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Deformation Due to Various Sources in Saturated Porous Media with Incompressible Fluid

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DEFORMATION DUE TO VARIOUS SOURCES INSATURATED POROUS MEDIA WITHINCOMPRESSIBLEFLUID

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Deformation Due to Various Sources in Saturated Porous Media with Incompressible Fluid

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Keywords : Deformation, porous medium, Normal mode analysis, pore pressure, source, incompressible fluid.

I. Introduction

Wave propagation in saturated porous media and the dynamic response of such media are of great interest in geophysics, acoustic, soil and rock mechanics and many earthquake engineering problems.

Biot [1] derived the basic equations of poroelastisity on the basis of energy principles. Privost[17] rederived these equations by use of mixture theory. Zienkiewicz ,Chang [18] and Zienkiewicz, Shiomi [19] derived the basic equations of poroelasticity by the use of principal of continuum mechanics . Gatmiri and Kamalian [4] adopted the later approach because it is more flexible and is based on a set of parameters with a clear physical interpretation to discuss different type of problem. Gatmiri and Nguyen [5] investigated two dimensional problem for saturated porous media with incompressible fluid.

Gatmiri and Jabbari [7,8] discuss time domain Green'᾽s functions for unsaturated soil for two dimensional and three dimensional solution. Gatmiri ,Maghoul and Duhamel[6] also discuss the two dimensional transient thermo-hydro-mechanical fundamental solution of multiphase porous media in frequency and time domains. Gatmiri and Eslami [9] discuss the scattering of harmonic waves by a circular cavity in a porous medium by using complex function theory approach.

Normal mode analysis approach has been successfully applied by different authors e.g. Ezzat, Othman and Karamang[3],Othman,Ezzat,Zaki and Karamang[12], Othman and Oman[14], Othman and Singh[15], Othman,Farouk and Hamied[11], Othman and Lotfy[13], Othman,Lotfy and Farouk[16], Ezzat,Zakaria and Karamang[2].Resently Kumar,Miglani and Kumar[10] investigated the different problems by using normal mode analysis in fluid saturated porous medium.

In the present paper, we obtain the components of stress and pore pressure for homogeneous isotropic porous saturated medium with incompressible fluid due to various sources. The resulting quantities are shown graphically to depict the effect of porosity.

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II. Governing Equations

Following Gatmiri and Nguyen [5],the basic equations are

Equation of motion :

$$\sigma_{ij,j} + f_i = \rho \ddot{u}_i + \rho_f \ddot{w}_i \tag{1}$$

Constitutive relation :

$$\sigma_{ij} = \lambda u_{i,i} \delta_{ij} + \mu (u_{i,j} + u_{j,i}) - \alpha p \tag{2}$$

Flow conservation for the fluid phase :

$$-\dot{w}_{i,i} + \gamma = \alpha \dot{u}_{i,i} + \frac{\dot{p}}{M} \tag{3}$$

Generalized Darcy's law :

$$p_{,i} = -\frac{1}{\kappa}\dot{w}_i - \rho_f \ddot{u}_i - m\ddot{w}_i \tag{4}$$

where u_i is the displacement of the solid skeleton, p denote the fluid pressure, w_i represents the average displacement of the fluid relative to the solid. The elastic constants λ and μ are drained Lame's constant. ρ_f is the fluid density, ρ_s is the solid density, $\rho = 1-n\ \rho_s + n\rho_f$ is the density of solid-fluid mixture and $m = \frac{\rho_f}{n}$ is the mass parameter where n is the porosity, κ is the permeability coefficient. α and M are material parameters which describes the relative compressibility of the constituents. f_i and γ denotes the body force and the rate of fluid injection in to the media.

Equations (1) and (4) with the aid of (2) and (3) in the absence of body force and the rate of fluid injection in to the media, reduce to

$$\mu u_{i,} + (\lambda+\mu)\, u_{i,ij} - \rho_1\, \ddot{u}_i - \alpha^* p_{,i} = 0\,, \tag{5}$$

$$\tau p_{,ii} - \frac{1}{M}\frac{\partial p}{\partial t} - \alpha^* \dot{u}_{i,i} = 0\,, \tag{6}$$

where

$$\rho_1 = \rho - \rho_f{}^2 \tau \frac{\partial}{\partial t},\quad \alpha^* = \alpha - \rho_f \tau \frac{\partial}{\partial t},\ \tau = \left[\frac{1}{\kappa} + m\frac{\partial}{\partial t}\right]^{-1}.$$

Formulation of the problem

We consider a homogeneous, isotropic conducting porous elastic layer of thickness 2H initially undisturbed. The origin of the coordinate system (x_1, x_2, x_3) is taken at the middle surface of the plate and x_3 - axis normal to it along the thickness. The surface $x_3 = \pm H$ is subjected to different sources. The $x_1 - x_2$ plane is chosen to coincide with the middle surface and x_3- axis is normal to it along the thickness.

For two dimensional problem, we take

$$u = (u_1, 0, u_3) \tag{7}$$

We define the non-dimensional quantities

$$x_1' = \frac{\omega}{c_1}x_1,\ x_3' = \frac{\omega}{c_1}x_3\ ,u_1' = \frac{\omega}{c_1}u_1\ ,\ u_3' = \frac{\omega}{c_1}u_3\ ,p' = \frac{p}{\lambda}\ ,c_1^2 = \frac{\lambda+2\mu}{\rho},\ t' = \omega t \tag{8}$$

where ω is the constant having the dimensions of frequency.

The displacement components are related by the potential functions φ and Ψ as

$$u_1 = \frac{\partial\varphi}{\partial x_1} - \frac{\partial\Psi}{\partial x_3}\ ,\ u_3 = \frac{\partial\varphi}{\partial x_3} + \frac{\partial\Psi}{\partial x_1} \tag{9}$$

Making use of equations (8) and (9), the equations (5) and (6) with aid of (7) after suppressing the prime for convenience, reduce to

$$(1 + a_1)\nabla^2\varphi - a_2 p - a_3\frac{\partial^2\varphi}{\partial t^2} = 0 \tag{10}$$

Ref.

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$$a_1\nabla^2\Psi - a_3\frac{\partial^2\Psi}{\partial t^2} = 0 \tag{11}$$

$$b_1\nabla^2 p - b_2\frac{\partial p}{\partial t} - \frac{\partial}{\partial t}\left[\nabla^2\varphi\right] = 0 \tag{12}$$

Where $a_1 = \frac{\mu}{\lambda+\mu}$, $a_2 = \frac{\alpha^*\lambda}{\lambda+\mu}$, $a_3 = \frac{c_1^2\rho_1}{\lambda+\mu}$, $b_1 = \frac{\tau\omega\lambda}{\alpha^* c_1^2}$ and $b_2 = \frac{\lambda}{\alpha^* M}$.

Notes

We assume the solution of equations (10) - (12) of the form

$$(\varphi, \Psi, p) = [f(z), g(z), h(z)]e^{i\xi(x_1-ct)} \tag{13}$$

where

$c = \frac{\omega}{\xi}$, where ξ is the wave number.

Making use of (13) in equations (10) - (12), eliminating h(z) from the resulting equations, we obtain

$$\left(\frac{d^2}{dz^2} - m_n^2\right) f(z) = 0 \tag{14}$$

where

$m_n^2 = \frac{-A_1 \pm \sqrt{A_1^2+4B_1}}{2}$, (n = 1,2) are the roots of equation (14) and

$$m_3^2 = A_2 - \xi^2 \tag{15}$$

and

$$\nabla = \frac{d}{dz} \ , A_1 = A - 2\xi^2 \ , B_1 = \xi^4 - A\xi^2 + B \ ,$$

$$A_2 = \frac{a_3}{a_1}\xi^2 c^2 \ , A = \left[\frac{a_3}{1+a_1}\xi^2 c^2 + \frac{b_2}{b_1} i\xi c + \frac{a_2}{b_1(1+a_1)} i\xi c\right] \text{ and } B = \frac{b_2 a_3}{b_1(1+a_1)} i\omega^3 c^3 .$$

The appropriate potential φ, Ψ, p can be written as

$$\varphi = [C_1 cos m_1 z + C_2 sin\, m_1 z + D_1 cos m_2 z + D_2 sin\, m_2 z]e^{i\xi(x_1-ct)} \tag{16}$$

$$\Psi = [E_1 cos m_3 z + E_2 sin\, m_3 z]e^{i\xi(x_1-ct)} \tag{17}$$

$$p = [r_1 C_1 cos m_1 z + r_1 C_2 sin\, m_1 z + r_2 D_1 cos m_2 z + r_2 D_2 sin\, m_2 z]e^{i\xi(x_1-ct)} \tag{18}$$

where

$$r_i = \frac{(1+a_1)}{a_2}\left[m_i^2 - \xi^2\right] + \frac{a_3}{a_2}\xi^2 c^2 \qquad (\text{ i =1,2}) . \tag{19}$$

With the help of equations (16) and (17), we obtain the displacement components u_1 and u_3 as

$$u_1 = [i\xi(C_1 cos m_1 z + C_2 sin\, m_1 z + D_1 cos m_2 z + D_2 sin\, m_2 z) + m_3(E_1 cos m_3 z - E_2 sin\, m_3 z)]e^{i\xi(x_1-ct)} \tag{20}$$

$$u_3 = [(-C_1 m_1 sin\, m_1 z + C_2 m_1 cos\, m_1 z - D_1 m_2 sin\, m_2 z + D_2 m_2 cos\, m_2 z) + i\xi(E_1 Dos m_3 z + E_2 sin\, m_3 z)]\, e^{i\xi(x_1-ct)} \tag{21}$$

III. Boundary Conditions

The boundary conditions at $x_3 = \pm H$ are

$$\sigma_{33} = -F_1 e^{i\xi(x_1-ct)} , \sigma_{31} = -F_2 e^{i\xi(x_1-ct)} , p = F_3 e^{i\xi(x_1-ct)} \tag{22}$$

where F_1 ,F_2 are the magnitudes of the forces and F_3 is the constant pressure applied on the boundary and

$$\sigma_{33} = R_1 \frac{\partial u_1}{\partial x_1} + R_2 \frac{\partial u_3}{\partial x_3} - \alpha p \, , \qquad \sigma_{31} = \frac{\partial u_1}{\partial x_3} + \frac{\partial u_3}{\partial x_1} \tag{23}$$

where

$$R_1 = \frac{\lambda}{\mu},\ R_2 = \frac{\lambda+2\mu}{\mu}.$$

Case 1 : For normal force $F_2 = F_3 = 0$,

Case 2 : For tangential force $F_1 = F_3 = 0$,

Case 3 : For pressure $F_1 = F_2 = 0$

Derivation of the secular equations

Substituting the value of u_1, u_3 and p from (20), (21) and (18) in the boundary condition (22) and with help of (23) after some simplifications, we obtain

$$\sigma_{33} = \Big[R_3\Big\{\Big(\frac{F_1a_{11}-F_3a_{22}-F_3a_{33}}{\Delta_{10}}\Big)\cos m_1z + \Big(\frac{F_2a_{44}}{\Delta_{20}}\Big)\sin m_1z\Big\} + R_4\Big\{\Big(\frac{F_3a_{55}-F_1a_{66}-F_3a_{77}}{\Delta_{10}}\Big)\cos m_2z - \Big(\frac{F_2a_{88}}{\Delta_{20}}\Big)\sin m_2z\Big\} - d_3\Big\{-\Big(\frac{F_2a_{99}}{\Delta_{20}}\Big)\sin m_3z + \cos m_3z\Big(\frac{-F_3b_{11}-F_3b_{22}+F_1b_{33}+F_1b_{44}}{\Delta_{10}}\Big)\Big\}\Big] e^{i\xi(x_1-ct)} \tag{24}$$

$$\sigma_{31} = \Big[2i\xi\Big\{m_1\Big(\frac{F_1a_{11}-F_3a_{22}-F_3a_{33}}{\Delta_{10}}\Big)\sin m_1z + m_1\Big(\frac{-F_2a_{44}}{\Delta_{20}}\Big)\cos m_1z - m_2\Big(\frac{-F_3a_{55}+F_1a_{66}+F_3a_{77}}{\Delta_{10}}\Big)\sin m_2z + m_2\Big(\frac{F_2a_{88}}{\Delta_{20}}\Big)\cos m_2z\Big\} + d_6\Big\{\Big(\frac{F_2a_{99}}{\Delta_{20}}\Big)\cos m_3z + \sin m_3z\Big(\frac{-F_3b_{11}-F_3b_{22}+F_1b_{33}+F_1b_{44}}{\Delta_{10}}\Big)\Big\}\Big] e^{i\xi(x_1-ct)} \tag{25}$$

For normal force: F_1=1, F_2=F_3 = 0

$$\sigma_{33} = \Big[R_3\Big\{\Big(\frac{F_1a_{11}}{\Delta_{10}}\Big)\cos m_1z\Big\} + R_4\Big\{\Big(\frac{-F_1a_{66}}{\Delta_{10}}\Big)\cos m_2z\Big\} - d_3\Big\{\cos m_3z\Big(\frac{F_1b_{33}+F_1b_{44}}{\Delta_{10}}\Big)\Big\}\Big] e^{i\xi(x_1-ct)} \tag{26}$$

$$\sigma_{31} = \Big[2i\xi\Big\{m_1\Big(\frac{F_1a_{11}}{\Delta_{10}}\Big)\sin m_1z - m_2\Big(\frac{F_1a_{66}}{\Delta_{10}}\Big)\sin m_2z\Big\} + d_6\Big\{\sin m_3z\Big(\frac{F_1b_{33}+F_1b_{44}}{\Delta_{10}}\Big)\Big\}\Big] e^{i\xi(x_1-ct)} \tag{27}$$

For Tangential Force: F_2=1 , F_1=F_3=0

$$\sigma_{33} = \Big[R_3\Big\{\Big(\frac{F_2a_{44}}{\Delta_{20}}\Big)\sin m_1z\Big\} + R_4\Big\{-\Big(\frac{F_2a_{88}}{\Delta_{20}}\Big)\sin m_2z\Big\} - d_3\Big\{-\Big(\frac{F_2a_{99}}{\Delta_{20}}\Big)\sin m_3z\Big\}\Big] e^{i\xi(x_1-ct)} \tag{28}$$

$$\sigma_{31} = \Big[2i\xi\Big\{m_1\Big(\frac{-F_2a_{44}}{\Delta_{20}}\Big)\cos m_1z + m_2\Big(\frac{F_2a_{88}}{\Delta_{20}}\Big)\cos m_2z\Big\} + d_6\Big\{\Big(\frac{F_2a_{99}}{\Delta_{20}}\Big)\cos m_3z\Big\}\Big] e^{i\xi(x_1-ct)} \tag{29}$$

For Pressure : F_1=F_2=0, F_3=1

$$\sigma_{33} = \Big[R_3\Big\{\Big(\frac{-F_3a_{22}-F_3a_{33}}{\Delta_{10}}\Big)\cos m_1z\Big\} + R_4\Big\{\Big(\frac{F_3a_{55}-F_3a_{77}}{\Delta_{10}}\Big)\cos m_2z\Big\} - d_3\Big\{\cos m_3z\Big(\frac{-F_3b_{11}-F_3b_{22}}{\Delta_{10}}\Big)\Big\}\Big] e^{i\xi(x_1-ct)} \tag{30}$$

$$\sigma_{31} = \Big[2i\xi\Big\{m_1\Big(\frac{-F_3a_{22}-F_3a_{33}}{\Delta_{10}}\Big)\sin m_1z - m_2\Big(\frac{-F_3a_{55}+F_3a_{77}}{\Delta_{10}}\Big)\sin m_2z\Big\} + d_6\Big\{\sin m_3z\Big(\frac{-F_3b_{11}-F_3b_{22}}{\Delta_{10}}\Big)\Big\}\Big] e^{i\xi(x_1-ct)} \tag{31}$$

Where

$$R_3 = R_1\xi^2 + R_2m_1^2 + \alpha r_1,\ R_4 = R_1\xi^2 + R_2m_2^2 + \alpha r_2,$$

Notes

Notes

$a_{11} = r_2 d_6 cos\, m_2 H sin\, m_3 H$,$a_{22} = d_2 d_6 cos\, m_2 H sin\, m_3 H$,$a_{33} = d_3 d_5 sin\, m_2 H cos\, m_3 H$,$a_{44} = r_2 d_3 sin\, m_2 H cos\, m_3 H$

$a_{55} = d_1 d_6 cos\, m_1 H sin\, m_3 H$,$a_{66} = r_1 d_6 cos\, m_1 H sin\, m_3 H$,$a_{77} = d_3 d_4 sin\, m_1 H cos\, m_3 H$,$a_{88} = r_1 d_3 sin\, m_1 H sin\, m_3 H$,

$a_{99} = (r_1 d_2 - r_2 d_1) sin\, m_1 H sin\, m_2 H$, $b_{11} = d_1 d_5 cos\, m_1 H sin\, m_2 H$, $b_{22} = d_2 d_4 sin\, m_1 H cos\, m_2 H$, $b_{33} = r_2 d_4 sin\, m_1 H cos\, m_2 H$, $b_{44} = r_1 d_5 cos\, m_1 H sin\, m_2 H$.

$\Delta_{10} = (-r_2 d_1 d_6 + r_1 d_2 d_6) cos m_1 H cos m_2 H sin m_3 H + r_2 d_3 d_4 sin\, m_1 H cos m_2 H\, cos\, m_3 H + r_1 d_3 d_5 cos m_1 H cos\, m_3 H\, sin\, m_2 H$,

$\Delta_{20} = (r_2 d_1 d_6 - r_1 d_2 d_6) sin\, m_1 H sin\, m_2 H cos m_3 H + r_2 d_3 d_4 cos m_1 H sin m_2 H sin m_3 H - r_1 d_3 d_5 sin\, m_1 H sin m_3 H cos m_2 H$,

$d_1 = R_1 \xi^2 - R_2 m_1^2$, $d_2 = R_1 \xi^2 - R_2 m_2^2$, $d_3 = (R_1 - R_2)\, i\xi\, m_3$, $d_4 = 2i\xi \mathrm{m}_1$, $d_5 = 2i\xi \mathrm{m}_2$, $d_6 = m_3^2 - \xi^2$.

IV. Special Case

In the absence of incompressible fluid, the boundary conditions reduce to

$$\sigma_{33} = -F_1 e^{i\xi(x_1 - ct)} , \sigma_{31} = -F_2 e^{i\xi(x_1 - ct)} \tag{32}$$

and we obtain the constituting expressions for stress components for elastic layer as

$$\sigma_{33} = \left[R_5 \left\{-\frac{F_1 d_6 sin m_3 H}{\Delta_{50}} cos m_4 z - \frac{F_2 d_3 sin\, m_3 H}{\Delta_{60}} sin\, m_4 z\right\} - d_3 \left\{-\frac{F_2 d_1 sin m_4 H}{\Delta_{60}} sin m_3 z + \frac{F_1 d_4 sin m_4 H}{\Delta_{50}}\, cos\, m_3 z\right\}\right] e^{i\xi(x_1 - ct)} \tag{33}$$

$$\sigma_{31} = \left[2i\xi \left\{m_4 \frac{F_2 d_3 sin\, m_3 H}{\Delta_{60}} cos\, m_4 z\right\} + d_6 \left\{\frac{F_2 d_1 sin m_4 H}{\Delta_{60}} cos m_3 z + \frac{F_1 d_4 sin m_4 H}{\Delta_{50}}\, sin\, m_3 z\right\}\right] e^{i\xi(x_1 - ct)} \tag{34}$$

For normal force: F_1=1 and F_2=0

$$\sigma_{33} = \left[R_5 \left\{-\frac{F_1 d_6 sin m_3 H}{\Delta_{50}} cos m_4 z\right\} - d_3 \left\{\frac{F_1 d_4 sin m_4 H}{\Delta_{50}}\, cos\, m_3 z\right\}\right] e^{i\xi(x_1 - ct)} \tag{35}$$

$$\sigma_{31} = d_6 \left[\frac{F_1 d_4 sin m_4 H}{\Delta_{50}}\, sin\, m_3 z\right] e^{i\xi(x_1 - ct)} \tag{36}$$

For Tangential Force: F_1=0 and F_2=1

$$\sigma_{33} = \left[R_5 \left\{-\frac{F_2 d_3 sin\, m_3 H}{\Delta_{60}} sin\, m_4 z\right\} - d_3 \left\{-\frac{F_2 d_1 sin m_4 H}{\Delta_{60}} sin m_3 z\right\}\right] e^{i\xi(x_1 - ct)} \tag{37}$$

$$\sigma_{31} = \left[2i\xi \left\{m_4 \frac{F_2 d_3 sin\, m_3 H}{\Delta_{60}} cos\, m_4 z\right\} + d_6 \left\{\frac{F_2 d_1 sin m_4 H}{\Delta_{60}} cos m_3 z\right\}\right] e^{i\xi(x_1 - ct)} \tag{38}$$

Where

$R_5 = R_1 \xi^2 + R_2 m_4^2$

$\Delta_{50} = d_1 d_6 cos m_4 H sin m_3 H + d_3 d_4 sin\, m_4 H\, cos\, m_3 H$,

$\Delta_{60} = -\, d_1 d_6 cos\, m_3 H sin\, m_4 H - d_3 d_4 sin\, m_3 H\, cos\, m_4 H$

V. Numerical Results and Discussion

With the view of illustrating the theoretical results and for numerical discussion we take a model for which the value of the various physical parameters are taken from Gatmiri and Ngyun[2007]:

$$\lambda = 12.5\text{MPa}\ ,\mu = 8.33MPa\ ,K_s = 10^5 MPa\ ,\ ,K_f = 0.22\times 10^4 MPa\ \ ,\rho_s = 2600Kg/m^3$$

$$\rho_f = 1000Kg/m^3\ ,k = 0.001m/s\ ,\alpha = 1, n = 0.3$$

The values of normal stress σ_{33} , tangential stress σ_{31} and pore pressure p for homogeneous isotropic porous saturated medium with incompressible fluid and elastic medium are obtained for t=1 and z=1 in the range $0 \le x \le 10$.

The solid line represent the value of σ_{33} in fluid saturated porous medium with incompressible fluid for normal force(NFSPM), long dash line represent the value of σ_{31} in fluid saturated porous medium with incompressible fluid for tangential force (TFSPM) and small dash line represent the value of p in fluid saturated porous medium with incompressible fluid for pressure (PFSPM) where as solid line with central symbol(NFEM) and small dash line with central symbol(TFEM) represent the value of σ_{33} and σ_{31} in elastic medium for normal and tangential force respectively.

Fig.1 shows the variation of normal stress component σ_{33} w.r.t distance x in fluid saturated porous medium with incompressible fluid and elastic medium. The value of σ_{33} in fluid saturated porous medium with incompressible fluid, in case of normal force, first increase and then starts decrease and in case of tangential force, it remains linear with small decrease and in case of normal pressure source, it first increase and then start decreasing. The value of σ_{33} in elastic medium first increase and then starts decreasing in case of normal force where as in case of tangential force there is sharp increase and then starts decreasing.

Fig.2 shows the variations of tangential stress component σ_{31} w.r.t distance x in fluid saturated porous medium with incompressible fluid and elastic medium. The value of σ_{31} in fluid saturated porous medium with incompressible fluid, in case of normal force, first starts with small increase and then starts decreasing. In case of tangential force, it shows small decrease where as there is a sharp decrease in case of normal pressure. The values of σ_{31} in elastic medium, show small increase in case of normal force and there is a sharp decrease and then starts increasing and ends with small decrease in case of tangential force.

Fig.3 shows the variation of pore pressure w.r.t distance x in fluid saturated porous medium with incompressible fluid. The values of p start with small decrease and increase in case of normal force and become linear in case of tangential force. There is sharp increase in case of pressure force.

VI. Conclusion

It is observed that the behaviour ofσ_{33} in case of normal force and tangential force is same although the value due pore pressure is more. Appreciable porosity effect is observed on normal stress component. The behaviour of σ_{31} in case of normal force and tangential force is opposite. In case of normal pressure the value of normal force is initially less as compared with tangential force.

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Notes

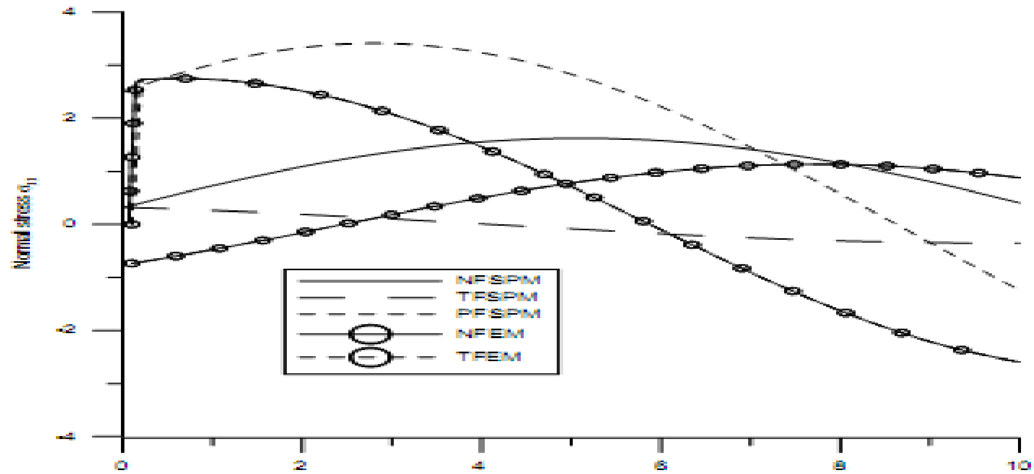

Fig.1 : Variation of normal stress component $\boldsymbol{\sigma}_{33}$ w.r.t horigentol distance x.

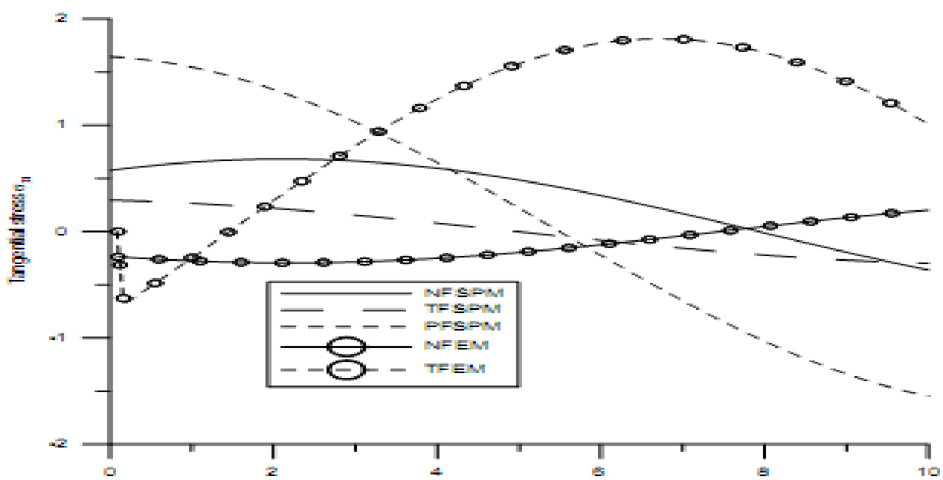

Fig.2 : Variation of tangential stress component $\boldsymbol{\sigma}_{31}$ w.r.t. horizontal distance x.

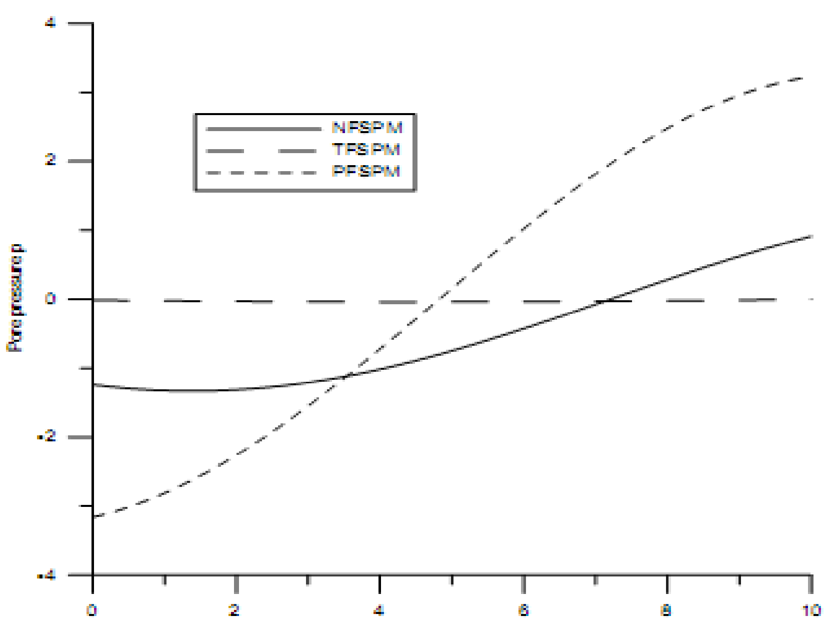

Fig.3 : Variation of pore pressure p w.r.t horizontal distance x.

Notes