Nonlinear static analyses for the seismic design of shallow tunnels

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Abstract

This paper introduces and validates a novel method for evaluating seismic-induced internal forces in the lining of a shallow circular tunnel. The method employs a static nonlinear analysis, typically used for structural systems, applied specifically to tunnels. In this decoupled approach seismic demand is represented by an elastic response spectrum, while seismic capacity is determined by applying horizontal static forces to the same numerical plane strain model used for the static design. The study outlines the key steps of the method and its effectiveness by comparing the results with time-domain dynamic analyses of the soil-tunnel model.

1. Introduction

In recent years there has been a growing awareness of the importance of seismic actions on tunnels, stimulated in part by damage to several underground structures during moderate to high intensity earthquakes. In current practice the seismic forces acting on the tunnel lining are assessed using rather simplistic methods that model the soil-lining interaction by linear springs connecting the lining to the free-field soil motion. More accurate methods would require time-domain dynamic analysis using full numerical models, but the relative complexity and cost are often impractical for standard projects. Therefore, this paper describes a decoupled design approach developed by the authors, as an intermediate complexity method exploiting the common static analysis performed to reproduce the construction sequence of the tunnel. In the method the seismic capacity of the system is represented by its capacity curve, derived from nonlinear pushover analysis of the soil-tunnel model. Then, the seismic demand is described by the elastic response spectrum of the considered action, modified to account for the tunnel's depth. The system performance is ultimately evaluated by comparing the demand and capacity on the acceleration-displacement (AD) response spectrum.

2. Case study

An idealized case, depicted in Figure 1, was developed to validate the method, described through a plane strain finite element model within the open-source analysis framework OpenSees [1]. The system's geometry consists of an 80×60 m soil domain, with a tunnel situated at a depth of 30 m. The tunnel has a diameter of 7 m, and its reinforced concrete lining is 0.5 m thick. This replicates a typical TBM-excavated urban tunnel.

The finite element grid was generated using a parametric mesh creator developed within the MATLAB framework. The soil domain was modeled using 4-noded stabilized single-point integration elements (SSPquad), and the soil mechanical behavior was simulated using an elastic-plastic constitutive model with kinematic hardening, known as PDMY [2]. The tunnel lining was discretised by two-noded elements characterized by linear elastic behavior (ElasticBeamColumn).

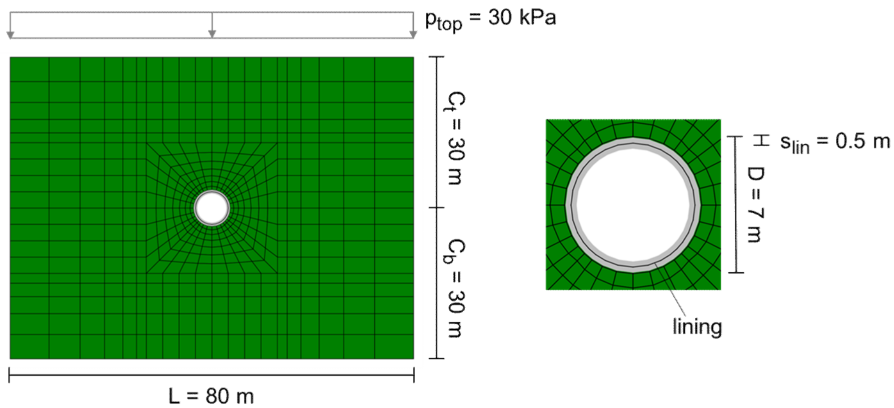

Figure 1. Finite element discretization of the reference model.

3. Capacity curve and seismic demand

In alignment with the Capacity Spectrum Method [3] for nonlinear static analysis of structural systems, this method derives independently the seismic capacity and demand, subsequently comparing these components on the AD plane. The capacity curve of the soil-tunnel system is derived by applying horizontal inertial forces incrementally to the numerical model, whose initial condition corresponds to the end of construction of the tunnel lining. The force distribution is assumed to be proportional to a uniformly distributed acceleration of amplitude $k_H \cdot g$ (g being the acceleration of gravity), that was see to reproduce with sufficient accuracy the deformation pattern associated with the first vibration mode of the system. In the pushover analysis the seismic coefficient k_H is gradually increased until a global plastic mechanism is activated. The capacity curve for the system at hand is shown in Figure 2a, where k_H is plotted as a function of the horizontal displacement d computed at the tunnel crown. Additionally, for each k_H, the pushover analysis provides the distribution of seismic-induced increments in internal forces across all lining sections. Figure 2a shows such increments in bending moment, normal force, and shear force in three lining sections of interest.

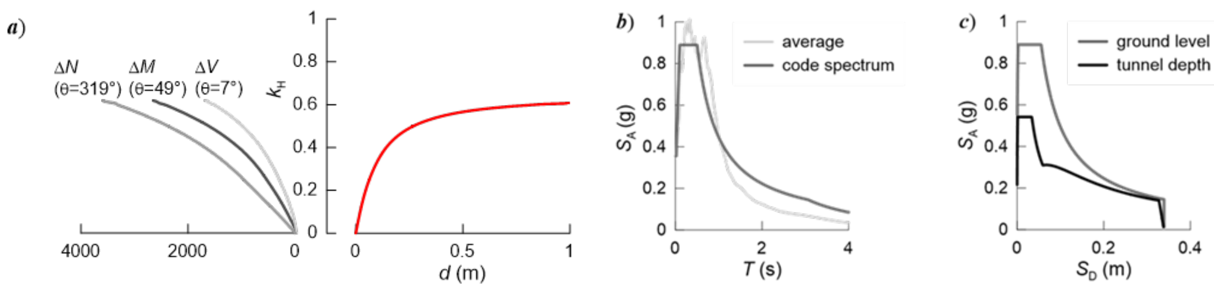

Figure 2. a) pushover curves in terms of displacement and seismic-induced increase of internal forces in the sections of interest; b) 5%-damped average elastic response spectrum at the ground level and interpolation with the Eurocode 8 shape; c) comparison between the AD spectrum considering or not the effect of the reduction factor β_D (tunnel depth and ground level, respectively).

In the validation of the proposed method, the seismic demand is represented by the average response spectrum at the ground surface. The latter was obtained by propagating eight selected accelerograms through a one-dimensional soil column that replicates the stratigraphic profile of the investigated deposit. This average spectrum, illustrated in Figure 2b, is interpolated using the spectral shape provided by Eurocode 8. Considering that the analysis focuses on the internal forces within the tunnel lining, it is essential to obtain the seismic demand at the tunnel depth. Figure 2c shows this adjustment, achieved by multiplying each point of the AD spectrum by the corresponding value of the reduction factor β_D, which accounts for the effect of the tunnel depth.

The reduction factor was obtained in analogy with the provisions of Eurocode 8 for retaining structures.

4. Implementation and validation

In the proposed method, the system performance is identified by the intersection of the seismic capacity and demand in the AD plane (performance point). In doing so it is necessary to adjust the elastic response spectrum to consider a damping ratio representative of the level of mobilised strength in the soil for the considered seismic scenario. This process begins with plotting the response spectrum for an initial damping ratio (e.g., $\xi = 5\%$). The latter is then evaluated assuming a Masing-type uloading-reloading rule and the resonse spectrum is iteratively modified until convenrgence on the damping ratio is achieved. The acceleration at the performance point is subsequently used in the nonlinear static analysis to determine the internal forces in the lining sections. The design procedure was validated by comparing the force increments obtained in the lining sections of interest with those derived from nonlinear time-domain analyses of the soil-tunnel model applying to the base the same accelerograms used to derive the average response spectrum. As shown in Figure 3b, the simplified approach slightly overestimates the bending moment; on the other hand, shear and normal forces are somewhat underestimated. Despite these discrepancies, the agreement between the two methods is considered satisfactory, given the simplicity of the proposed design approach.

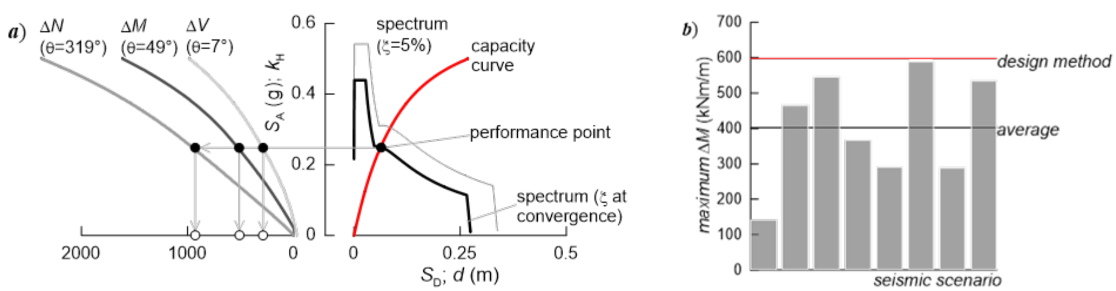

Figure 3. a) layout of the method implementation and b) reperentation of the maximum seismic bending moments in the lining obtained with time-domain dynamic analyses (gray bars), their average (black line) and using the proposed method (red line).

5. Conclusions

The proposed method regards seismic action as an equivalent static action, extending traditional design analyses related to construction phases. This approach allows for the design of the system without the need of time-domain dynamic analyses, whereas still accounting for the nonlinear behavior of the soil-tunnel system. The present study demonstrates that the method predicts earthquake-induced lining forces quite satisfactorily, specifically for the case of a shallow circular tunnel.

As a future development, the method will be utilized in a parametric study to enhance its general applicability and to facilitate the creation of design charts.

References

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