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Undrained Seismic Response of Underground Structures

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ABSTRACT

Underground structures must be able to support both static and seismic loads. Progress has been made in the last few years in understanding the soil-structure interaction mechanisms and the stress and displacement transfer from the ground to the structure during a seismic event. While all this has been well-established for structures under drained conditions, there is little information regarding the behavior of buried structures under undrained conditions.

This paper presents results of dynamic numerical analyses using FLAC 2D, for tunnels under undrained conditions. The analyses consider soil-structure interaction and excess pore pressure generation. Comparisons between drained and undrained analysis are provided, including the effects of the tunnel cross section. The results show that undrained conditions tend to reduce deformations for flexible structures and increase them for stiffer structures. While no remarkable influence of the tunnel shape is found for both drainage conditions, a trend appears of larger deformations for circular tunnels under undrained loading.

Introduction

The engineering community has had, for quite some time, the perception that underground structures are safe during an earthquake. The argument has been based on the idea that during earthquakes underground structures follow the deformation of the surrounding ground and, because the structure is confined, no damaging stresses are produced. However, the damage observed in recent earthquakes demonstrates that such perception is not correct. For example, during the earthquakes in Japan in 1995, Turkey and Taiwan in 1999 and China during the Wenchuan earthquake in 2008, among others, severe damage and even collapse occurred on a number of underground structures.

Progress has been made in the last few years on the understanding of the soil-structure interaction mechanisms and the stress and displacement transfer from the ground to the structure during a seismic event. There are two approaches used for the seismic design of underground structures. One is the free field approach (Hendron and Fernandez, 1983; Merritt et al., 1985), which assumes that the structure follows the free field deformations of the ground and accommodates them without loss of its integrity. However, because the presence of the structure changes the deformations of the ground around it, Hendron and Fernandez (1983) and Merritt et al. (1985) suggested to compute deformations taking into account the tunnel opening, given that most tunnels in competent ground would behave as perfectly flexible structures. This assumption however may result in extremely conservative designs, particularly for stiff structures in a soft medium. Instead, the behavior of a tunnel embedded in the ground should be considered as a coupled problem, and so the second approach consists of a dynamic analysis with soil-structure interaction.

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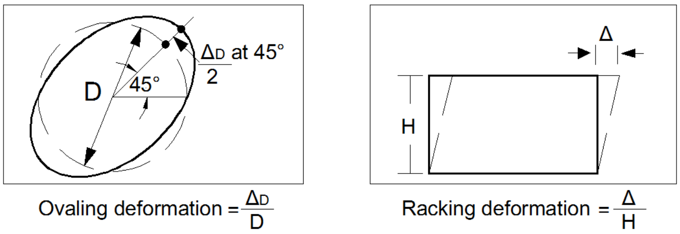
It is well established that the most critical demand on underground structures is caused by shear waves traveling perpendicular to the tunnel axis (e.g., St. John and Zahrah, 1985), which cause distortions of the cross section of the tunnel (ovaling for a circular tunnel, and racking for a rectangular tunnel; see Figure 1). The analysis must then consider two key aspects: one, the distortion of the cross section due to the ground motion; and two, the possible amplification associated with reflection and refraction of the waves impinging on the tunnel (Hendron and Fernandez, 1983). Analytical studies by Paul (1963), Yoshihara (1963), Hendron and Fernández (1983), Merritt et al. (1985) and Monsees and Merritt (1988) showed that the dynamic amplification of stress waves impinging on a tunnel is negligible when the wave length (λ) of peak velocities is at least 8 times larger than the width of the opening, which is usually the case for most structures located far from the seismic source. In these cases the seismic load can be computed as pseudo-static.



Ovaling deformation $= \frac{\Delta_D}{D}$ Racking deformation $= \frac{\Delta}{H}$

Figure 1. Distortions for circular and rectangular tunnels (Adapted from Bobet, 2010)

When a static analysis is appropriate, analytical solutions can be used to estimate ground and structure deformations. A number of closed-form solutions are available (e.g. Merritt et al., 1985; Wang, 1993; Penzien, 2000; Hashash et al., 2001; Bobet, 2003; Huo et al., 2006; Bobet et al., 2008), and are based on the fundamental concepts of elasticity, e.g. Timoshenko and Goodier (1970), and relative stiffness put forward by Einstein and Schwartz (1979). The analytical work clearly shows that the most important parameter determining distortion of the cross section of a tunnel is the relative stiffness between the structure and the ground and that the shape and depth of the structure have second-order effects (Bobet, 2010). While all this has been well-established for structures under drained conditions, i.e. when no excess pore pressures are generated, there is little information regarding the behavior of buried structures under undrained conditions, i.e. when excess pore pressures are generated and not dissipated quickly enough.

The paper provides dynamic numerical results for deep underground structures with circular and rectangular cross sections subjected to repeated cycles of a sinusoidal velocity with constant amplitude under undrained loading. The objectives of the work are: (1) determine if a relation, similar to that found for drained analysis, between the wave length of seismic motions and a characteristic dimension of the tunnel exists, such that a “pseudo-static” analysis can be used; (2) compare the effect of drainage conditions and tunnel shape on seismic response, given by the distortion of the cross section. In the analyses, the following assumptions are made: a tied interface, i.e. no relative displacement between structure and medium, and that the ground and the liner remain within their elastic regimes. Although a linear elastic behavior may be a limiting simplification, the results are informative and can be used as a first approximation; they can also be appropriate for competent ground. Most importantly, they are very valuable to identify the key variables for the problem and provide an understanding of the fundamental mechanisms for soil-structure interaction when the development of excess pore pressures is considered.

Dynamic Undrained Analysis

Dynamic analyses are performed using the two dimensional numerical code FLAC 7.0. Plane strain conditions are assumed. The model has a total size of 200 m x 200 m. Free-field boundaries on the sides and quiet boundaries at the bottom of the discretization are used. These are absorbing boundaries that prevent the reflection of waves back into the model (Lysmer and Kuhlemeyer, 1969; FLAC, 2011). Square elements 1 m x 1 m are used far away from the tunnel, and a finer mesh, also of square elements, but with a smaller size of 0.5 m x 0.5 m is used close to the tunnel. The seismic load consists of a sinusoidal horizontal velocity applied at the bottom of the model with amplitude 1 m/s. As mentioned, tunnels with different shapes and sizes are used in the simulations (see Sections 2.2 and 2.3), but all have a liner with a thickness of 0.4 m, which is modeled as a beam. The elastic parameters are E_m= 500 MPa and ν_m= 0.25 for the ground, and ν_l= 0.30 for the liner. The Young´s modulus of the liner (E_l) changes depending on the target relative stiffness. As it will be shown, the elastic properties of the materials and the magnitude of the input load (i.e. the amplitude of the seismic velocity) do not affect the conclusions because distortions are normalized with respect to those of the free field.

Effect of Frequency on Tunnel Distortion

Analytical studies by Paul (1963), Yoshihara (1963), Hendron and Fernández (1983), Merritt et al. (1985) and Monsees and Merritt (1988) showed that the dynamic amplification of stress waves impinging on a tunnel is negligible when the rise time of the pulse is larger than about two times the transit time of the pulse across the opening; that is, when the wave length (λ) of peak velocities is at least 8 times larger than the width of the opening. In these cases the seismic load can be considered as pseudo-static. While such statement has been used and validated by different authors for underground structures under dry or drained conditions, the effect of frequency (f) on the seismic response of tunnels under undrained conditions has not been investigated. The wave length (λ) can be obtained as the ratio between the shear wave velocity in the medium (C_s), and the frequency (f) of the dynamic input.

Figure 2 shows results of dynamic undrained numerical analyses when the wave length, or input frequency, is changed. The figure plots the maximum distortions of a circular and a rectangular tunnel normalized with respect to the free-field distortions, as a function of λ/D or λ/B ratio (bottom horizontal axis), where D and B are the diameter and width of the opening, respectively (maximum distortion occurs at maximum amplitude of the sinusoidal input velocity). For comparison purposes, the top horizontal axis presents the values of the input frequency. The analyses are done for both drained and undrained conditions. Details of how distortions are obtained are given in the next two sections. The circular tunnel has a flexibility ratio of 0.125 (stiff tunnel) and the rectangular tunnel has a flexibility ratio of 7.5 (flexible tunnel). The flexibility ratio (F) reflects the flexural stiffness of the system and is an important parameter related to the ability of the lining to resist distortions imposed by the ground (Einstein and Schwartz, 1979). In this paper, definitions of flexibility ratio provided by Peck et al. (1972) for circular tunnels (Equation 1), and by Wang (1993) for rectangular single barrel tunnels with equal wall and slabs thickness (Equation 2) are used.

$$F = \{(E_m)(1 - \nu_l^2)(R^3)\} / \{6(E_l)(I_c)(1 + \nu_m)\} \quad (1)$$

$$F = \{(G_m)(LH^2 + HL^2)\} / \{24(E_l)(I_r)\}$$

(2)

In Equations 1 and 2, E_m, υ_m and G_m are, respectively, the Young's modulus, Poisson's ratio and Shear modulus of the medium; E_l and υ_l are the Young's modulus and Poisson's ratio of the liner; R and I_c are the tunnel radius and moment of inertia of the liner for a circular cross section, and B and I_r are the tunnel width and moment of inertia of the liner for a rectangular cross section.

When F < 1, the structure is stiffer than the ground, and so its deformations are smaller than those of the free-field, i.e. of the ground without the structure. If F > 1, the structure is more flexible than the ground it replaces, and so its distortions are larger than the free field. If F = 1 the tunnel and the ground have the same stiffness, and so the structure´s deformations should be those of the free field (Bobet, 2010).

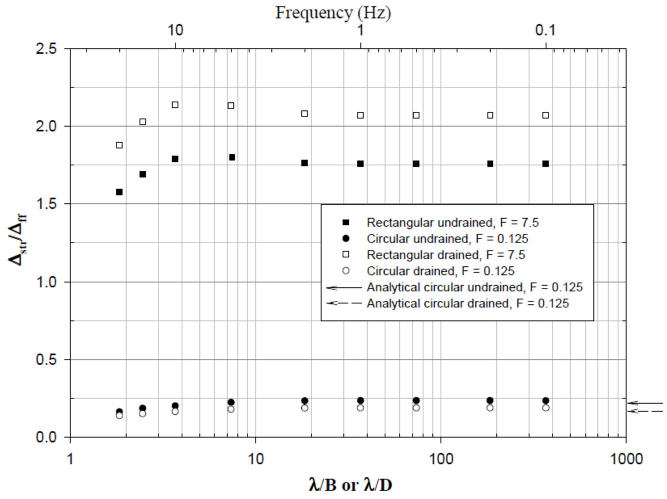


Figure 2. Effect of frequency on tunnel distortion

Figure 2 shows that the rectangular tunnel (F=7.5) has larger normalized distortions than the circular tunnel (F=0.125). This is expected because of the amplification of the deformations associated with a tunnel more flexible than the soil it replaces. The figure also shows that undrained loading, compared to drained loading, decreases the distortions of flexible tunnels, while increases those of stiff tunnels (the effect of drained/undrained conditions is discussed in the next two sections). At very low frequencies (high λ/D, λ/B ratios), where inertia effects are negligible, it is expected that the seismic results would converge to the static results. Indeed this is the case, as shown in Figure 2, where the analytical (static) results for circular tunnels (Bobet, 2010) are included as arrows on the right side of the figure. At very high frequencies (very low λ/D, λ/B ratios), normalized distortions have low values, even lower than those for the static case, then tend to increase up to a point, and decrease as frequencies decrease (as λ/D, λ/B increase). Beyond a λ/D or λ/B ratio of about 8 (input frequencies lower than 5-10 Hz, in this case), the results do not change with frequency, and so a pseudo-static analysis may be sufficient to estimate the dynamic distortions of a tunnel. Figure 2 only shows two cases, but similar results are obtained for a large number of cases that explore the effects of shape and stiffness (not included for clarity). Thus, similar to drained loading, the seismic response of tunnels located far from the epicenter of the earthquake, where it is expected that the ratio between the wavelength of the seismic ground motions and the size of the tunnel is larger than 8, can be approximated with a pseudo-static analysis.

Undrained Response of Circular Tunnels

A tunnel 8 m in diameter (D) with a liner 0.40 m thick is used for the analyses. The input seismic motions consist of a sinusoidal velocity with amplitude of 1 m/s, imposed at the bottom of the discretization, with a frequency of 1 Hz that, given the dimensions of the tunnel, corresponds to a λ/D ratio of 37. Both drained and undrained scenarios are considered. The tunnel distortions for a circular tunnel are obtained as the ratio between the change in diameter and the initial diameter, as shown in Figure 1.

Figure 3 shows the results of the analyses for a wide range of relative flexibility ratios, F, ranging from 0.025 (relatively very stiff tunnel) to 15 (relatively very flexible tunnel). The inset in the figure contains results for stiff tunnels, i.e. for $F \leq 1$. The tunnel distortions (maximum distortions, i.e. at peak amplitude of input velocity) are normalized by those of the free field; that is, the distortions of the ground obtained without the tunnel. For an elastic analysis, free field distortions can be computed using Equations 3 and 4, where γ_{ff} is the free-field shear strain, V_s is the input peak particle shear velocity, and C_s is the shear wave velocity of the ground.

$$\{(\Delta D_{ff}) / D\} = \{\gamma_{ff} / 2\} \qquad (3)$$

$$\gamma_{ff} = V_s / C_s \qquad (4)$$

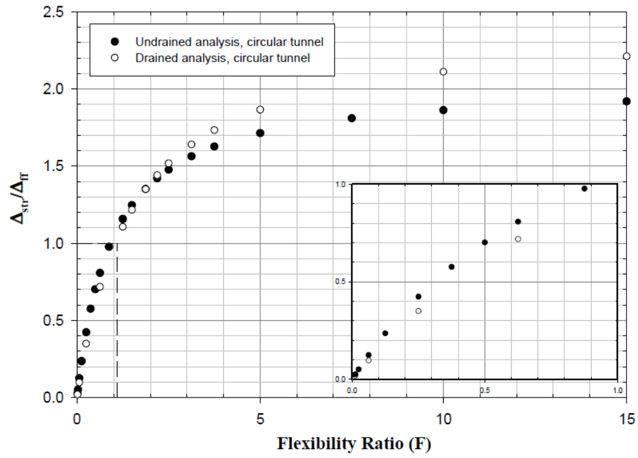


Figure 3. Normalized distortions for circular tunnels

It can be seen in Figure 3 that the higher the flexibility ratios, the higher the normalized distortions for both drainage conditions. This is expected because, as F increases, the tunnel becomes much more flexible than the soil it replaces. It also can be noticed in Figure 3 that the undrained loading increases (decreases) distortions of stiff (flexible) tunnels compared to those with drained loading**.** This conclusion**,** obtained from full dynamic analyses**,** is in good agreement with that found by Bobet (2010), who conducted a static analysis using analytical and numerical solutions.

Undrained Response of Rectangular Tunnels

Dynamic drained and undrained analyses are performed for rectangular tunnels. Two different tunnel shapes are investigated: one square, with dimensions 4x4 m, and one rectangular with dimensions 4 m high (H) and 8 m wide (B). These correspond to shape factors, β, equal to one and two, defined as the width to height ratio of the tunnel. All cases have a liner thickness of 0.40 m. As with the circular tunnels, a sinusoidal velocity is imposed at the bottom of the simulation with a frequency of 1 Hz and amplitude of 1 m/s. Table 1 contains the geometry of the tunnels as well as the λ/B ratio. The structure distortions are computed as the difference between the horizontal displacement of the upper and the lower slabs normalized with respect to the height (H), as shown in Figure 1; as with the circular tunnel, maximum distortions are considered. Figure 4 plots the results from the dynamic numerical simulations. The inset in the figure highlights the distortions of stiff tunnels. The tunnel distortions are normalized with respect to those of the free field, which for an elastic analysis are equal to the free field shear strain ((Δ_{ff} / H) = γ_{ff}).

Table 1. Geometry and λ/B ratios used for rectangular tunnels

Shape factor (β)	**Height, H (m)**	**Width, B (m)**	**Wave length (λ)**	**λ/B**
1	4	4	295	74
2	4	8	295	37

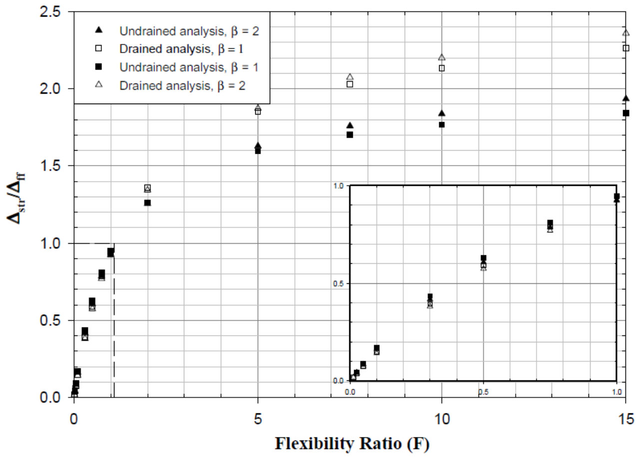


Figure 4. Normalized distortions for rectangular tunnels

The trends observed for rectangular tunnels are similar to those found for circular tunnels. As it can be seen in Figure 4, the higher the flexibility ratio, the higher the normalized distortions for both drainage conditions. For rectangular tunnels, and analogous to what is found for circular tunnels, the undrained scenario increases the distortions of stiff tunnels and decreases the distortions of flexible tunnels compared to the drained scenario. These observations are consistent with those reached by Bobet (2010) using static analytical and numerical models.

Discussion

Figure 5 compares results obtained from circular and rectangular tunnels under both drained and undrained loading. What is interesting is that there are no remarkable differences between the results from circular and rectangular tunnels for drained loading, except for flexible tunnels with flexibility ratios larger than 5, where normalized distortions increase from circular to square to rectangular tunnels. The trend is somewhat opposite for undrained loading, where a large influence of the tunnel shape is observed for both stiff and flexible tunnels, with the largest distortions corresponding to those of the circular tunnels. Overall, the differences are modest for both drainage conditions, which support the notion that the most important factor controlling the seismic deformation of a tunnel is its relative stiffness, rather than the shape of the opening.

Due to space limitations, excess pore pressure plots are not included (excess pore pressures are those induced in the medium to prevent volumetric deformations). However, it has to be pointed out that, during seismic loading, the magnitude of the excess pore pressures, and their distribution around the opening, depend on the relative flexibility ratio. For flexible tunnels, high positive excess pore pressures are produced. As a result, the effective stresses of the ground surrounding the tunnel are small compared to the drained case, hence smaller deformations are induced. For stiff tunnels, small positive excess pore pressures, or even negative excess pore pressures are produced. In this case, the effective stresses on the ground increase relative to the drained case, and so higher deformations occur.

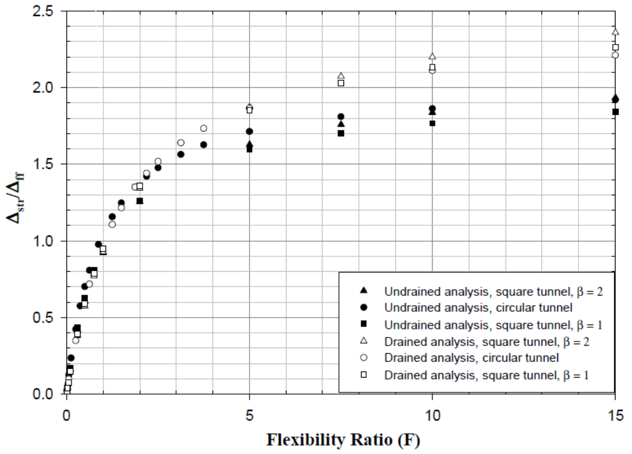


Figure 5. Effect of shape and relative stiffness on distortions for both drainage conditions

Summary and Conclusions

The paper explores the dynamic undrained response of circular and rectangular tunnels. Undrained response occurs in a saturated medium when the excess pore pressures generated are not dissipated quickly enough, which is the situation that may arise during an earthquake. A number of deep tunnels with different cross sections and relative stiffness are investigated using a dynamic numerical model. In the simulations, it is assumed that the behavior of the tunnel support and the ground remain within their elastic regimes and that the contact at the ground-structure interface is tied. Two scenarios are considered: drained and undrained loading.

Similar to the cases with drained loading, the effect of frequency on the seismically-induced deformations of the tunnel is negligible when the wave length (λ) of the seismic motions is at least 8 times the size of the tunnel opening. This is an important result since it supports the notion of conducting static analyses when the tunnel is far from the seismic source, where frequencies of the seismic motions are between 0.1 and 10 Hz (Dowding, 1985; Bobet, 2010).

The results of the undrained analyses show that for stiff tunnels the deformations are larger than those obtained for a drained analysis; and for flexible tunnels, the deformations are smaller. The reason for such behavior is found on the development of excess pore pressures. Excess pore pressures around the tunnel decrease and can even become negative as the tunnel becomes stiffer than the ground; hence, effective stresses in the ground increase, triggering higher deformations. The opposite occurs for flexible tunnels, where large positive excess pore pressures decrease the effective stress of the ground, and so the deformations decrease. The effect of tunnel shape is minor or even negligible compared to the type of loading, drained or undrained, and the relative stiffness of the tunnel with respect to the ground.

Although an elastic analysis is performed, and arguably may not correspond well with the actual behavior of soils, the results are relevant as they help understand better the interplay that exists between tunnel, ground and loading conditions. The results presented are part of an on-going research aimed at characterizing the response of underground structures in a saturated medium subjected to seismic loading.

Acknowledgments

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