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SEISMIC GUIDELINES FOR TUNNELS ON ROCK

Nava-Tristán O. E.[1], Ulises Mena Hernández[1], Enrique Mena Sandoval[2] and Elisa Andrade[2]

[1] *Researcher, Gerencia de Ingeniería Civil, Instituto de Investigaciones Eléctricas, Cuernavaca, Mexico*
[2] *Researcher, Gerencia de Estudios de Ingeniería Civil, Comisión Federal de Electricidad, Mexico City, Mexico*
Email: oenavat@iie.org.mx, umena@iie.org.mx, enrique.mena@cfe.gob.mx, elisa.andrade@cfe.gob.mx.

ABSTRACT :

A seismic guideline for lining tunnels on rock is presented. This guideline will be contained by first time into the Seismic Design Chapter of the seismic design handbook of CFE. The seismic recommendation for tunnels will be fundamentally oriented to evaluate the deformations in both directions: longitudinal axis (axial and curvature) and transverse axis (ovaling). These seismic recommendations were adapted to the new criteria of the seismic hazard of Mexico, where the acceleration and the proposed design spectra are continuums within the Mexican territory. The seismic design criteria to analyze the tunnels' longitudinal direction are based on the solution of free field theory. Whereas the solution for analyzing the tunnels' transverse direction, it is considered the plane strains state; in order to carry out these analyses, an equations to evaluate the strain to determining bending and the axial force are used, later both are compared with a maximum permissible strain. In the same way, an abacus of practical and simple use is proposed to determine if the tunnel expires, based with the criterion of unitary transverse strain before dynamic solicitations, knowing only the elastic properties of the rock and the lining material. In spite of the little information that exists on seismic effects in tunnels, these recommendations will try to cover the concepts that must be checked and the parameters that must be using in the tunnels' seismic design.

KEYWORDS: free-field, seismic guidelines, tunnels, rock, abacus**.**

1. INTRODUCTION

From a structural analysis point of view, the existing recommendations for seismic analysis and design of tunnels have focused in the tunnels' lining (Kuesel, 1969; St. John and Zahrah, 1987; Wang, 1993 and Monsees, 1996). Those recommendations are used to determine the deformations induced by shear waves in longitudinal and transverse direction of a tunnel. The earlier analyses were used in order to determine the effects in tunnel's longitudinal direction, obtaining the equation's solution of wave in one dimension proposed by Newmark (1968), based on the free-field theory. Kuesel (1969) was the first one who applied it in tunnels. The equations to calculate the strains by ovaling effect are based on the shell theory for a circular cylinder (Flügge, 1960).

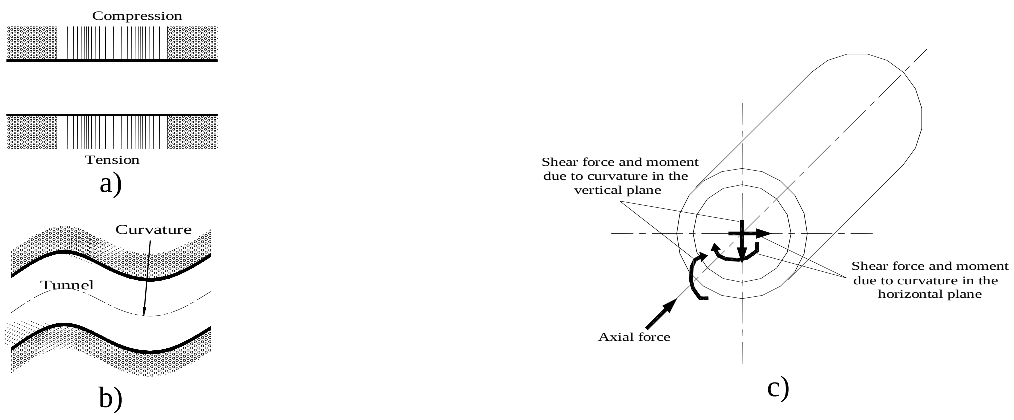
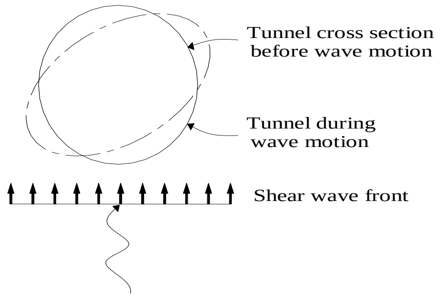


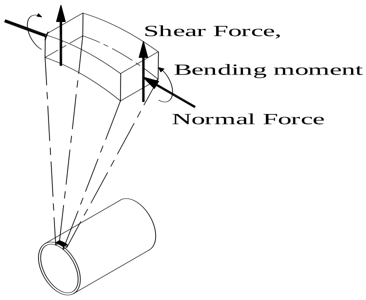
Figure 1.1. a) Axial deformation along tunnel; b) Curvature deformation along tunnel (St. John y Zahrah, 1987) y c) Induced forces and moments caused for waves propagating along tunnel axis (Hashash *et al*., 2001).

The Seismic loads on tunnels have two effects: a) faulting and b) shaking. Regarding the faulting is part of other studies. This paper will focus in describing the deformation types that cause the shaking effects in tunnels.

Notice, that the propagation of seismic waves in a circular tunnel generate deformations, forces and bending moment in longitudinal (figure 1.1) and transversal (figure 1.2) directions. Besides, portals slope faults, geological faults systems, stiffness' abrupt changes of tunnels (joints, port) and ground's stiffness changes were not considered in this paper.



a)



b)

Figure 1.2. a) Ovaling deformation of cross section (St. John y Zahrah, 1987) y b) Induced circumferential forces and moments caused by waves propagating perpendicular to tunnel axis (Hashash *et al.*, 2001).

2. INDUCED STRAINS DUE TO SHEAR WAVES

As mentioned, the seismic waves induce axial and curvature deformations in longitudinal direction, as well as, ovaling in transversal direction. In this sense, the developing equations in this paper are described in order to determine the strain in tunnel's circular section in rock or hard soil.

2.1. Longitudinal strains

St. John y Zahrah (1987) proposed equations in order to calculate the longitudinal strains for body and surface waves, based on works conducted by Newmark (1968) y Kuesel (1969). In the case of shear waves, simplifications were done based on basic relations of wave length, L, angular frequency, ω, maximum velocity, $v_{máx}$ and maximum acceleration, $a_{máx}$. The strain, ε, in longitudinal direction, caused by shear waves, that exert itself with angle of incidence, is obtained using equation 2.1 (St. John y Zahrah, 1987):

$$\varepsilon = \frac{v_{máx}}{C_s} \cdot \sin(\phi) \cdot \cos(\phi) \pm \frac{a_{máx}}{C_s^{\,2}} \cdot R \cdot \cos^3(\phi) \tag{2.1}$$

Some authors have suggested an angle of incidence equal to ϕ = 45º (*e.g.* Hashash *et al.*, 2001) in order to obtain the maximum value of strain. This value allows to obtain acceptable results in the pre design stage of tunnels, or in the design of small tunnels. However, in case of an important tunnels or tunnels with high effective radius (R > 2.0 m), the maximum value of strain must be calculated using the angle of incidence, ϕ_c (eq. 2.2), since, depending on the soil movement and tunnels' radius parameters, the strains can be different from the estimated ones with an angle of incidence equal to 45º (figure 1.1). For a radius of R=10.0m, ϕ_c is in a interval between 43.6 º and 42.2 º, for wave's propagation velocities between 800 and 415 m/s, respectively.

$$\phi_c = \arcsin\left(\frac{\sqrt{8a^2 - 4a + 1} - 1}{4a - 2}\right); \quad \rightarrow \quad a = \frac{v_{máx} C_s}{3 a_{máx} R} \tag{2.2}$$

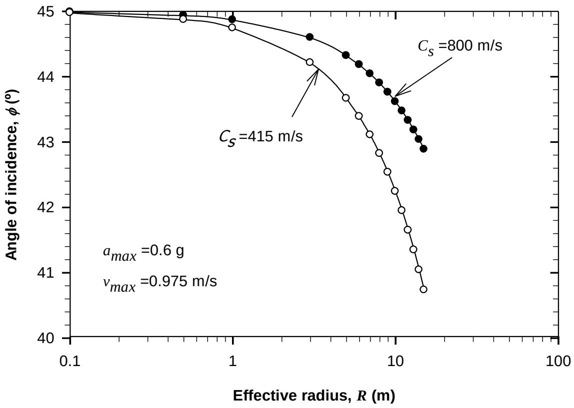


Figure 2.1. Critical angle of incidence *vs*. effective radius of the tunnel lining.

2.2. Transversal strains

The ovaling's deformation development occurs when the waves propagate in a perpendicular way of the tunnels' axis. In order to carry out the deformation analysis, the bi-dimensionally transversal section or a deformations' flat states must be considered (Wang, 1993).

Ground's angular deformation can be defined in a two different ways: considering the ground is non perforated (figure 2.2a) and the ground is perforated (figure 2.2b).

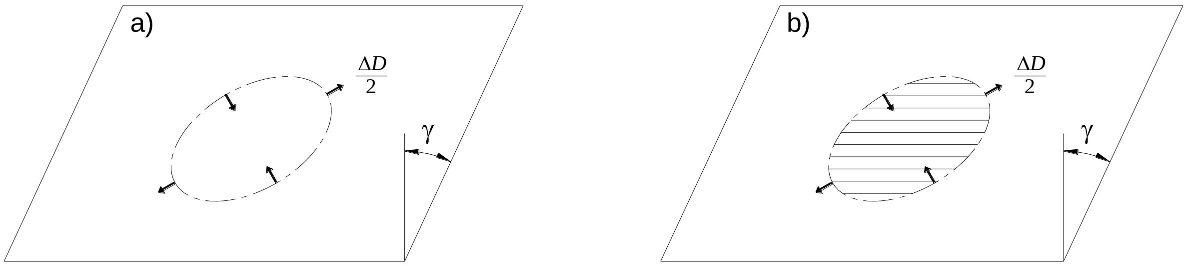


Figure 2.2. Free-field shear distortion of non-perforated and perforated ground circular shape (Wang, 1993)

Diametrical strain, ΔD/D, can be obtained using equation 2.3, when the ground is non perforated. When the ground is perforated, equation 2.4 is applying. Ground is considered like rock or hard soil.

$$\left(\frac{\Delta D}{D}\right)_{máx} = \pm\frac{\gamma_{máx}}{2} \tag{2.3}$$

$$\left(\frac{\Delta D}{D}\right)_{máx} = \pm 2\cdot\gamma_{máx}\cdot(1-\nu_m) \tag{2.4}$$

Both equations are assumed that the lining is not exist, and the tunnel–ground interaction is rejected. Equation 2.4 provides a reasonable criteria in order to determinate the maximum diametrical strain with a tunnel with less rigid than the ground that surround it, F>20 (Peck *et al.*, 1972).

Equations used to calculate the ovaling deformations are based on shell theory for a cylinder (Flügge, 1960). The strains caused by shear waves in the tunnel's transversal section can be calculated for normal force, ε_{Tov}, and by bending moment, ε_{bov}, (Wang, 1993):

Caused by normal forces:

$$\varepsilon_{Tov} = 3 \cdot (1-\nu_m) \cdot \frac{V_{máx}}{C_s} \cdot \frac{t}{R} \tag{2.5}$$

Caused by bending moment:

$$\varepsilon_{bov} = \frac{1}{2} \cdot \frac{E_m}{E_L} \cdot \frac{(1-\nu_L{}^2)}{(1+\nu_m)} \cdot \frac{V_{máx}}{C_s} \cdot \frac{R}{t} \tag{2.6}$$

Where, t is the lining thickness, ν is Poisson's ratio and E is modulus of elasticity. The m index corresponds to the ground type (rock or hard soil) and L index correspond to lining's material. The strain by ovaling, ε_{ov}, is obtained adding the equations 2.5 y 2.6, in other words:

$$\varepsilon_{ov} = \frac{V_{máx}}{C_s} \cdot \left[3 \cdot (1-\nu_m) \cdot \frac{t}{R} + \frac{1}{2} \cdot \frac{E_m}{E_L} \cdot \frac{(1-\nu_L{}^2)}{(1+\nu_m)} \cdot \frac{R}{t} \right] \tag{2.7}$$

Equations 2.1 y 2.7 are used in California, USA, in dynamic design of tunnels (Wang, 1993; Monsees, 1996; USACE, 1997; Hashash *et al.*, 2001). This is because; the results are acceptable where the lining is less flexible than the ground. In a particular case, the strain by ovaling must be less than the diametrical strain of free-field, taking into account the ground perforated.

$$\varepsilon_{ov} < \left(\frac{\Delta D}{D} \right)_{máx} \quad \rightarrow \quad \varepsilon_{ov} < 2\gamma_{máx} (1-\nu_m) \tag{2.8}$$

The maximum angular deformation, $\gamma_{máx}$, can be calculated using site's response analysis programs. However, acceptable values can be obtained using equation 2.10 (Dobry *et al.*, 1976):

$$\gamma_{máx} = \frac{V_{máx}}{C_s} \tag{2.9}$$

As mentioned, an acceptable values are obtained applying equations 2.8 and 2.9, when the flexibility ratio (Höeg, 1968; Peck *et al.*, 1972; Mohraz, *et al.*, 1975) is greater than 20 (F > 20). Flexibility ratio can be obtained using a simplify form.

$$F = 2 \frac{E_m}{E_L} \frac{(1-\nu_L{}^2)}{(1+\nu_m)} \left(\frac{R}{t} \right)^3 \tag{2.10}$$

In tunnels' pre design, equation 2.7 can be normalized using:

$$\frac{\varepsilon_{ov}}{\frac{V_{máx}}{C_s}(1-\nu_m)} = 3\frac{t}{R} + \frac{1}{2}\frac{E_m}{E_L}\frac{(1-\nu_L{}^2)}{(1-\nu_m{}^2)}\frac{R}{t} \tag{2.11}$$

Inequality 2.8 is simplified replacing equation 2.9 in 2.11:

$$3\frac{t}{R} + \frac{1}{2}\frac{R}{t}F' < 2 \tag{2.12}$$

Where, F´ is the ground's properties relation *vs* lining, defined like:

$$F' = \frac{E_m}{E_L}\frac{(1-\nu_L^{\,2})}{(1-\nu_m^{\,2})} \tag{2.13}$$

Like, the inequality 2.12 depends only of R/t ratio and the ground's properties relation, an abacus was generated in order to aid in tunnels' pre design for different values of F' (figure 2.3). In this abacus, the strain by ovaling, ε_{ov}, can be estimated, as well as, the strain provided by normal force and bending moment (see 3.2.2).

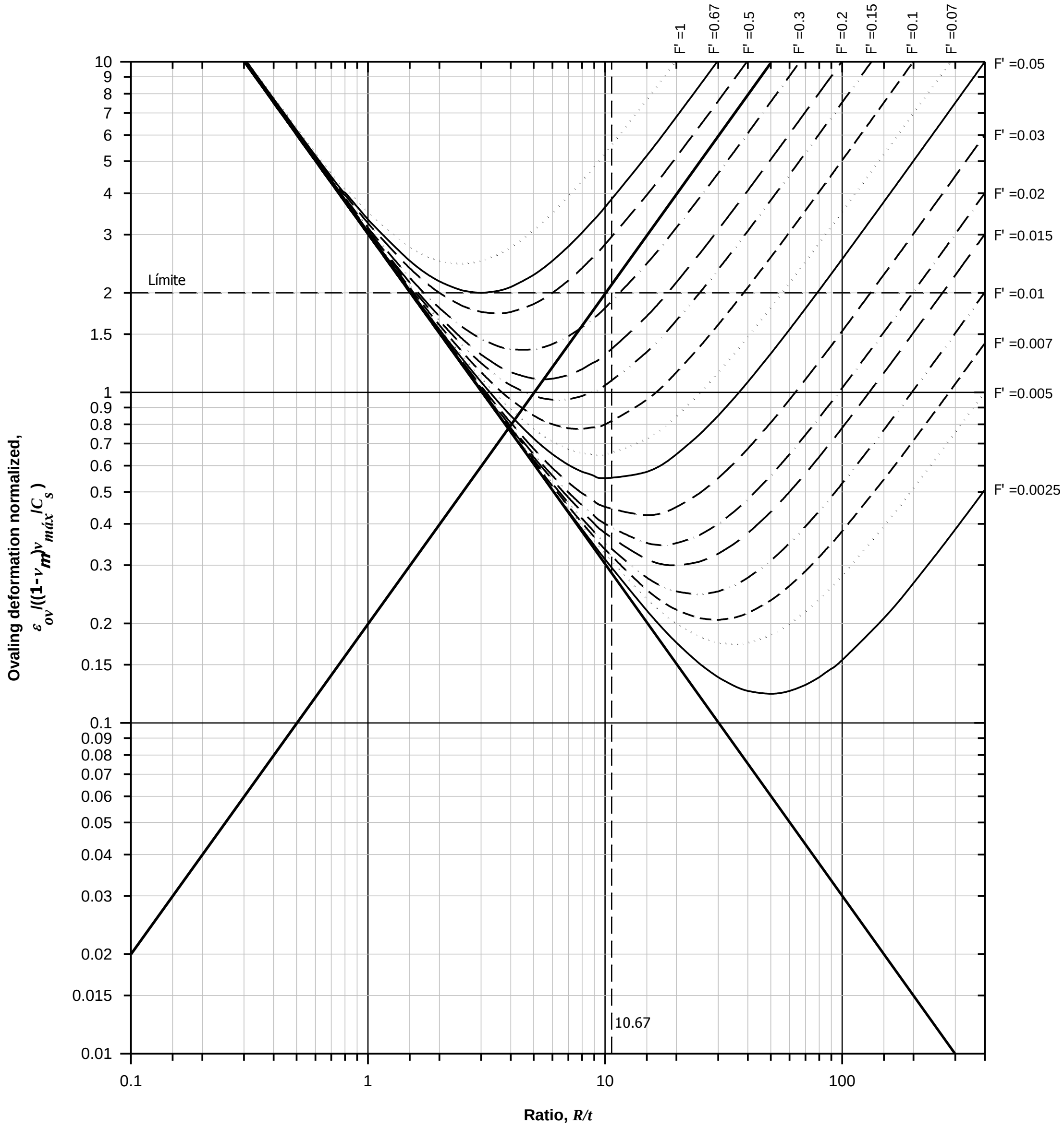


Figure 2.3. Ovaling abacus used in the tunnels' pre design stage.

Moreover, it also presents equations corresponding to a permissible interval of the R/t ratio, where the value equal to 2 is the border with the intersection with the curves' family (see Figure 2.3). These values are defined as allowable:

$$\left(\frac{R}{t}\right)_{mín} = \frac{2-\sqrt{4-6F'}}{F'} \quad \text{and} \quad \left(\frac{R}{t}\right)_{máx} = \frac{2+\sqrt{4-6F'}}{F'} \tag{2.14}$$

The discriminate of equations 2.14 must comply with 2.15 in order to obtain results inside the real numbers field.

$$0 < F' < 2/3 \tag{2.15}$$

Tunnel's geometrical properties are used to verify if the tunnels comply with the allowable maximum deformation by ovaling (diametrical strain maximum), inside the interval:

$$\left(\frac{R}{t}\right)_{mín} \leq \frac{R}{t} \leq \left(\frac{R}{t}\right)_{máx} \tag{2.16}$$

On the other hand, notice that figure 15.1 exists a minimum value for the normalized strain by ovaling, corresponding to a optimum value of the tunnels' geometrical properties, $(R/t)_{opt}$. In this stage, the deformation induced by normal force is equal to deformation induced by bending moment.

$$\left(\frac{R}{t}\right)_{ópt} = \sqrt{\frac{6}{F'}} \quad \text{and} \quad \left(\overline{\varepsilon_{ov}}\right)_{mín} = \sqrt{6F'} = \frac{6}{\left(\frac{R}{t}\right)_{ópt}} \tag{2.17}$$

3. COMPUTE OF INDUCED STRAINS DUE TO SHEAR WAVES

In order to show the abacus efficiency, a tunnel's circular section with concrete lining is proposed to review, considering dynamic conditions. The ground is basalt.

$\varepsilon_{ad} = 0.003$ (longitudinal direction)	$E_L = 27.46$ GPa	$\nu_L = 0.20$
$v_{máx} = 0.12$ m/s	$E_m = 10.7$ GPa	$R = 3.20$ m
$a_{máx} = 2.21$ m/s^2	$\nu_m = 0.25$	$t = 0.30$ m
$C_s = 2\,500.0$ m/s		

3.1 *Longitudinal strains*

First step is to obtain the critical angle of incidence, since the tunnel is considered important, using equation 2.2.

$$a = 14.0766 \quad \rightarrow \quad \phi_c = 44.57^{o} \tag{3.1}$$

In order to obtain the maximum strain of lining, caused by shear waves, using the critical angle of incidence, the equation 2.1 is applied.

$$\varepsilon = \pm 24.0 \times 10^{-6} \pm 0.41 \times 10^{-6} = \pm 24.41 \times 10^{-6} \tag{3.2}$$

With this the proposed tunnel's section is verified. The allowance deformation in longitudinal direction complies in the compression section.

$$\boxed{\therefore \;\; \varepsilon < \varepsilon_{ad} \quad \rightarrow \quad 24.41 \times 10^{-6} < 0.003} \tag{3.3}$$

3.2 *Transversal strains*

Tunnels' strain by ovaling can be reviewed according with the following ways.

3.2.1 Solution A. Traditional method

In order to estimate the strain by ovaling, the angular and maximum diametrical strains must be calculated, using the equations 2.10 and 2.9.

$$\gamma_{máx} = 48 \times 10^{-6} \quad \rightarrow \quad \left(\frac{\Delta D}{D}\right)_{máx} = 72 \times 10^{-6} \tag{3.4}$$

Later the strain by ovaling is calculated using equation 2.8.

$$\varepsilon_{ov} = 86.73 \times 10^{-6} \tag{3.5}$$

In this case, the proposal tunnel's section not comply with the transversal deformation condition (eq. 2.9)

$$\boxed{\varepsilon_{ov} > \left(\frac{\Delta D}{D}\right)_{máx} \quad \rightarrow \quad 0.00008673 > 0.000072} \tag{3.6}$$

3.2.2 Solution B. Abacus method

First step is to obtain the R/t ratio and the properties ratio F' (equation 2.14):

$$\frac{R}{t} = 10.67 \quad y \quad F' = 0.399 \approx 0.40 \tag{3.7}$$

Using the graph (figure 2.3), the value of curve for F' = 0.40 can't be obtained. However, with the normalized strain, the lines corresponding to normal force and bending moment are obtained, using 2.13.

$$\frac{\varepsilon_{ov}}{\frac{V_{máx}}{C_s} \cdot (1 - \nu_m)} = 3 \cdot \frac{t}{R} + \frac{1}{2} \cdot F' \cdot \frac{R}{t} \tag{3.8}$$

Downward line corresponds to values of normal force (first term of equation), while upward line corresponds to values of bending moment (second term of equation). Notice, that the first term is always the same for any ground condition, while the second one depends of F', however the linear curve's slope is the same in any case. The deformation value by normal force is equal to 2.1, while the deformation value by bending moment is equal to 0.28, obtaining by the lines' intersection with the R/t ratio, which is obtained from 3.7

$$\frac{\varepsilon_{ov}}{\frac{V_{máx}}{C_s} \cdot (1 - \nu_m)} = 2.1 + 0.28 = 2.38 \tag{3.9}$$

As mentioned, the proposal tunnel's section not complies with the transversal deformation condition, since is greater than 2(inequality 2.13). Besides, the strain value, ε_{ov}:, can be obtained using equation 3.9.

$$\boxed{\varepsilon_{ov} = (2.38) \cdot \frac{V_{máx}}{C_s} \cdot (1 - \nu_m) = (2.38) \cdot \frac{0.12}{2500.0} \cdot (1 - 0.25) = 0.0000857} \tag{3.9}$$

The above mentioned value is similar to the one was calculated by the equations (0.00008673).

3.2.3 Solution C: Comparison of R/t ratio. (Maximum and minimum allowable values)

In this case, it's verified that F' = 0.399 complies the equation 2.17. Finally, the maximum and minimum values of the R/t ratio are obtained, considering the value equal to 10.67, for the tunnels geometrical. The allowable values are obtained using equations 2.15 and 2.16 for R/t ratio.

$$\left(\frac{R}{t}\right)_{mín} = 1.84 \quad y \quad \left(\frac{R}{t}\right)_{máx} = 8.19 \tag{3.10}$$

Like, R/t = 10.67 is outside from the allowable interval, the allowable strain by ovaling is not complies.

4. CONCLUSIONS

Taking into account, the considerations that were made in order to determinate the proposal equations to generate the abacus and to determinate the allowable values for R/t, implicitly, the theories that simplified the problem are included, and the same way, the limitations. Nevertheless, the proposal for tunnels' design described in this article might use in the practice while more rigorous proposals do not exist. In the other words, proposals where considering a better reality of the physical phenomenon, that appears in a tunnel during an earthquake. On the other hand, the Solution C, in spite of it can not obtain the strain values, this solution is useful because of is easy to estimate if the tunnel will comply the allowable strain condition, during the seismic pre design. Finally, it was demonstrated that the proposal abacus aid in a easy and quick way if tunnels complies with the deformation condition by ovaling.

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