\cos(\alpha_1 a)+D_{11}\cos(\alpha_2 a))+\{\left(\frac{-D_4\cos(\alpha_2 a)}{D_3\cos(\alpha_1 z)}\right)(D_1+D_3)\cos(\alpha_1 a)+ (D_2+D_4)\cos(\alpha_2 a)+(D_5\sin(\alpha_1 a)+D_6\sin(\alpha_2 a)+D_7\sin(ka))\}/((D_8\cos(ka)-D_9\sin(ka))2N\gamma^2 k)] \quad (14)$$

and

$$D_{10}=2N\gamma^2+(A+Q\delta_1)(r^2+h_1{}^2)$$

$$D_{11}=2N\gamma^2+(A+Q\delta_2)(r^2+h_2{}^2)$$

In the case of a radially symmetric disturbance, continuity of the medium demands that the radial displacements at the line of symmetry must be zero. From the equation (4) it is obvious since $u=0$ when $r=0$

3.2 Impervious surface

From the equation (4), we have $\frac{\partial s}{\partial z}=\left[A_1 D_3\alpha_1\sin(\alpha_1 z)+B_1 D_4\alpha_2\sin(\alpha_2 z)\right]J_0(kr)e^{ipt}$.

Invoking the third boundary condition, we obtain

$$\frac{A_1}{B_1}=\frac{-D_4\alpha_2\sin(\alpha_2 a)}{D_3\alpha_1\sin(\alpha_1 a)}. \tag{15}$$

Substitution of (15) in the first boundary condition yields

$$\frac{C_1}{B_1}=\frac{-D_4(D_1+D_3)\alpha_2\cos(\alpha_1 a)\sin(\alpha_2 a)}{2D_3N\beta k^2\sin(\alpha_1 a)\cos(\beta a)}+\frac{(D_2+D_4)\cos(\alpha_2 a)}{2N\beta k^2\cos(\beta a)}. \tag{16}$$

Substituting (15) and (16) in the expression for $\sigma'_{rr}+s$, we obtain

$$\sigma'_{rr}+s=-(B_1[\left(\frac{-D_4\alpha_2\sin(\alpha_2 a)}{D_3\alpha_1\sin(\alpha_1 a)}\right)D_{10}\cos(\alpha_1 a)+D_{11}\cos(\alpha_2 a))+$$
$$\{\left(\frac{-D_4\alpha_2\sin(\alpha_2 a)}{D_3\alpha_1\sin(\alpha_1 z)}\right)(D_1+D_3)\cos(\alpha_1 a)+(D_2+D_4)\cos(\alpha_2 a)+(D_5\sin(\alpha_1 a)+$$
$$D_6\sin(\alpha_2 a)+D_7\sin(ka))\}/((D_8\cos(ka)-D_9\sin(ka))2N\gamma^2 k)])e^{ipt} \tag{17}$$

Letting $r\to 0$ in the expressions for $\sigma'_{rr}+s$ and σ'_{rz}, we obtain

$$\sigma'_{rz}=0,\quad \sigma'_{rr}+s=B_1F_2e^{ipt}, \tag{18}$$

where

$$F_2=[\left(\frac{-D_4\alpha_2\sin(\alpha_2 a)}{D_3\alpha_1\sin(\alpha_1 a)}\right)D_{10}\cos(\alpha_1 a)+D_{11}\cos(\alpha_2 a))+\{\left(\frac{-D_4\alpha_2\sin(\alpha_2 a)}{D_3\alpha_1\sin(\alpha_1 z)}\right)(D_1+D_3)\cos(\alpha_1 a)+$$
$$(D_2+D_4)\cos(\alpha_2 a)+(D_5\sin(\alpha_1 a)+D_6\sin(\alpha_2 a)+D_7\sin(ka))\}/((D_8\cos(ka)-D_9\sin(ka))2N\gamma^2 k)] \tag{19}$$

4. Numerical Results and Discussion: Now we introduce non-dimensional parameters to compute the quantities F_1 and F_2 for a non-dissipation case (that is, when $b=0$), which are approximations for the $\sigma'_{rr}+s$ in the case of pervious surface and impervious surface, respectively, the non dimensional parameters are as fallows;

$$a_1=\frac{P}{H},a_2=\frac{Q}{H},a_3=\frac{R}{H},a_4=\frac{N}{H},$$
$$d_1=\frac{\rho_{11}}{\rho},d_2=\frac{\rho_{12}}{\rho},d_3=\frac{\rho_{22}}{\rho},$$
$$\tilde{x}=\left(\frac{V_0}{V_1}\right)^2,\tilde{y}=\left(\frac{V_0}{V_2}\right)^2,\tilde{z}=\left(\frac{V_0}{V_3}\right)^2,m=\frac{c}{c_0},\tau\equiv\frac{p}{c_0}=mk,\ m=\frac{\tau a}{ka}$$

where m is non-dimensional phase velocity, τ is non-dimensional frequency, and

$$\rho=\rho_{11}+2\rho_{12}+\rho_{22},H=P+2Q+R,c=\frac{p}{k},c_0{}^2=\frac{N}{\rho},V_0{}^2=\frac{H}{\rho}. \tag{20}$$

Using non-dimensional variables defined in (20) into F_1 and F_2 given by (14) and (19), respectively, one obtains an explicit relation between non-dimensional quantities F_i/F_0 *(i=1,2,* $F_0=Hk^2$ *)* and z/a for given materials, keeping non-dimensional frequency τa fixed. Three sets of material parameters are employed for computational work, which are presented in the table I. Of three, first two are given by Biot (Biot 1956) and third set is pertaining to sandstone saturated with kerosene given by Fatt (Fatt 1957). In material-II, mass coupling parameter is present while in material-III, elastic parameters (Lame constants) are dominant. For materials I & II Poisson ratio is 0.47, whereas for material-III it is 0.25. Quantity F_i / F_0 computed against z/a for three given materials, each for pervious boundary and impervious boundary. Computations are performed for various values of τa (Davids & Kumar 1957), the values τa are 0.83 (Set 1), 1.64 (Set 2) , and 2.13 (Set 3). Numerical results are presented graphically in figures 1-4. All the curves are symmetric with respect to y-axis. For the material–I and material–II, all the values in the case of pervious and impervious surfaces are negative, which correspond to tension, whereas for the case of material–III, and pervious surface, all values are positive. Positive values correspond to stress. It is interesting to note, all the values are positive that in the case of material–III and impervious surface.

Table-1

Material	a_1	a_2	a_3	a_4	d_1	d_2	d_3	x	y	z
I	0.61	0.0425	0.305	0.034193	0.5	0	0.5	1.671	0.812	14.623
II	0.61	0.0425	0.305	0.034193	0.65	-0.15	0.65	2.388	0.909	18.002
III	0.843	0.065	0.208	0.234	0.901	-0.001	0.101	0.999	4.763	3.851

From the Fig.1, it is clear that tension decreases as *ka* and τa increase, but in the neighbourhood of $ka = 0$ the trend is reversed. When *ka* and τa are high, that is in the case of set 3, the values of material-I and that of material-II are coinciding, which means that mass coupling parameter does not have any influence when *ka* and τa are relatively higher. From the Fig.2, it is seen that the values of pervious surface and the values of impervious surface are closer in the case of material-I which is not the true in the case of material-II which clear from Fig.3 .Therefore, from Fig.2 and Fig.3, one can infer that the values are affected by the nature of the surface in the case of material-I. It is the mass coupling parameter present in material-II making above distinction. Fig.4 corresponds to material–III and it is found that impervious values are higher than that of pervious values. In either case the values decrease as *ka* and τa increase. In the case of pervious surface the curves are concave upwards and in the case of impervious surface the curves are concave downwards.

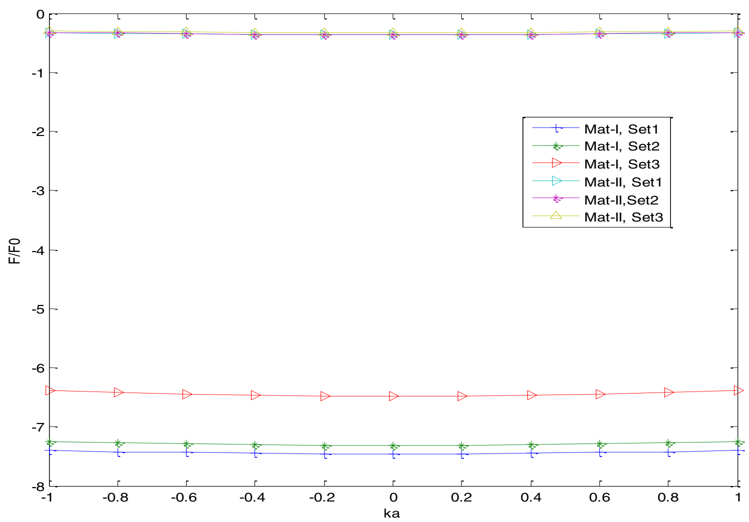

Figure.1. Variation of F_i / F_0 with z/a in Material-I& Material-II for Pervious Surface.

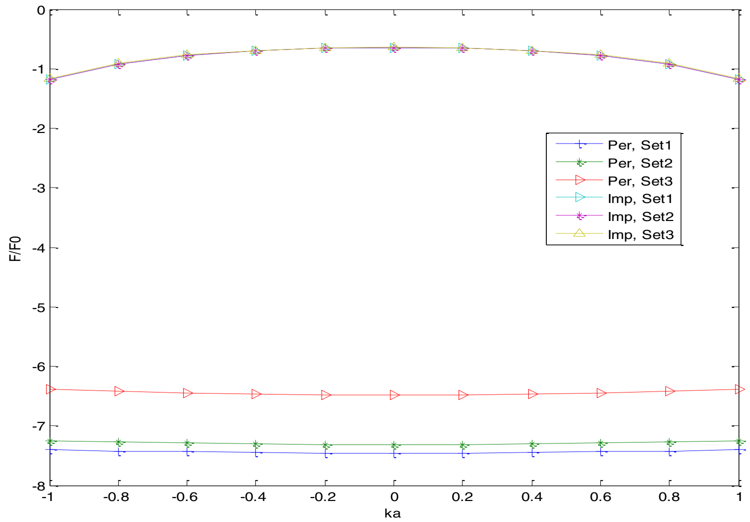

Figure.2. Variation of F_i / F_0 with z / a in Material-I for both Pervious & Impervious Surface.

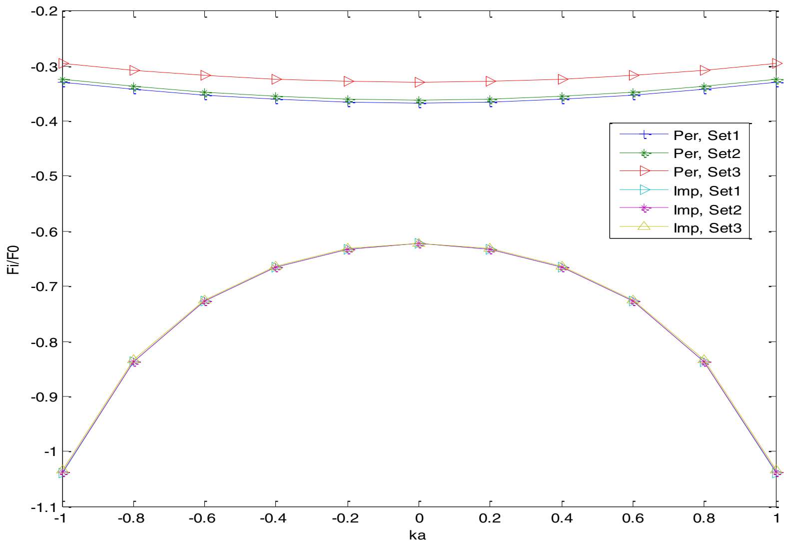

Figure.3. Variation of F_i / F_0 with z / a in Material-II for both Pervious & Impervious Surface.

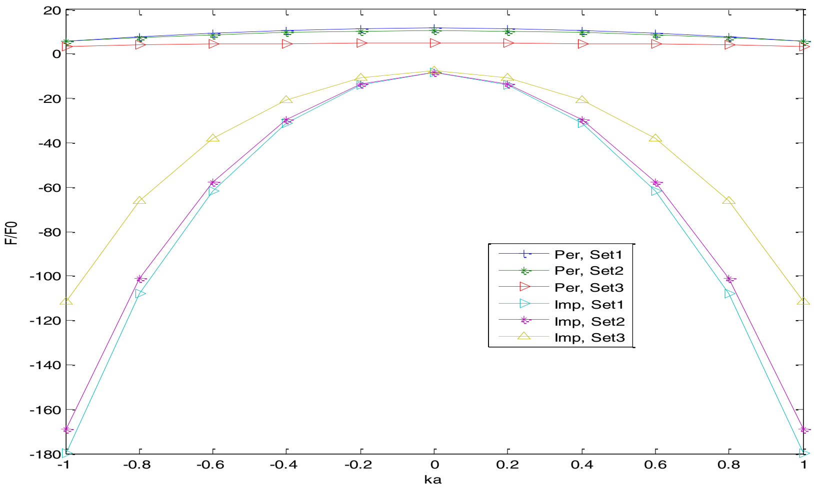

Figure.4.Variation of F_i / F_0 with z / a in Material-III for both Pervious and Impervious Surface.

4. Conclusion

The study of static stress waves in a poroelastic flat slab under an excitation is made using Biot's theory. It is seen that how the radial static stress components are affected in view of the traction free boundary conditions on the surfaces $z = -a$ and $z = a$ our analysis is confined to a periodic disturbance, however, because of the Fourier integral theorem; it is possible to extend the conclusions to pulse propagation as well. The radial normal static stress at the centre is computed against thickness of the slab for three types of materials. Numerical results show the following conclusions: All the curves are symmetric with respect to y-axis. The values pertaining to material-I and material-II are negative, which correspond to tension whereas the values of material-III in the case of impervious surface are positive that correspond to stress. Mass coupling parameter does not affect the values when both wave number and frequency are high nature of surface influences the values in presence of mass coupling parameter and impervious surface values are greater than that of pervious surface when elastic constants are higher.

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