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Procedure for the seismic analysis of reinforced concrete tunnels using the finite elements method

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Abstract: Considering the sensitivity of reinforced concrete tunnels moving on soft soil foundations to earthquake action, some degree of damage to earthquake action, and the uncertainty of tunnel dynamic performance under earthquake action, an analysis procedure based on the finite element method is proposed, which considers ground deformation caused by earthquake action. The analysis can obtain the stress-strain states produced in the tunnel structure as a consequence of the seismic action, which are compared with the kinematic procedure for the seismic analysis of tunnels.

Key words: tunnel; soft soil; seismic analysis; spring; displacements; parameters

1 Introduction

At present, many tunnel damage cases have been recorded, either due to collapse or lining cracking. Authors such as Asakura et al. (1998), El Nahhas et al. (2006), Kontogianni and Stiros (2003), Lanzano et al. (2008), Wang et al. (2001), Yashiro et al. (2007) emphasized the vulnerability of tunnels to seismic events.

Although underground structures are less vulnerable than surface structures to earthquake movements, it is still necessary to ensure their safety in ground earthquake movements (Avilés and Shimon Pérez, 2014). This is because these structures are limited by the surrounding medium, so they are unlikely to move significantly without being affected by the environment, or to be subjected to amplification of vibration produced by seismic waves (Dowding & Rozen, 1978).

For this reason, for a long time, the design and construction of most tunnels did not consider the impact of earthquakes. It was not until the 1960s that seismic design programs were first included in underground projects (Wang, 1993).

In recent years, various studies have been conducted to determine the factors that affect the performance of underground structures (Wang, 1993), successfully establishing seismic design concepts for tunnels, with the aim of enabling the structure to withstand displacement or deformation loads applied to it (González, 2016).

The design methods of underground structures currently used are mainly based on quantitative analysis methods, because the development of element or finite difference model software has led to new tools for evaluating the seismic response of these structures (Solans et al., 2014).

2 Materials and methods

The research comprised the following phases:

·The historical evolution of research related to the dynamic analysis of reinforced concrete tunnels under seismic loads. In addition, the current trends and existing methods and tools for dynamic analysis of such structures were identified and evaluated.

·Identify and select parameters that characterize the dynamic performance of reinforced concrete tunnels in soft soil under earthquake action.

·A finite element based program has been proposed for the dynamic analysis of reinforced concrete tunnels on soft soil foundations in areas with medium and high seismic danger in Cuba.

3 Results

Based on the proposed procedure, which allows obtaining response parameters, such as stress, deformation states and resultant forces, it is possible to evaluate the dynamic behaviour of reinforced concrete tunnels in soft soil, located in areas of medium and high seismic hazard in Cuba, as well as to characterise their dynamic response to seismic actions, in addition to serving as a tool in the development of disaster prevention and mitigation plans involving this type of structures.

Since the design action of underground structures is usually represented by the deformation imposed on the structure by ground motion, Avilés and Pérez (2014) developed a method of dynamic interaction between soil and tunnel structure. They also developed design standards based on the calculation of static values of shear and bending moment values, multiplied by amplification factors that consider the dynamic effect of the soil.

Among the various methods used for tunnel design, the simplest one is to ignore the interaction between the tunnel and the surrounding soil. Under these conditions, first estimate the terrain deformation in the free field, and then design tunnels to adapt to these deformations.

Then, a program for analyzing the structure of soft soil tunnels was proposed, which is based on the finite element method to establish a calculation model. The model considers the longitudinal and transverse deformation of the structure and the flexibility of the soil. This flexibility is introduced through the use of the concept of elastic springs, which can connect the geometric shape of the tunnel with the surrounding environment. On the basis of these springs, a soil free field seismic displacement relative to the structural foundation is applied to represent seismic action.

Overall, the proposed program consists of three basic stages: (1) deriving the maximum topographic displacement and estimating the axial and lateral stiffness of the soil; (2) establishing a computational model based on the use of finite elements; (3) control status service restrictions and failures.

In the first phase or stage of the procedure, the maximum ground displacement is derived (equations 1 and 2) and the axial and lateral stiffness of the soil are estimated (equation 4), based on the simplified procedure of Avilés and Pérez (2014) for the design of tunnels in soft soil.

(1) Axial deformation:

(2) Flexible deformation:

The effective propagation speed is determined according to equation 3, which depends on the values of soil sedimentation depth and soil dominant period.

(3) The dominant wavelength can be reasonably estimated using Equation 4.

(4) The deformation and curvature coefficients of the terrain can be obtained from Table 1 based on the wave types considered.

Table 1.Terrain deformation and curvature coefficient

Type of coefficient	S-waves	P-waves	Rayleigh waves
	2	1	1
	1	1.6	1

The axial and lateral stiffness of the soil per unit of tunnel length is determined according to equation 5.

In the second phase or stage of the process, with the help of professional software SAP2000 V20.2.0, a mathematical model was established considering the invariant of mechanical modeling and structural analysis (geometry, materials, applied loads and the connection between the structure and the ground). At this stage, based on the stiffness values defined in the previous step and the application of axial and bending deformations, the concept of elastic springs is introduced into the structure to simulate the connection between the structure and the surrounding environment.

To determine the state of the applied load, it is recommended to use the recommendations of the "AASHTO Code" (National Association of Highway and Transportation Officials, 2017).

In the third stage, considering the control of service and fault limit states, the maximum displacement caused by the implemented actions was reviewed. In addition, the limit states of bending, bending compression, shear force, torsion, buckling, and the effects of fatigue were also examined.

3.1 Program validation--case study

To validate the program, an elliptical tunnel was modeled based on the following data:

· Seismic parameters: maximum terrain acceleration, maximum terrain velocity.

· Geotechnical parameters: soil dominant period, effective propagation velocity, soil shear modulus, soil Poisson's coefficient, and soil density.

· Structural parameters: burial depth, tunnel length, tunnel inner diameter, lining thickness, concrete elastic modulus, and concrete Poisson's coefficient.

Phase 1: Determine the maximum terrain displacement and estimate the axial and lateral stiffness of the soil

Based on the simplified program of Avilés and Pérez (2014), the terrain displacement values (equations 1 and 2) and spring stiffness (equation 5) were determined.

-Maximum ground displacement for axial deformation:

- Maximum ground displacement for bending deformation:

- Axial and lateral stiffness of soil:

Phase 2: Development of the calculation model

The development of the calculation model used professional software SAP2000 V.20.2.0, which can approximate the geometric structure of the tunnel and affect the supporting medium by including elastic springs and all possible load states.

3.2 Actuating loads

When establishing the calculation model, the following load states were considered: structural self weight (DC), ground vertical thrust (EV), ground horizontal thrust (EH), surface live load, horizontal component of surface live load, seismic action (EQ), static load caused by tunnel backfilling, and live load caused by tunnel transit. The load combinations to be used are defined in the AASHTO specifications (American Association of State Highway and Transportation Officials (AASHTO), 2017).

3.3 Seismic action model

Fig. 1 depicts the geometric cross-section of the tunnel, which was developed using finite element method and connected to the surrounding environment (soil) through elastic springs (Fig. 2) to simulate the interaction between the structure and soil. In addition, it can also be observed how the free-field seismic displacements of the soil, relative to the base of the structure, are imposed at the base of the horizontal springs.

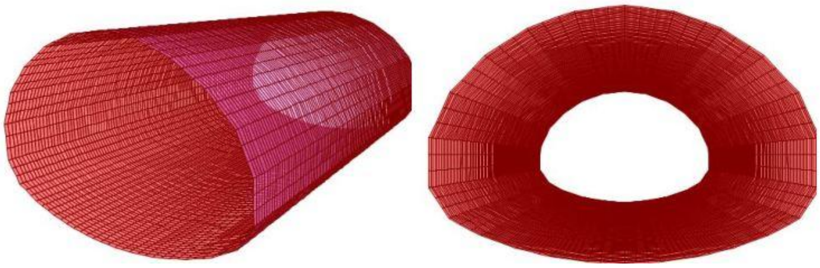

Fig. 1. Geometric representation of tunnels

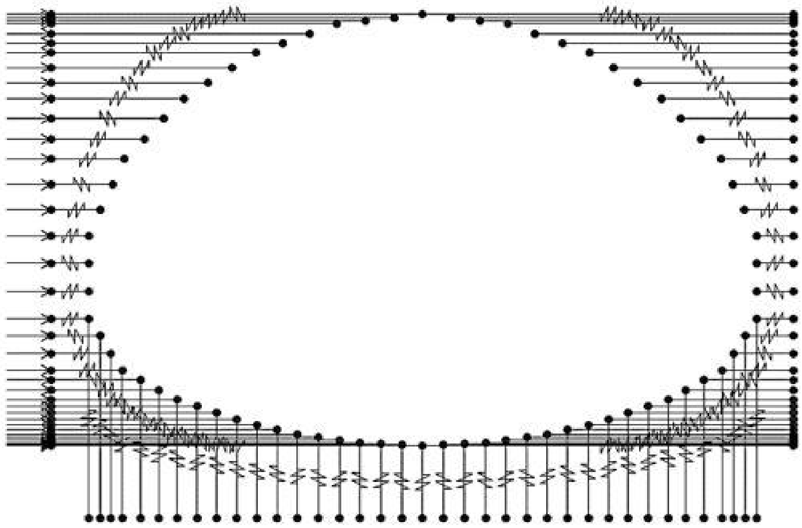

Fig. 2. Schematic diagram of seismic displacement distribution

The spring on the right side of the tunnel should be a fixed support rather than a sliding support, while the spring on the left wall should be seismic displacement. If the direction of the maximum acceleration is opposite, the fixed bracket will be applied to the spring on the left wall, while the seismic displacement will be applied to the bottom of the right spring in the opposite direction.

3.4 Result analysis

Due to modeling, in addition to evaluating the bending and elliptical deformation caused by earthquake action, stress and reaction can also be used to express the response of the structure to the applied load state.

Table 2 shows a comparison between some of the results derived from the application of the proposed method, with respect to the simplified procedure proposed by Avilés and Pérez in 2014. Variations ranging between 15% and 20 % are observed, which can be considered adequate if the complexity of the model performed is taken into account.

Table 2. Result comparison

Description	u/m	Avilés and Pérez (2014)	SAP2000	Dif. (%)
Maximum circumferential normal force	kN	1432.4	1690.23	18.0
Maximum circumferential bending moment	kN-m	883.7	748.845	15.3
Maximum shear force generated by bending	kN	24769.9	29448.6	18.9

Maximum axial force corresponding to longitudinal deformation	kN	143443	172131.1	20.0
Maximum bending moment corresponding to longitudinal deformation	kN-m	985564	831955	15.6

4 Conclusion

Based on the finite element method (MEF) modeling and combined with the soil structure iteration effect, the results proposed by Avilés and Pérez (2014) were validated with good numerical approximations.

The results obtained from the MEF model are consistent with typical faults observed in such structures under significant seismic events. In addition, critical points of stress and deformation concentration were found in the areas with obvious faults described in the literature.

This program is applicable to various location conditions, support conditions, and depths of tunnels, which achieves higher accuracy in determining structural response, enabling structural analysis of tunnels with highly complex geometric and soil conditions.

This program integrates the two most commonly used methods in underground structure evaluation: free-field deformation method and the soil-structure interaction method.

Conflicts of interest

The author declares no conflicts of interest regarding the publication of this paper.

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