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PROBABILISTIC SEISMIC DEMAND MODELS FOR THE ASSESSMENT OF UNDERGROUND STRUCTURES

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Abstract

Underground structures (e.g., tunnels, subway stations, underground parking lots, etc.) are increasingly constructed in seismic-prone areas to facilitate the expanding needs of modern societies. The significant downtimes and the accompanying costs associated with seismically induced damage to underground structures led to an increasing interest of the scientific community in the vulnerability assessment of this infrastructure against the seismic hazard. In addition, the performance-based design of new underground structures against seismic hazard has also gained increased attention from practitioners. A critical step in both design and vulnerability assessment of tunnels and underground structures is the development and use of rational Probabilistic Seismic Demand Models (PSDM), which describe the relationship between the amplitude of seismic hazard and the seismic response of the examined structure. Various approaches have been proposed in the literature to develop PSDMs for the assessment of tunnels or underground structures, e.g., subways, against ground seismic shaking and seismically induced ground failures. This paper discusses critical aspects of these approaches, based on a thorough review of the relevant state-of-the-art. Emphasis is placed on the modeling approaches proposed to simulate the seismic response of the structure and the surrounding ground, the determination of the seismic capacity of underground structures, as well as the selection of adequate intensity measures to describe the severity of the seismic hazard. In addition to the review of the existing literature, an effort to propose novel PSDM models for the assessment and design of circular tunnels is presented, based on an ongoing extended numerical study carried out in the frame of research project INFRARES (www.infrares.gr). The discussion highlights acknowledged gaps in the field, and topics calling for further investigation are presented.

Keywords: Tunnels; PSDM; Seismic vulnerability; Seismic Resilience

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1 INTRODUCTION

Tunnels, subways and large embedded structures, such as underground parking lots, are constructed at an increasing rate in seismic prone areas, to facilitate the expending needs of modern societies. Their importance highlights the need for a rigorous seismic design (i.e., for new structures), as well asadequate assessment of their current condition and their vulnerability against seismic hazard (i.e., for existing structures). Various methodologies have been presented in the recent literature for the seismic analysis, design and vulnerability assessment of tunnels and underground structures [1], [2], with most of these methodologies focusing on the effects of ground seismic shaking. The development of appropriate *Probabilistic Seismic Demand Models (PSDM)*, which correlate the intensity of seismic hazard with the seismic response of the examined structure, constitutes a vital step toward the proposal of an efficient vulnerability assessment method. Moreover, the development of a rational PSDM is a key element for a performance-based seismic analysis method.

This paper initially discusses critical aspects of available methodologies for the derivation of PSDMs for the assessment of tunnels or underground structures based on a literature review. Emphasis is placed on modelling approaches proposed to simulate the structural response and the response of surrounding ground, the determination of the seismic capacity of underground structures, as well as the selection of ‘optimal’ intensity measures for the description of the intensity of the seismic hazard. Furthermore, a methodology for the development of novel PSDM models for the assessment and design of circular tunnels is proposed, based on an ongoing extended numerical study carried out in the frame of research project INFRARES (www.infrares.gr).

2 SEISMIC DEMAND MODELS FOR EMBEDDED STRUCTURES

Most of the available PSDMs for the assessment of embedded structures were developed in the frame of analytical studies aimed at proposing analytical fragility functions to estimate the vulnerability of such structures, when subjected to ground seismic shaking in their transverse direction. *Fragility functions* (i.e., fragility surfaces or fragility curves normally expressed by a lognormal probability distribution) link the probability of exceeding a predefined level of damage due to the examined hazard (e.g., the seismic hazard), with the measure selected to describe the intensity of this hazard. The level of structural damage is commonly expressed by a set of discrete *Limit States* (*LS*) or *Damage States* (*DS*), defined by means of thresholds of a parameter used to describe the structural performance, i.e., the *Engineering Demand Parameter* (*EDP*). The severity of the examined natural hazard is expressed by an Intensity Measure (*IM*) for instance, the Peak Ground Acceleration (*PGA*).

The analytical studies employed 2D numerical models (analysis in plain strain) to perform static or dynamic analyses of the selected ground-structure configurations and compute the structural demand for an increasing level of ground shaking. The analyses were conducted using various *Finite Element (FE)* or *Finite Difference (FD)* codes (e.g., ABAQUS, MIDAS, PLAXIS 2D, FLAC 2D, FLAC 3D etc.).

Most approaches proposed analyses in total stresses and under the assumption of undrained conditions for the ground. Various constitutive models were used to simulate the ground response against seismic shaking, from simplified approximations, such as the equivalent linear approximation to more advanced nonlinear models (e.g., nonlinear models with multi-nested yield surfaces). Figure 1a summarizes the variety of constitutive models used to simulate ground response in studies assessing the vulnerability of various types of embedded structures subjected to ground seismic shaking in the transversal direction.

With reference to the simulation of the lining, most of the studies for mountain tunnels in rock or bored tunnels in alluvial employed a linear elastic model (Figure 1b). The damage index and the damage states thresholds were defined using a separate section analysis for the examined liners, accounting for the effect of axial loading on the capacity of the liners in a simplified manner. Some researchers used concentrated plasticity models to account for the nonlinear seismic response of tunnel liners, i.e., by using inelastic zones/hinges (e.g., [3]). For large rectangular embedded structures (e.g., subways), more advanced nonlinear models were used to simulate the response of concrete liners (e.g., [4]).

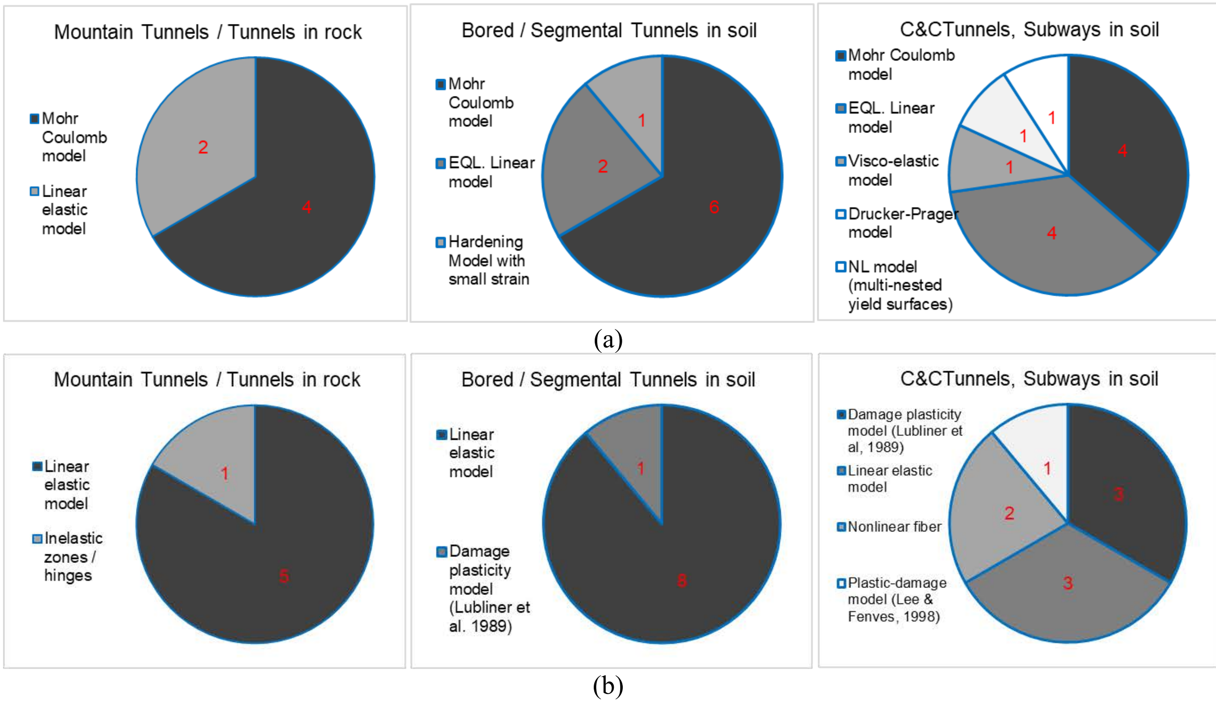
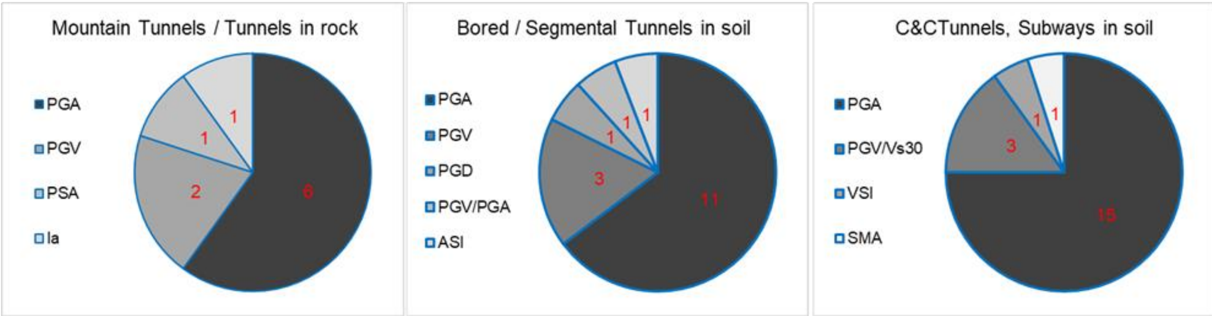


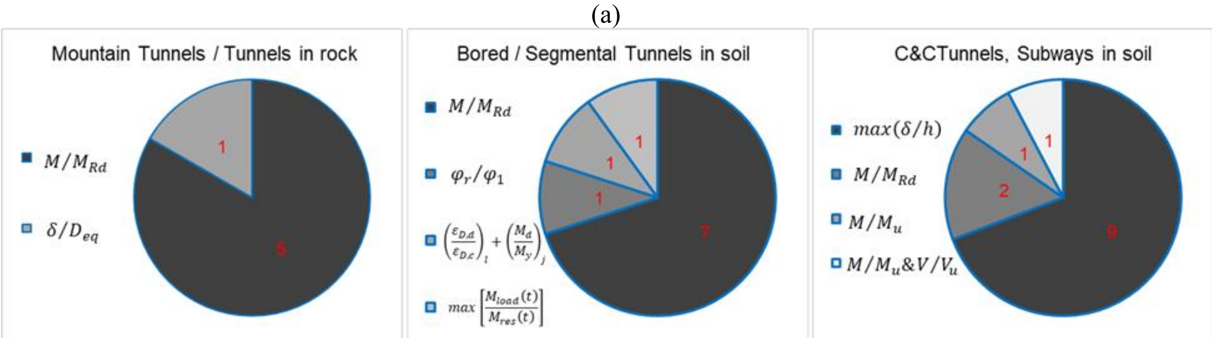
Figure 1: Constitutive models used to simulate the response of (a) ground and (b) the liner in vulnerability assessment studies of various types of embedded structures subjected to ground seismic shaking in the transversal direction.

Peak Ground Acceleration (*PGA*) and Peak Ground Velocity (*PGV*) have been used widely as *IMs* to develop PSDMs and analytical fragility functions for embedded structures subjected to ground seismic shaking in the transversal direction (Figure 2a). Some efforts to identify optimal *IMs* as per definitions of [5], [6] and [7] have recently been presented in the literature for the assessment of embedded structures.

Figure 2b summarizes the *EDPs* used for assessing the performance of various types of embedded structures in relevant vulnerability assessment studies. Argyroudis & Pitilakis [8] proposed the ratio of acting bending moment over the capacity bending moment of the lining (i.e., M/M_{Rd}) as an *EDP* for the assessment of bored circular and cut & cover tunnels in soft soil. This metric was then adopted by many researchers. The capacity bending moment was estimated based on section analyses of the examined liners that were carried out separately for various levels of axial loading. Despite the simple and straightforward definition of this *EDP*, the uncoupled approach proposed to compute the lining capacity and, hence, the *EDP*, does not accurately capture the variation of capacity with time during ground shaking, associated with the variation of axial forces acting on the liner during ground shaking. In addition to the metric proposed by Argyroudis & Pitilakis [8], different *EDPs* were used by researchers, with most definitions being based on ratios of acting internal forces over capacity of the liners. Some studies (referring mainly to the assessment of metro stations) introduced *EDPs* based on the deformation of the embedded structure due to ground shaking.



(a)



(b)

Figure 2: (a) Intensity Measures (*IMs*) and (b) Engineering Demand Parameters (*EDPs*) used in vulnerability assessment studies of various types of embedded structures subjected to ground seismic shaking in the transversal direction.

Regardless of the selected *IM* and *EDP*, most analytical studies proposed least-squares regression analyses on data sets of *EDP-IM*, in the log-log space to establish the PSDM ([9]). This approach is generally associated with a large number of dynamic or static analyses to establish the required data sets of *EDP-IM*, which demand a high computation effort. Artificial Neural Network (ANN) approaches were recently proposed for the development of PSDM (e.g., [10]), reducing the computational effort. The main disadvantage of ANN-based approaches to the moment is the effort required to train properly the ANN model given that available data from field records are generally not available; therefore, the use of output results from numerical analyses is mandatory.

3 SEISMIC DEMAND MODELS FOR CIRCULAR TUNNELS

A comprehensive numerical methodology for the derivation of analytical fragility functions for the vulnerability and resilience assessment of tunnels is currently under development in the frame of research project INFRARES. The methodology focuses on the assessment of circular tunnels in soil when subjected to ground seismic shaking in the transverse direction. A critical step of the methodology is the development of new PSDMs for circular tunnels. This section briefly presents the methodology.

After the selection of the ground-tunnel configurations to be examined, as well as the selection of the ground motions to be used in the analyses, the main steps of the methodology refer to: (a) the determination of the capacity of the examined tunnel, and (b) the estimation of the demand, which is related to the expected response of the tunnel for the selected ground motions.

For the determination of the capacity, nonlinear pushover analyses of the ground-tunnel configurations are proposed, whereas for the estimation of demand, nonlinear full dynamic time history analyses are employed. Figure 3 illustrates the proposed numerical models for the two steps. The open-source finite element code OpenSees [11] is used herein to perform the analyses.

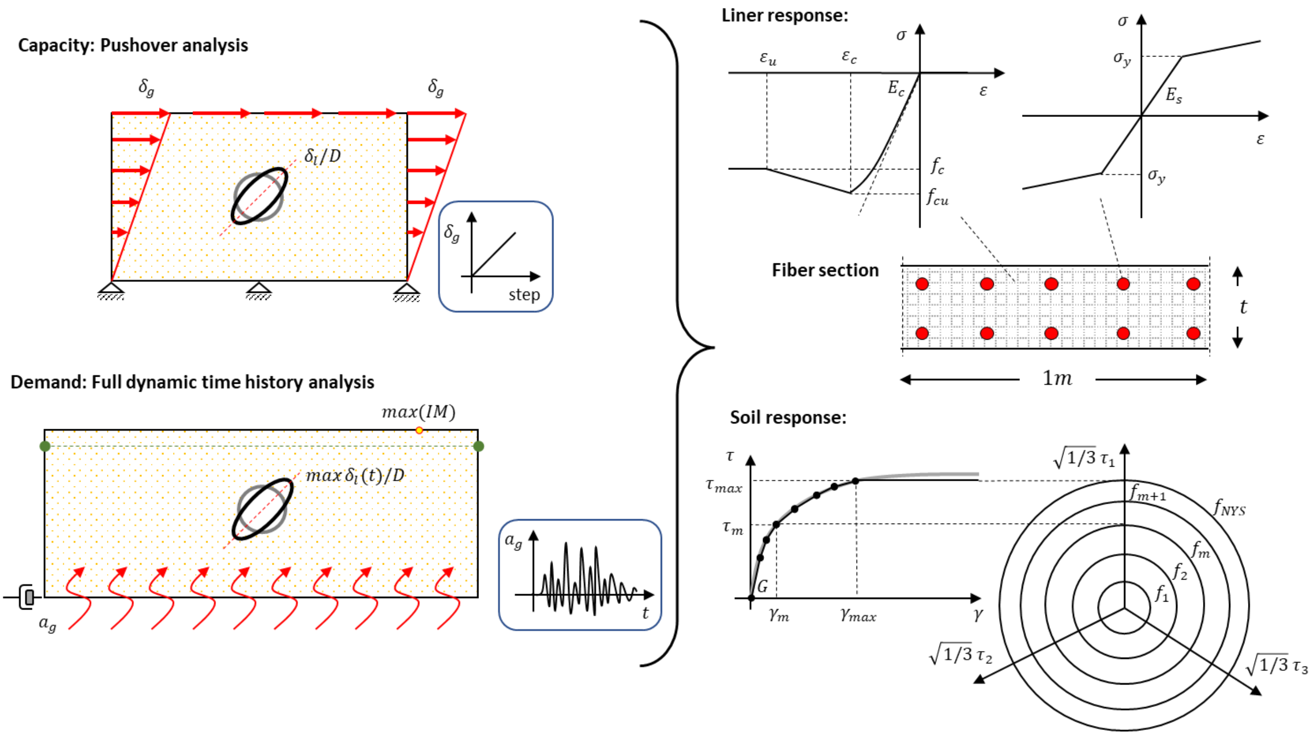


Figure 3: Numerical models used to evaluate the demand and capacity of the examined ground-tunnel configurations against ground seismic shaking in the transverse direction.

3.1 Pushover analysis

A two-dimensional (2D) numerical model of the selected ground-tunnel configuration is developed in OpenSees to perform nonlinear pushover analyses. The dimensions of the ground domain are selected based on the actual geometry of the examined tunnel (dimensions, burial depth etc), also accounting for potential boundary effects on the computed liner response. The side boundaries of the model are introduced at a distance from the tunnel, which is tuned accordingly. Plane-strain elements represent the ground, whereas 64 beam elements are used to simulate the liner. The ground response is simulated with a nonlinear multi-yield-surface J_2 plasticity constitutive model *('PressureIndependMultiYield Material')*, assuming that its shear behavior is insensitive to the confinement change. The concept of distributed material inelasticity and the fiber model approach is employed to simulate the liner response. Thus, the. *'Concrete01'* material is used to simulate the response of concrete, whereas for the steel reinforcement the *'Steel01'* material is used. Figure 3 illustrates the response of all constitutive models described above for uniaxial loading. The models are calibrated according to the actual mechanical properties of the examined ground-tunnel configurations. A penalty-based frictional contact element that follows the Coulomb frictional behavior is used to simulate the ground-tunnel interface. The *'ZeroLengthContactASDimplex'* element is employed for this purpose, with the coefficient of friction being set equal to 0.5.

Each analysis is conducted in steps as follows: 1. Initially, the geostatic stress field is introduced on the ground. 2. Subsequently, the tunnel cavity is excavated, and the liner is activated.

3. Finally, the ground-tunnel system is subjected to a monotonic simple shear deformation pattern within a pushover analysis step. During the latter step, the numerical model is fixed at the base boundary in both horizontal and vertical directions, while a ground deformation pattern is introduced on both side boundaries of the model (Figure 3), replicating a simple shear deformation field imposed on the examined configuration. The deformation level δ_g increases gradually, causing an ovaling deformation of the examined tunnel. This ovaling is expressed as the ratio of the diametric deflection of the tunnel δ_l over the diameter of tunnel *D,* which constitutes the *EDP* for the tunnel. The strain energy U of the liner for each loading step of the pushover analysis is computed as:

$$U = \int \frac{1}{2} \sigma_{ij} \varepsilon_{ij} dv \tag{1}$$

where σ_{ij} and ε_{ij} are the tensors of stress and strain, respectively, and v is the volume of the liner. An 'equivalent force' F_G that is introduced on the liner ring due to the ground deformation may be computed as the derivative of the strain energy U with respect to the selected *EDP*, i.e., δ_l/D (Figure 4a). The derivative of F_G with respect to δ_l/D constitutes a measure of an 'equivalent generalized stiffness of the liner', k_G, which drops during the gradual increase of ground deformation δ_g due to the nonlinear response of the liner (Figure 4b). Distinct Limit States (LS_i) may be defined by setting the thresholds of δ_l/D for which the stiffness of ring k_G drops by a certain degree compared to the initial stiffness of the ring k_{G0}, e.g., $k_G/k_{G0} = 20\%, 40\%,$ for minor and moderate damage states, respectively. The application of the methodology for various parameters that control the seismic response of tunnels may allow the formation of a set pushover curves similar to those presented in Figure 4, which subsequently may allow the quantification of the uncertainty related to both the definition of capacity and definition of limit states.

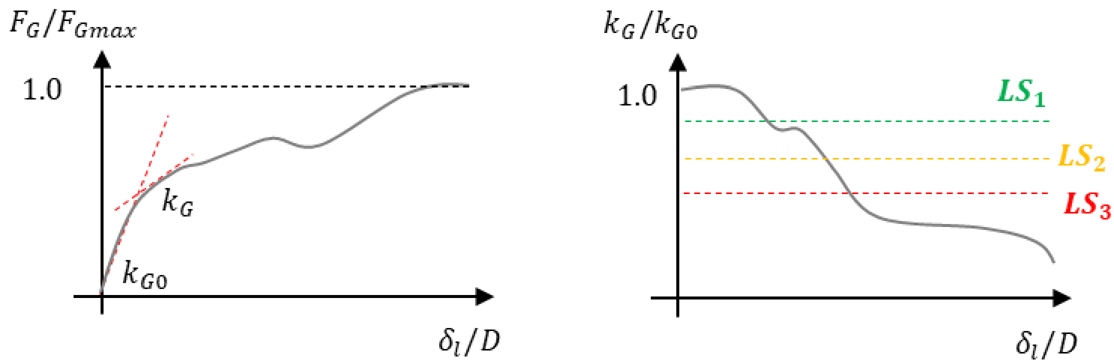
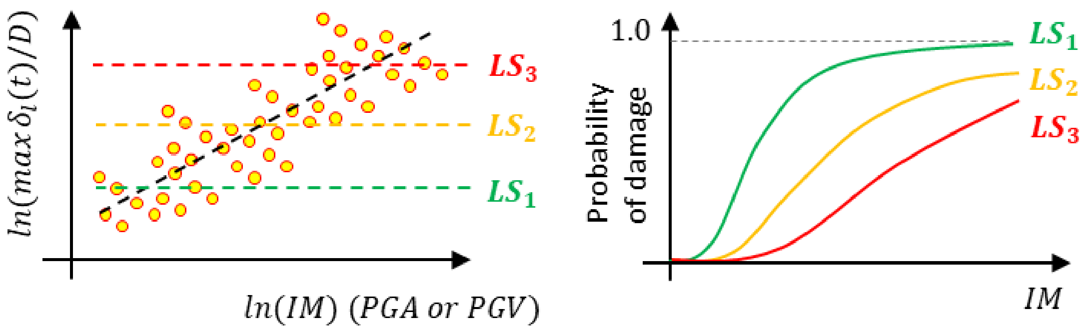


Figure 4: Definition of 'equivalent force' F_G introduced on the liner ring of a circular tunnel due to the ground deformation; definition of equivalent generalized stiffness of the liner ring, k_G to ovalization and definition of Limit States (LS).

3.2 Full dynamic time history analysis

A similar simulation strategy is followed to perform dynamic time history analysis of the examined ground-tunnel configuration to determine the demand for of the selected ground motions. The 2D numerical model of the selected ground-tunnel configuration is again developed in OpenSees. This model is more extended in the horizontal direction (compared to the one employed in pushover analysis) to reduce potential boundary effects caused by 'reflections' of seismic waves on the side boundaries. In addition, tie constraints are introduced between the nodes of the side boundaries of the model (Figure 3), imposing the same translational displacements in horizontal and vertical directions), simulating in a simplified way a simple shear response of the ground in 'free-field' conditions. The finite stiffness of the underlying bedrock is simulated via a Lysmer-Kuhlemeyer dashpot that is introduced at the base of the ground domain. The seismic load is introduced at the base of the ground domain through the dashpot as a horizontal force time history, which is proportional to the known velocity time history of the selected ground motion. In addition to the damping induced by the hysteretic behavior of the ground, an additional damping of 2% is introduced in the analysis as Rayleigh damping to simulate energy dissipation at very small shear strain levels of the ground.

Through the analysis, time histories of the diagonal distortions of the tunnel $\delta_l\ (t)$, as well as the acceleration, velocity, and displacement at the ground surface and tunnel depth are computed. The maximum value of the normalized over the diameter of tunnel *D*, diagonal distortion of the tunnel $\delta_l\ (t)$ is used as *EDP*, whereas the *PGA*, *PGV* and *PGD* at the ground surface (computed as the maxima of relevant time histories) are used as *IMs*. New PSDMs are finally proposed based on least-squares regression analyses on data sets of *EDP-IM*, in the log-log space (Figure 5a). Combining these models with the definitions of limit states made via the pushover analyses discussed in *Section 3.1*, analytical fragility functions may be constructed, as per Figure 5b.



(a) (b)

Figure 5: (a) Development of a PSDM for circular tunnels in soft soil, (b) development of analytical fragility curves.

4 CONCLUSIONS

The paper presented critical aspects and assumptions of available methodologies for the development of PSDMs models for the assessment of embedded structures based on a review of the state-of-the-art. In addition, the main steps of an analytical methodology for the development of novel PSDM models for the assessment and design of circular tunnels were presented. The main novel aspects of the proposed analytical method are:

- the proposal of a nonlinear numerical simulation approach of the selected soil-tunnel configurations to define both the capacity of the tunnel, as well as the demand, and
- the definition of an EDP for circular or horse-shoe type tunnel based on a displacement-based metric which accounts for the whole 'stiffness of the ring' and fits better with the physics of the problem in hand.

The methodology is currently applied on various ground-tunnel configurations, covering crucial parameters affecting the seismic response of tunnels to develop PSDMs and analytical fragility functions for such configurations.

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