ENGINEERING MODEL FOR THE SEISMIC RESPONSE OF BURIED TUNNELS

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ABSTRACT

This paper presents a modification of the methodology proposed by Constantoloulos et al.(1979) and generalized to other types of structures by Navarro (1992) for the seismic design of a tunnel buried in a granular backfill layer which, in turn, is on a rigid half-space. The method allows a static analysis of the tunnel and of the surrounding soil from the movements in the free-field seismic response. Two kinds of seismic waves are considered: shear waves and compression waves travelling vertically in the plane of the cross-section of the tunnel. The results obtained using the simplified method and those computed from a full-numerical modeling of the problem are compared.

KEYWORDS

Soil-structure; interaction; buried tunnels; simplified model.

INTRODUCTION

Buried structures such as tunnels, galleries, etc. subjected to earthquakes receive the various types of seismic waves that are propagated through the soil. The resulting displacements induced at points of the structure generate a state of stress in these structures which deserves consideration in their design. The phenomenon may be studied by a three-dimensional finite element modeling of the soil-structure system and a subsequent time domain analysis of the model using the statiscally independent seismic accelerograms.

To improve the analytical system, Constantopoulos et al (1979) developed a simplified method based on the fact that the tunnel movement is similar to that of the surrounding soil so that no soil-tunnel interaction need be considered. The main feature of this methodology is that the analyses required are static, using a set of loads that is equivalent to the dynamic actions themselves. The method was later extended by Navarro (1992) to other types of structure.

The analyses required in the Constantopoulos method are of two kinds: one longitudinal and the other transversal. In the former, the tunnel is modeled as an elastic beam joined by appropriate springs to the

surrounding field; the seismic waves considered are vertical Love and Rayleigh waves. In the transversal analysis, a cross-section of the tunnel is considered, the loads on it being pressures obtained from the stresses on the surrounding soil when the free field is submitted to the same dynamic action; the seismic waves considered are the vertical shear and compression waves and the horizontal Raleigh waves.
In this paper, considering the shear and compression waves, an alternative methodology is proposed for the horizontal analysis of buried structures, based on the use of static models in which soil movements are imposed derived from the free field movements.

DYNAMIC BEHAVIOUR OF THE TUNNEL-SOIL FORMATION

To measure the soil-tunnel interaction in terms of displacement, a detailed modal analysis was made, and for purposes of comparison a set was obtained of the seismic response spectra at different points of the tunnel and of the surrounding soil.

Modal analysis.

The frequencies and mode shapes of the soil-structure were obtained from a two-dimensional finite element model in plane strain of 100 m length and a height (depending on the stratum) varying between 12 m and 20 m. The lower edge of the model is fixed, assuming a rock foundation, with an elastic modulus far higher than that of the stratum considered. In the centre of the model, and at different depths, is placed a cross-section of the tunnel of various side measurements between 2 m and 5 m. The surrounding soil was discretized in a square mesh with nodes 0.5 m. apart, using rectangular elements of four nodes and two degrees of freedom per node. The cross-section of the tunnel was represented by beam elements defined by the thickness of the walls. For the finest possible adjustment of the displacements, incompatible modes were suppressed.

A first conclusion from the analyses is that the frequencies and mode shapes of the soil modes are hardly affected by the presence of the tunnel. Table 1 shows the case of a tunnel of 2 m by 2 m at a depth of 2 m in a stratum of 12 m thickness with a elastic modulus of 50 N/m^2, where the frequencies of the first six modes show the scant effect of the tunnel on the dynamic behaviour of the soil-tunnel system.

Table 1 - Frequencies and Modes. 12 m Stratum (E = 50 N/m^2)

Cross-section of the tunnel 2 m x 2 m at a depth of 2 m		
Frequency (Soil-tunnel)	Mode	Frequency (Free field)
1.948	Horiz.	1.946
2.102	Vert.	2.099
2.495	Hor./Ver.	2.490
2.999	Hor./Ver.	2.983
3.428	Hor./Ver.	3.425
3.704	Hor./Ver.	3.689

The first mode is horizontal in all the cases analysed, the second vertical, and from the third the modes are mixed, the tunnel accompanying the movement of the soil with small turns. From the third mode on, the participation factors are low, so in subsequent analyses, only the first two, taken separately, are considered.

Table 2 shows the frequencies of the first mode in strata of 12 m, 16 m and 20 m thickness, in two types of material (a soft soil with an elastic modulus of E=50 N/m^2 and a hard soil of E=300 N/m^2), and square sections with walls of 2 m, 3 m and 5m at different depths. The Table also gives the free field frequencies, and shows the scant influence of the size and position of the tunnel on the dynamic behaviour of the soil-tunnel system, at least within the limits of the study.

Table 2. First Mode Frequenties for Different Layers and Cross-Sections

		LAYER, H=12 M			LAYER, H=16 M			LAYER, H=20 M			
		DEEP		FREE-FIELD	DEEP		FREE-FIELD	DEEP			FREE-FIELD
SOIL	SECTION	2 M	4 M		8 M	10 M		2 M	12 M	14 M	
	2*2	1.984	1.949		1.463	1.464		1.141	1.171	1.171	
SOFT	3*3	1.951	1.953	1.964	1.467	1.462	1.461	1.143	1.170	1.170	1.169
	5*5	1.973	1.967		1.469	1.468		1.180	1.175	1.174	
	2*2	4.768	4.766		3.578	3.576		2.795	2.860	2.861	
HARD	3*3	4.770	4.762	4.766	3.571	3.561	3.578	2.800	2.853	2.851	2.863
	5*5	4.775	4.727		3.534	3.527		2.882	2.831	2.830	

Even though, as already stated, the presence of the cross-section of the tunnel in the soil has very little influence on the frequencies and mode shapes, this influence has been objectified. comparing separately for the first two modes, the mode shapes in free-field conditions and in presence of the tunnel. From these comparisons a distance d from the axis of the tunnel has been determined, which defines an influence zone of the modal displacements due to the presence of the tunnel. The criterion established for the determination of this zone of the influence is that the tunnel presence does not affect at point P in the surrounding soil when

$$\delta_t - \delta_{FF} \cdot / \delta_{FF} < 0.05 \qquad (1)$$

being δ_t the modal displacement at point P when the tunnel is present and δ_{FF} the modal displacement in the free-field condition.

The zone of influence is restricted in general terms to a border area along the vertical sides of the cross-section of the tunnel, similar in width at the top and the bottom. When the tunnel is close to the rigid half-space, it suffers a small bend due to the fixed edge but also dependent on the elastic characteristics of the stratum (greater at higher elastic modulus). This means that two inclined border areas appear in the influence zone below the cross-section of the tunnel. Distance d is defined as the horizontal distance from the centre of the tunnel to the outer edge of the influence zone, delimited by the horizontal lines passing through the corners of the cross-section of the tunnel. In the case of the horizontal movement (first mode), Figs. 1 and 2, using different layer thicknesses (12 m, 16 m and 20 m) and different tunnel sizes (3 m and 5 m), show graphs d-q-E, in which d is the influence distance, q the distance between the lower edge of the tunnel and the rigid layer, and E the elastic modulus of the soil.

Spectral analysis.

The importance of the soil-tunnel interaction is also analysed in the frequency domain using the FLUSH code (Lysmer et al., 1975). These analyses confirm the results of the modal analysis. Figure 3 compares the horizontal response spectra at points A and B of the cross-section of the tunnel for horizontal excitation with those obtained at the same points in free-field conditions. They are seen to be very similar, with maximum differences of less than 10% - 12% near the natural frequency of the layer. In the spectra of vertical excitation, the differences are even smaller.

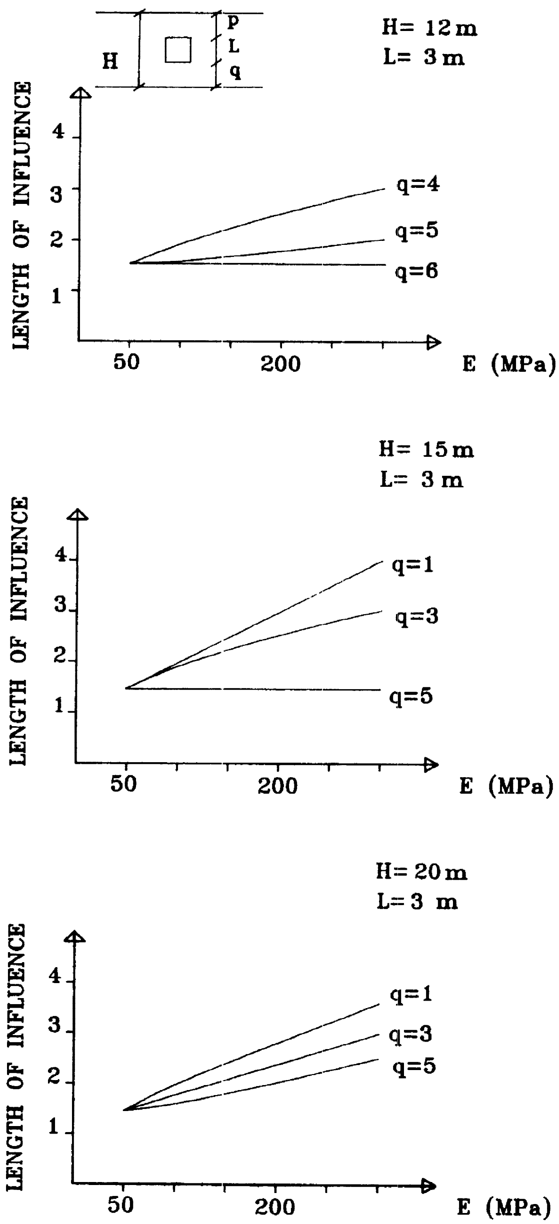

Fig. 1. Lenght of influence for cross-section of side 3 m.

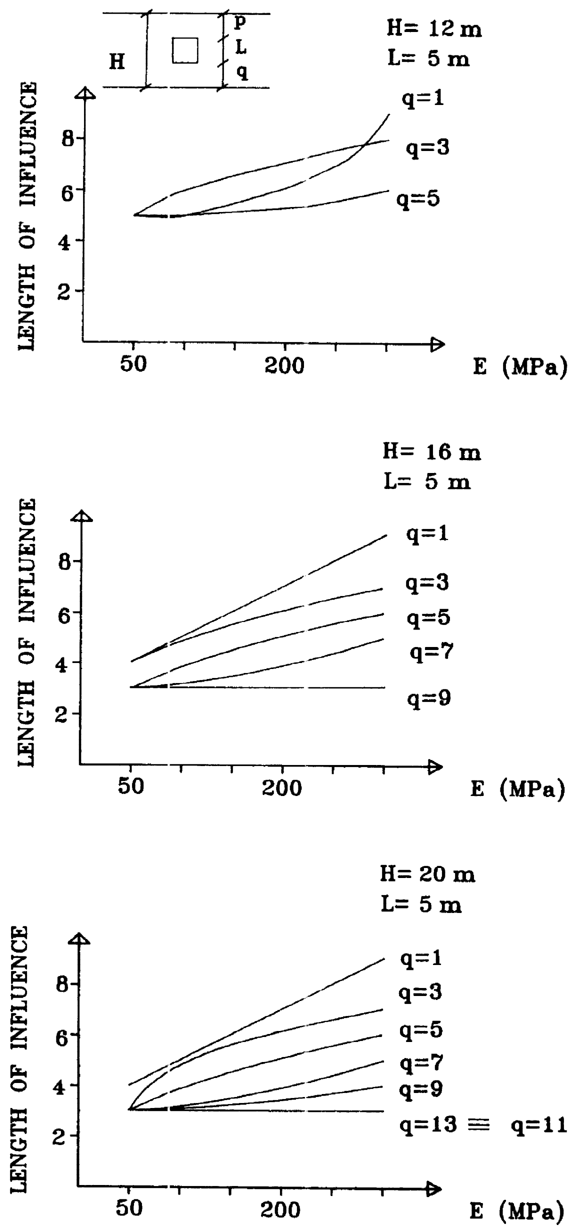

Fig. 2. Lenght of influence for cross-section of side 2 m.

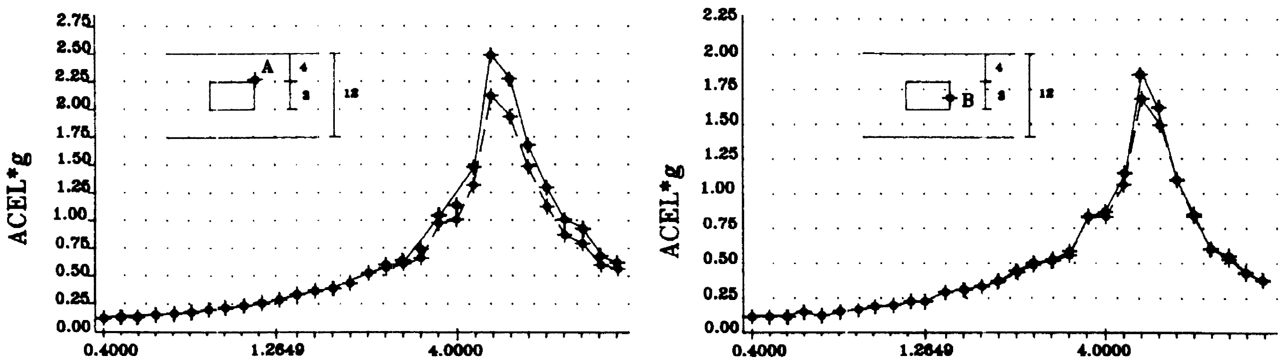

Fig.3. Horizontal response spectra at points A and B (continous line) and at its level in free-field condition (dotted line). Damping ratio 5 %.

PROPOSED METHODOLOGY

Seismic input.

The seismic action on the soil-tunnel system that has to be considered is the effect of two earthquakes, one horizontal and the other vertical, but statistically independent. The response of the structure can also be obtained by a spectral modal analysis, taking two independent spectra (horizontal and vertical), obtained by scaling the official spectra (Regulatory Guide 1.60, etc) or adjusting them to the characteristics of the soil and of the expected earthquake.

Horizontal movement.

The study of the horizontal movement is made in two stages: first a dynamic analysis of the free field and then the static analysis indicated in the following paragraphs.

Free-field analysis. From the dynamic analysis of the soil profile (free-field situation), using the time-history (accelerograms,...), the maximum displacements at each node may be obtained for example as follows. First, the angular deformations (γ_{xy}) may be obtained from the shear stresses. Longitudinal deformations may be considered null since the normal stresses are null because the movement is horizontal . So the horizontal displacements related to the mesh nodes are only due to angular deformations according to the expression

$$\Delta l = \gamma_{xy} h \qquad (2)$$

where h is the difference between the height of the nodes on the same vertical. The accumulation of these relative displacements gives the absolute horizontal displacements at the nodes of the mesh. If a spectral modal analysis is made, it is possible to obtain directly the maximum horizontal displacements of the nodes.

Static model. Once the influence distance d is known for a specific case, a static model is defined, composed of a section of the surrounding soil, of horizontal dimension of 2*d and a vertical dimension corresponding to the thickness of the stratum, the base being fixed. The section of the tunnel, defined by beams in accordance with the thickness of the walls (Fig. 4), is placed in the centre of the model. The only load on the model, consists of horizontal displacements imposed by axial forces on the boundary nodes, equivalent to those obtained in the free field. The axial forzes imposed on the nodes are

$$N = E\Omega\delta / L \qquad (3)$$

where Ω, L and E are the section, the length and the elastic modulus assigned to the "truss" element, and δ the displacement to be imposed on the node. If the truss elements are defined with a sufficiently high rigidity in relation to that of the surrounding soil, they will absorb completely the N axil. There are codes, however, such as the ANSYS that allow direct introduction of the free field displacements.

<u>Vertical movement</u>.

Here again, the study is in two stages, although in this case the correct introduction of the vertical movements in the static model requires a definition of the mode shapes of the surrounding soil with the cross-section of the tunnel and a scaling of this with the vertical movement obtained in the free-field.

<u>Free-field analysis</u>. From the dynamic analysis of the soil profile (free-field situation), using the time-history (accelerograms,...), the normal stresses are obtained, and hence the longitudinal vertical strains (ε_y). Angular deformations may be considered null since the tangential stresses come from a vertical movement. The vertical displacements in the nodes of the mesh are therefore due only to vertical strains according to the expression

$$\Delta l = \varepsilon_y h \qquad (4)$$

where h is the difference in the height of the nodes on the same vertical. Accumulating the relative displacements one can obtain the absolute vertical displacements at the nodes of the mesh. As stated earlier, a spectral modal analysis gives directly the maximum vertical displacements of the nodes.

<u>Static model</u>. Once the influence distance d is known for a specific case, a static model may be defined, composed of a section of the soil of horizontal dimension 2*d and vertical dimension according to the thickness of the layer, the base being rigid. A section of the tunnel, defined by beams in accordance with the thickness of the walls (Fig.5) is placed in the centre of the model. Using "truss" elements, the only load introduced at the top and sides of the model consists of the modal vertical displacements of the soil with the tunnel (second mode), those of the top edge of the soil scaled with the vertical free field displacement. The code may allow these to be introduced directly.

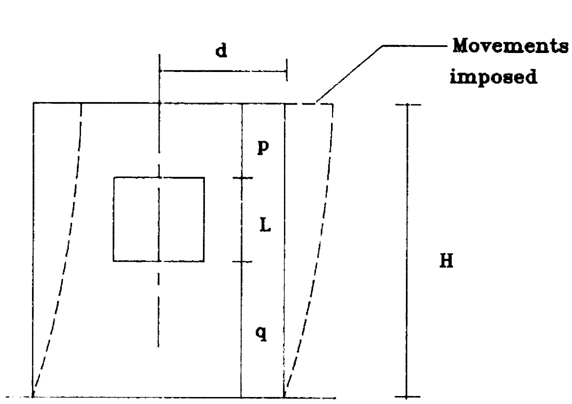

Fig.4. Estatic model for horizontal movement

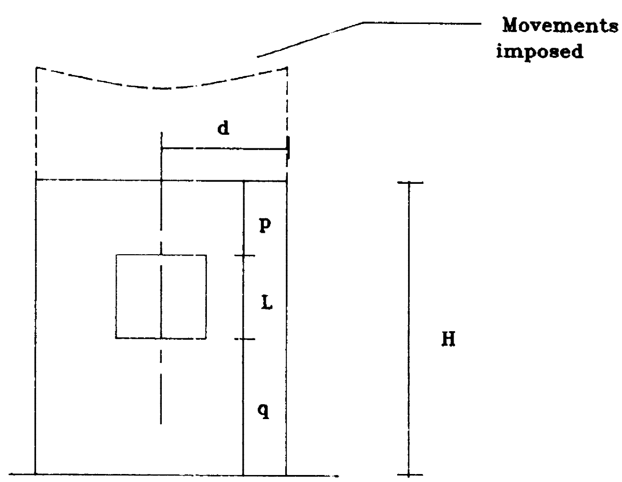

Fig.5. Estatic model for vertical movement

APPLICABILITY OF THE PROPOSED METHODOLOGY

Checks of the usefulness of the proposed methodology have been made in several cases of layers of thicknesses between 12 m and 20 m and of variable elasticity, with concrete cross-section of the tunnel measuring between 2 m and 5 m placed at different depths in the soil.

Two cases are presented here of strata subjected to horizontal movement as defined by the horizontal spectrum of the Regulatory Guide 1.60, scaled to 0.15g. The features of the two cases are shown in Table 3. In each one, a spectral modal analysis is made of the soil-tunnel system, and a simplified static analysis, considering the distances d obtained respectively in Figs. 1 and 2. These distances are d=1.5 m for the 3 m cross-section of the tunnel and d=5 m for the 5 m cross-section of the tunnel. However, in the first case a distance of d = 2 m is adopted, giving a soil margin of 0.5 m at each side of the section.

Table 4 shows the stresses (axil force and bending moment) at the weakest points (upper and lower corners) in both the dynamic and static analyses of the cases under study. Considering the most sought after (in these cases the lower corners) since the reinforcement of these structures, given their small size, would be uniform, it is seen that in case B the static analysis gives stresses slightly above those in the dynamic analysis. In case A, the stresses in the static analysis would have to be multiplied by 1.17 to give those of the dynamic analysis.

In all the cases analysed, whether of horizontal or of vertical excitation, the coefficient required to multiply the static analysis stresses to obtain those of the dynamic analysis is below 1.3, even at the least favourable point. So it would seem that a coefficient of K=1.5 applied to the simplified static analysis proposed here is amply sufficient to cover the stress state obtained from a complete dynamic analysis of the soil-tunnel system.

Table 3. Characteristics of the cases under study.

	Layer (H)	Section (L)	Width (e)	Depth of the tunnel (p)	Elastic Modulus (E)
CASE A	20	5m*5m	0.5m	8m	300N/m^2
CASE B	12	3m*3m	0.3m	2m	75N/m^2

Table 4. Axial forces and bending moment obtained in the cases under study.

		Upper Corner		Lower Corner	
		Axil Force (N)	Bending M. (Nm)	Axil Force (N)	Bending M. (Nm)
CASE A	Dynamic Analysis	0.232E6	0.343E6	0.290E6	0.390E6
	Static Analysis	0.170E6	0.253E6	0.216E6	0.335E6
CASE B	Dynamic Analysis	0.041E6	0.089E6	0.055E6	0.104E6
	Static Analysis	0.029E6	0.066E6	0.054E6	0.108E6

CONCLUSIONS

The article presents a simplified method for the seismic design of buried structures. The methodology is a modification of that proposed by Constantopoulos et al.(1979).

Even though it is accepted that with an earthquake the movement of the structure is similar to that of the surrounding soil, the seismic influence is objectified, and the distance of this influence is determined separately for the first two modes, the presence of the structure having no practical importance beyond this distance.

The analyses made from the static model, in which free field displacements at certain distances of influence are introduced, show that the stress state is similar to that obtained from dynamic analysis. In any case, this is guaranteed by the application of a coefficient of K=1.2-1.3.

REFERENCES

Gómez Masso, A. and Atalla, I. (1984). Finite Element versus simplified methods in seismic analysis of underground structures. Earthquake Engng. Struc. Dyn. 12:347-367.

Constanttopoulos, I. V. et al. (1979). Dynamics analysis of tunnels. Proc. 3rd. Inf. Conf. Num. Meth. Geomech.

Constantopoulos, I. V. et al. (1980). Seismic analysis of buried tunnels. Proc. 7th. World Conf. Earthquake Engng.

Cristiano, P. P. et al. (1983). Response of buried tunnels to earthquake excitation. Trans. 7th. Int. Conf. Struct. Mech. Reactor Technology, Vol. K:287-294

Navarro, C. and Samartin, A. (1988). Simplified longitudinal analysis of buried tunnels. Software For Engng. Workstations 4 : 3-10.

Navarro, C. (1992). Effect of adjoining structure on seismic response of tunnels. Int. J. Num. Anal. Meth. Geomech.

Navarro, C. (1992). Seismic analysis of underground structures. Proc. 10 th. World Conf. Earthquake Engng.

UNSNRC. Regulatory Guide 1.60. Desing response spectra for seismic desing of Nuclear Power Plants.