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MODIFIYING A CIRCULAR ANALYSIS METHOD FOR CONSIDERING THE SCATTERING OF EARTHQUAKE WAVES IN AN OPENING IN ROCK

H. R.Vosoughifar [1]

ABSTRACT

In this paper a proper method for modifying the circular analysis in order to consider the scattering of earthquake waves in an opening in rock has been presented. The effect of earthquake on the underground structures depends on various parameters including the peak acceleration, intensity and duration of the earthquake and also the earthquake waves scattering at quake time. In most of the previously used methods, an advantage was taken of the circular solution method based on a simple geometry model. In some numerical methods, the advantage has been taken of the complex geometry and the area stress together. In all those cases, however, it is necessary to understand the stress behavior, strain, resistance criteria and rock fracture mechanism. When an underground structure such as a tunnel is digged out, some displacements will occur in the rock surrounding the tunnel during the time which would cause the distribution of stress. Engineers, choose the type and the dimension of the tunnel lining based on this distribution as qualitative. The circular solution is the best method of recognizing the plastic, elastic-plastic and elastic zones in an environment like the underground structures. This analytical method is performed by using the boundary element technique solution. The circular solutions available for underground structures are approximate and based on the static and dynamic loads. On the other hand, this method can't account for the wave scattering mentioned above. In this paper, a new analytical solution is presented for considering the circular solution method together with the criteria of wave scattering. The scattering of earthquake waves has been studied using the analytical solution. This solution can also be used to analyze the transient scattering problems. Case studies have shown that the stress level in an underground structure boundary may be increased by 250 and 1000 percent in P and SV wave pattern respectively due to the scattering. Therefore, a proper method for modifying the circular solution based on wave scattering should be evaluated. With appointing the plastic and elastic-plastic areas, researchers and designers will be able to apply this method in their analytical processes correctly.

Keywords: Underground Structures, Circular Analysis Method, Scattering

INTRODUCTION

Precise analysis of underground structures is very sophisticated in dynamic mode mainly because the interaction between structures and the infinite soil environment hasn't been properly understood yet. One of the effective items known is the wave scattering in underground structures. For the first time Pao & Mow (1973) investigated the diffraction of Elastic Waves around a hollow cylinder in an infinite environment. Later on, Manolis & Beskos (1988) evaluated scattering problems using the parametric boundary element method. Kobayashi & Nishimura (1994) scrutinized the effect of wave

[1] Assistant Professor of Civil Engineering Department, Faculty of Technology, Islamic Azad University, Tehran South Branch, and Post-Doc student in Berkeley University Email: Vosoughifar@Gmail.com, Vosoughifar@Fretco.ir

scattering in hydrodynamic force problems. The latter research was accomplished by Labish with studying the interaction curves and diffraction of elastic waves. Achenbach and Kitiahara (1986) studied the transmission and reflection of an oblique incident plane wave with an special array of spherical holes and superposing an infinite number of wave modes. Karl and Lee (1991) used a generalized method for studying scattering of SH waves in an underground cylindrical hole. The deformation near a circular underground hole subjected to a P wave pattern was investigated in the form of Fourier-Bessel series by Lee and Karl (1993). Some other similar studies have been done by Lee and Cao (1989), Cao and Lee (1990) and Lee and Karl (1992) about the elastic wave scattering in a 2-D plane.

Labouisse and et al. (1988) demonstrated that calculating a) the deformation and stability of a tunnel, b) volume increase and c) plastic deformation under strong ground motions is necessary. In all of those initial theories, the Mohr-Coulomb fracture model was used. The closed solution method was evaluated to incorporate the analytical and numerical methods. Sharan (2003) used this method to investigate the stress in circular openings in the Hoek-Brown media. In this approach, a solution was carried out to withdraw from elastic-plastic zone. With this presumption, computations were carried out to cover the elastic and plastic zones with in the model. Lately, these analytical methods have been used to solve the elastic-plastic problems of underground structures based on the Hoek-Brown failure criterion by Carranza (2004). The circular solution method was offered by Brown and et al. (1983). This method is applied as a solution for the strain-softening rock mass problem. Accordingly this solution is able to model three zones; elastic, elastic-plastic and plastic zones. Figure 1 shows a circular opening and those three mentioned zones around it.

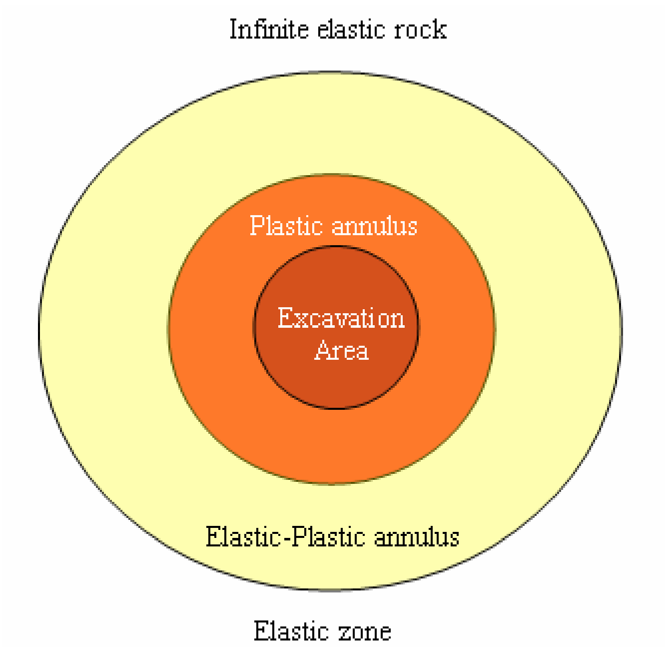


Figure 1. A circular opening in an infinite rock mass

THE MODEL OF ROCK MASS BEHAVIOUR

Most of the researchers have used the Mohr-Coulomb linear criterion for the rock mass. Experimental informations have shown that the strength criteria are nonlinear. Moreover, using a proper model of rock behavior is still ambiguous. Hoek and Brown investigated this problem and developed an empirical peak strength criterion for the rock mass according to equation 1.

$$\sigma_1 = \sigma_3 + (m\sigma_c\sigma_3 + s\,\sigma_c^2)^{1/2} \tag{1}$$

In this equation, the major and minor principal stresses at the failure area are σ_1 and σ_3 respectively. The uniaixial compressive strength of the intact rock material is σ_c. Constant coefficients m and s depend on the failure qualification and the classification of rock before being subjected to the failure stresses σ_1 and σ_3. Theses parameters estimate the hanger based on the rock specification as measured by Barton & Lein (1974). They change via various amounts of Lunder's Q (Barton 1974) factor or Bieniaawski's Rock Mass Rating (RMR) (1973). Equation 1 is used for estimating the initial rock mass strength. Parameters m and s must be reduced to m_r and s_r in a broken rock. In this case, the residual strength of the broken rock mass should be calculated using equation 2 (Brown 1983).

$$\sigma_1 = \sigma_3 + (m_r \sigma_c \sigma_3 + s_r\ \sigma_c^2)^{1/2} \tag{2}$$

The strength criterion given by equations 1 and 2, offers an advantage over other approaches in determining the overall in situ rock mass strength. The Strength reduction from the peak and continued deformation near the residual strength are both accompanied by the plastic dilation. Some elastic volume increase will also occur when the stresses are reduced. This phenomenon will be influenced by any change in the elastic module, for example when the rock mass is broken. How ever, this effect hasn't been considerd in the strength criteria mentioned above. This subject defines the gradient of the ε_1 vs. ε_3 vs. ν curves, where ε_1 and ε_3 are the major and minor principal strain in the rock mass and ν is the volumetric strain in the rock around the underground structure. Figure 2 shows the model of material behavior which was used in analysis. The parameters α, f, h, may vary when σ_1 and σ_3 change . Experimental data is required to determine these parameters.

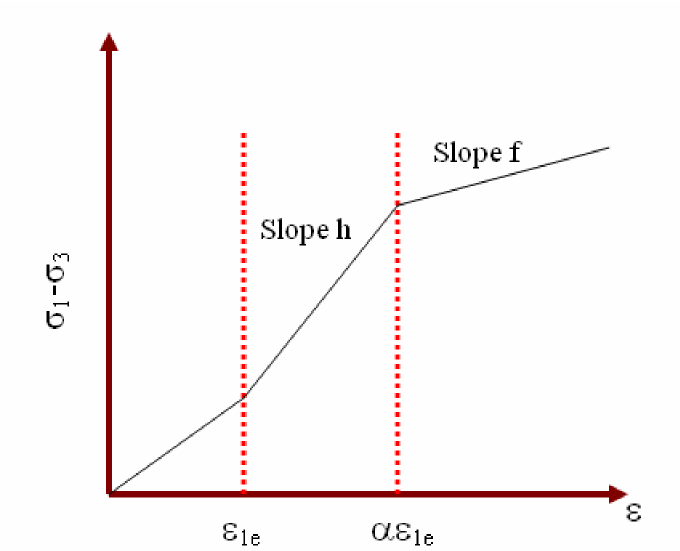


Figure 2. The Material behavior model used in the solution

In this case, the solution is carried out for 3 zones. The elastic zone around the tunnel, the inner plastic annulus and the elastic-plastic zone intervening these two zones.

The Stress-Strain Model

Although many complex problems in engineering have been solved by numerical methods, to apply the recommended model to the rock mass behavior, a simple axial symmetric problem should be considered. In this model, a circular underground structure of radius r_i is recommended in a hydrostatic stress field (σ_i) (Mohamed et al. 2003). Some of the available solutions incorporate the proximity of the underground structure face or construction process to the interaction curve of ground-support. In this process all of the strain increment will occurre in the planar surface. Because of the axial symmetry, the tangential stress (σ_θ) and radial stress (σ_r) will be the principal stresses. Therefore

σ_θ and σ_r are the major and minor principal stresses instead of σ_1 and σ_3. The corresponding stress model is shown in figure 3.

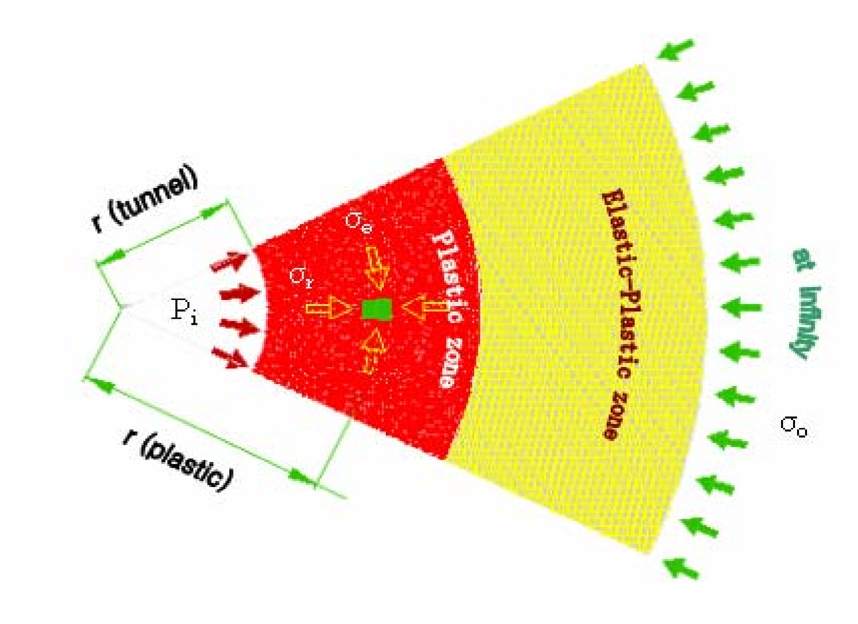


Figure 3. Stress and displacement fields in the plastic annulus around a circular opening

DISTRICT OF QUAKE WAVES ON UNDERGROUND STRUCTURES

There are two types of earthquake waves, body and surface waves. The energy and deformation of waves decrease with depth increment. In depths equal to the wave length manifold, the mentioned waves disappear. Surface waves are weakend a little by increase in distance because energy decrement in body and surface waves is related to reciprocal of the distance and reciprocal of the square of distance respectively. Some parts of the quake waves veer and some parts deflect when the waves collide with an irregular environment such as underground structure. When the P–SV waves scatter, the total displacement and forces in traction fields at the boundary of the unlined underground structure are give by equation 3.

$$u = u^i + u^s$$
$$P = P^i + P^s \qquad (3)$$

Where u^i, u^s, P^i and P^s are incident and scattered wave displacement fields and incident and scattered force tractions, respectively. Having the incident wave displacement, u^i, the boundary displacements can be obtained by solving the matrix equation in conjunction with equation 3 (Manolis and Beskose, 1988).

P WAVE

In this case the radiated waves are given by equation 4, where x_1 axis is perpendicular to x_2 axis and other parameters are shown in figure 4 (Moeen and et al.1988).

$$u_1^i = A_0 \sin\theta_0 \exp(ik_1(x_1 \sin\theta_0 + x_2 \cos\theta_0))$$
$$u_2^i = A_0 \cos\theta_0 \exp(ik_1(x_1 \sin\theta_0 + x_2 \cos\theta_0)) \qquad (4)$$

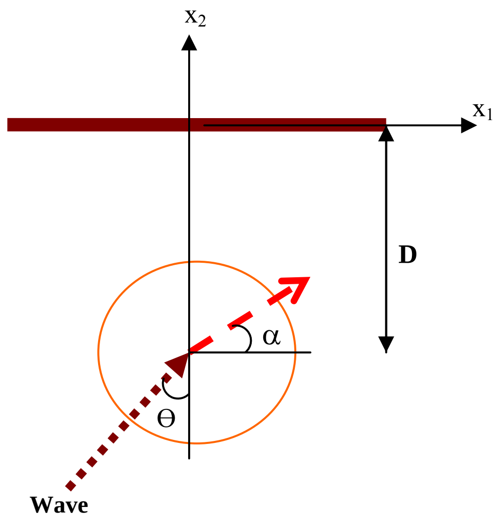


Figure 4. The circular underground structure against the earthquake waves

These waves reflect as P and SV waves after colliding with the opening. The deformed component of the reflected P wave is given by equation 5.

$$u_{1p}^{r} = A_1 \sin\theta_1 \exp(ik_1(x_1 \sin\theta_1 - x_2 \cos\theta_1))$$
$$u_{2p}^{r} = -A_1 \cos\theta_1 \exp(ik_1(x_1 \sin\theta_1 - x_2 \cos\theta_1)) \qquad (5)$$

The deformed component of the reflected SV wave can be expressed as the following equation.

$$u_{1sv}^{r} = A_2 \cos\theta_2 \exp(ik_2(x_1 \sin\theta_1 - x_2 \cos\theta_2))$$
$$u_{2sv}^{r} = A_2 \sin\theta_2 \exp(ik_2(x_1 \sin\theta_2 - x_2 \cos\theta_2)) \qquad (6)$$

For asmuch as the stress amount on the earth surface is zero, equation 7 can be expressed.

$$k_1 = \frac{\omega}{c_1}, \qquad k_2 = \chi k_1 = \frac{\omega}{c_2}$$
$$\theta_1 = \theta_0, \qquad \sin\theta_2 = \chi^{-1} \sin\theta \qquad (7)$$
$$A_1 / A_0 = (\sin 2\theta_0 \sin 2\theta_2 - \chi^2 \cos^2 2\theta_2)/(\sin 2\theta_0 \sin 2\theta_2 + \chi^2 \cos^2 2\theta_2)$$
$$A_2 / A_0 = (2\chi \sin 2\theta_0 \cos 2\theta_2)/(\sin 2\theta_0 \sin 2\theta_2 + \chi^2 \cos^2 2\theta_2)$$

The χ value in above equations is beeing calculated by equation 8.

$$\chi = \sqrt{\frac{2(1-\upsilon)}{1-2\upsilon}} \qquad (8)$$

Where notations A and θ are amounts of wave amplitude and the convection angle of x_2 axis, k_1 and k_2 are the P and SV wave numbers and c_1 and c_2 are the velocity of P and SV waves respectively.

SV WAVE

The displacements of SV radiated waves are given by equation 9 (Lee and Karl 1992).

$$u_1^i = -A_0 \cos\theta_0 \exp(ik_2(x_1 \sin\theta_0 + x_2 \cos\theta_0))$$
$$u_2^i = A_0 \sin\theta_0 \exp(ik_2(x_1 \sin\theta_0 + x_2 \cos\theta_0)) \qquad (9)$$

These reflected P and SV waves are the same as P waves. The deformed components of reflected P and SV waves can be expressed by equations 4 and 5. In these equations, parameters are the same as equation 10.

$$k_2 = \frac{\omega}{c_2}, \qquad k_1 = \chi^{-1} k_2 = \frac{\omega}{c_1}$$
$$\theta_2 = \theta_0, \qquad \sin\theta_1 = \chi \sin\theta_0 \qquad (10)$$
$$A_1 / A_0 = (-\chi \sin 4\theta_0)/(\sin 2\theta_0 \sin 2\theta_1 + \chi^2 \cos^2 2\theta_0)$$
$$A_2 / A_0 = (\sin 2\theta_0 \sin 2\theta_1 - \chi^2 \cos^2 2\theta_0)/(\sin 2\theta_0 \sin 2\theta_1 + \chi^2 \cos^2 2\theta_0)$$

MODIFYING THE CIRCULAR ANALYSIS METHOD

The modified circular analysis method and flowchart of the solution are presented in figure 5. The input data in the circular solution method are the followings: the principal pressure strength, σ_c, constant values of the rock strength, m and s, the gradients which are shown in figure 2, f and h, constant values of the broken rock, m_r and s_r, α content, the related strain on immanent strength, local hydrostatic stress σ_o (P_o) and the inner radius of the tunnel or underground structure, r_i.

CASE STUDY

To perform a case study first the dimness parameter is defined as equation 11.

$$a_0 = \omega r_i / c_2 \qquad (11)$$

In this equation ω is the reflected wave frequency and c_2 denotes the shear wave velocity. These parameters consider the effects of the frequency, radius and environmental specifications together. The elastic module in this case study is equal to 100 MPa. The density of the media is 1600 kg/m^3 and the ratio of Poisson is equal to 0.25. If the earthquake frequency is low, the amount of $\sigma_{\theta\theta}/\sigma_o$ may be equal to 1.00. With increase in frequency, $\sigma_{\theta\theta}/\sigma_o$ grows and at high levels of frequency those amounts will be able to accrete. Finally, at very high levels of frequency, some sub junctions has been seen.

In part one of the study, a tunnel was assumed under P waves. This tunnel was analyzed for a value of the opening radius equal to 1 meter. It was probated at scattered waves of 30, 45, 60 and 75 angles with dimness frequency domain between 0.1 and 1 Hz. The pertinent results in this stage of analysis are shown in figure 6. In order to study the effects of the SV waves, a tunnel was assumed with an opening radius equal to 1 meter against foresaid radiation angles. The results of these series are shown in figure 7. If the radiation angle becomes greater than a special angle, the reflected wave of type P will be parallel to the earth surface. The amount of critical angle is equal to 35.62 degrees. This value has been calculated via mathematical-numerical analysis.

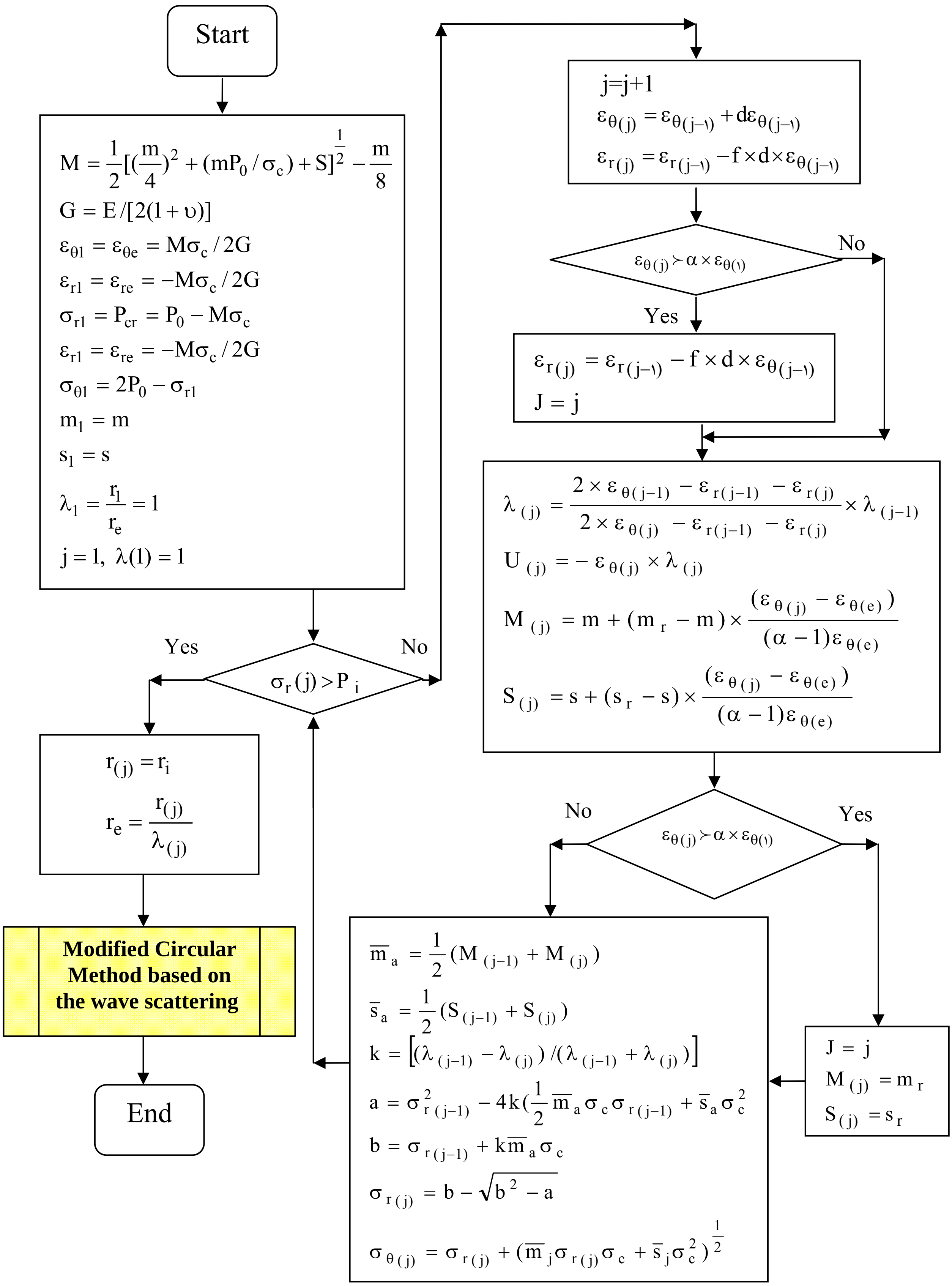
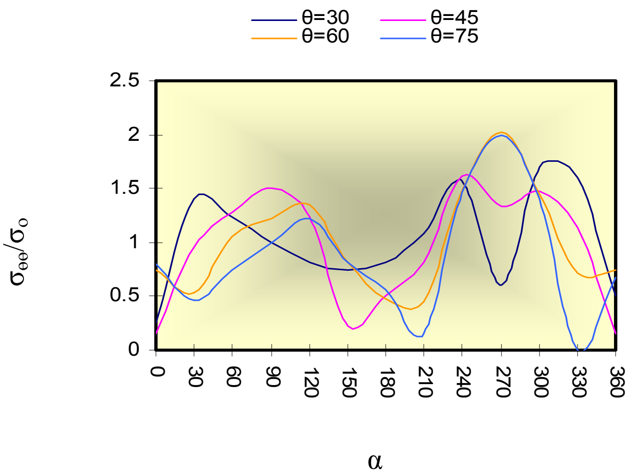
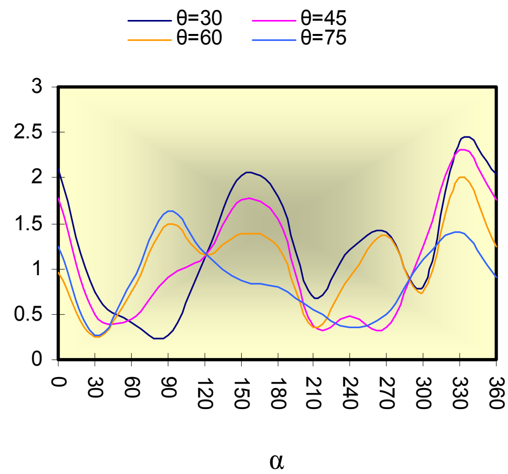


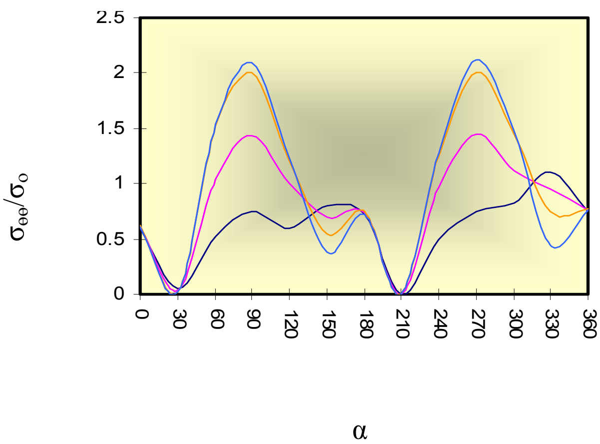
Figure 5. The modified circular analysis method and flowchart solution



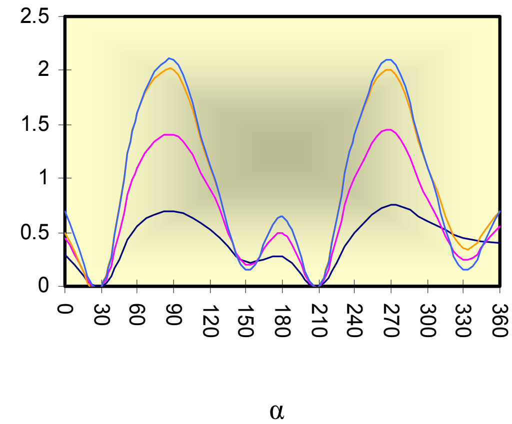
Circular tunnel, P wave, a_o=1.0, D/R=2.0



Circular tunnel, P wave, ،a_o=1.0 ،D/R=5.0

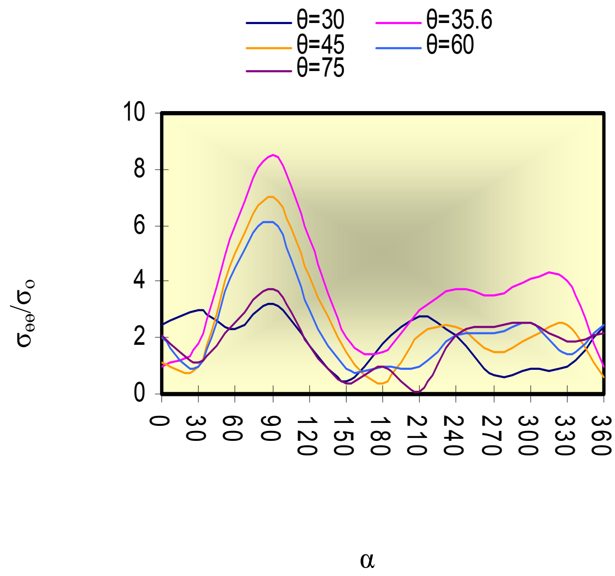


Circular tunnel, P wave, a_o=0.1, D/R=2.0

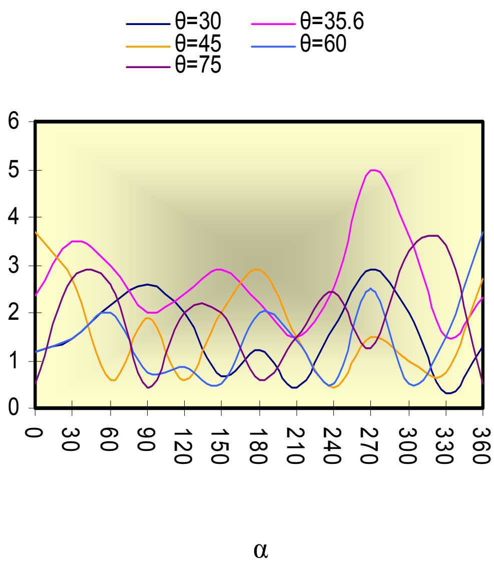


Circular tunnel, P wave, a_o=0.10, D/R=5.0

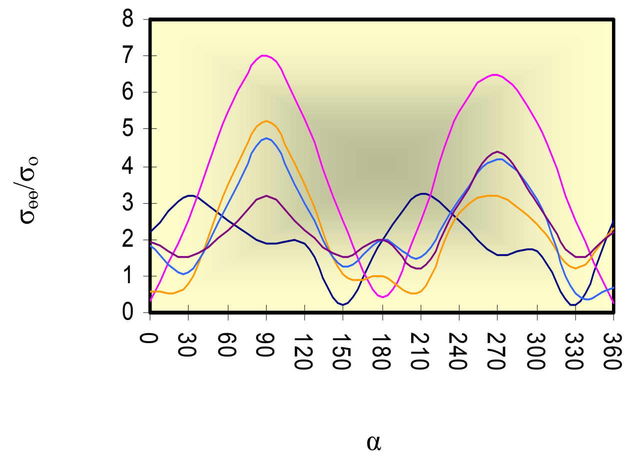
Figure 6. The results for P wave scattering



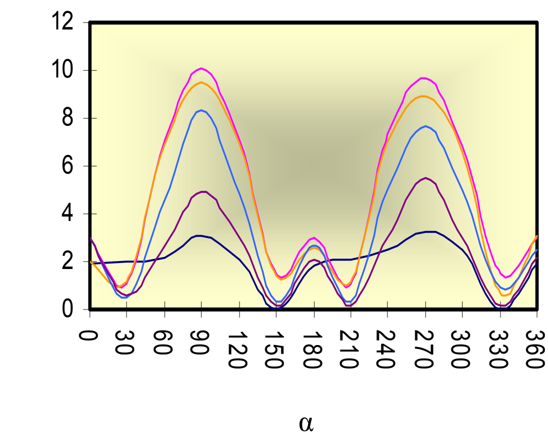
Circular tunnel, SV wave, a_o=1.0, D/R=2.0



Circular tunnel, SV wave, a_o=1.0, D/R=5.0



Circular tunnel, SV wave, a_o=0.1, D/R=2.0



Circular tunnel, SV wave, a_o=0.1, D/R=5.0

Figure 7. The results for scattering of SV wave

CONCLUSION

According to this study, the following general results are concluded:

- In this paper the effect of wave scattering on the normalized elastic radial displacements occurring around the excavation face of a circular underground structure is investigated by using the stress analysis.
- Analytical solutions have been evaluated to predict the seismic behavior of underground structure and the ground deformations of shallow and deep tunnels. The oval-shaped ground deformation pattern is imposed on the boundary conditions. To calculate the displacement at the underground opening we should consider the real non-uniform ground deformation

pattern. The gap parameter is used to describe the displacement at the opening. Two case studies (P and SV waves) have been done to check the applicability of the proposed analytical solution.

- Although the analytical solution presented in this paper is limited in scope, it appears to be useful for a preliminary design of underground structures and to predict the behaviour of these structures against scattering of earthquake waves.
- The effect of earthquake on underground structures depends on various parameters including the peak acceleration, intensity and duration of the earthquake and the scattering of earthquake waves at quake time.
- The seismically induced deformations imposed to an underground structure can be approximated with an analytical analysis when the seismic motions are applied with wave scattering.
- Currently available circular solutions for underground structures are approximate, based on static and dynamic loads and unable to consider the scattering of waves. A new analytical solution has been presented in this paper combining circular solution method and criteria of of wave scattering. The scattering of the earthquake waves has been considered by using the analytical solution. This method can also be used to analyze transient scattering problems.
- An important finding of this research is that the amount of $\sigma_{\theta\theta}$ increases upto 250 percent of the σ_o value at scattering fields in P wave cases. Albeit this present is based on the underground structure depth, other parameters such as the earthquake radiation angle and dimness frequency are mostly important.
- The maximum value of $\sigma_{\theta\theta} / \sigma_o$ for conditions of radiation wave frequency equal to 1 and D/R=2 is 8.5. The amount of $\sigma_{\theta\theta} / \sigma_o$ will reach to 7.00 with depth increase ($D/R = 5$).
- The stress in an underground structure boundary may increase upto 250 percent in P wave and 1000 percent in SV wave manners. These increments are caused by wave cattering in the underground structure. Therefore it is necessary to considere the scattering of earthquake waves in design processes.

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