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Recent Advances in Seismic Vulnerability Assessment of Tunnels and Underground Structures

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ABSTRACT

Tunnels and underground structures are constructed at an increasing rate in seismic prone areas to facilitate expanding transportation needs. The importance of these types of structures in modern societies, as well as the significant downtimes associated with seismically induced damage on them, led to an increasing interest of the scientific community and practitioners on the vulnerability assessment of this infrastructure against seismic hazard. Various methodologies have been recently proposed to estimate the vulnerability of bored tunnels in rock or alluvial and cut and cover or underground structures, e.g., subways, in alluvial, against ground seismic shaking and earthquake induced ground failures. This paper discusses critical aspects of these methodologies, based on a thorough review of relevant state-of-the art, carried out in the frame of research project INFRARES (www.infrares.gr). Emphasis is placed on the numerical tools employed to estimate analytically the fragility of examined structures in relevant studies, the constitutive models used to simulate the seismic response of ground and structures, the determination of the capacity of examined structures, the selection of appropriate seismic intensity measures, methods used to develop rational probabilistic seismic demand models, the estimation of uncertainties related to seismic vulnerability of underground structures, as well as the methods for selecting fragility functions from existing ones in assessment studies of actual case studies. Through the discussion, acknowledged gaps in the literature are highlighted and topics calling for further investigation are presented. In addition, an up-to-date database of available fragility functions for tunnels and underground structures developed within INFRARES is presented.

Keywords: tunnels, subways, fragility functions, seismic vulnerability, resilience

INTRODUCTION

Considering the high costs of construction and maintenance of tunnels and large underground structures, as well as the risks associated with the response of such infrastructure against natural hazards, relevant mitigation measures are commonly considered in early design stages, with any inevitable remaining level of risk, i.e., ‘residual risk’ being identified (Andreotti & Lai, 2019). This approach is applicable in the designing process of new tunnels, when the type and level of severity of natural hazards are well defined; however, it is not applicable for the risk assessment of existing infrastructure, particularly when considering ageing phenomena, which lead to a degrading condition of the infrastructure with time. The vulnerability of these infrastructures against ground natural hazards is key in assessing of risk, and hence the resilience of transport networks

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(Argyroudis, 2022). In this context, various methodologies have been recently presented in the literature for the vulnerability assessment of civil infrastructure, including studies referring to tunnels and embedded structures. Most of them focused on the response and vulnerability of tunnels and underground structures against seismic hazard (i.e., ground shaking and earthquake-induced ground failures), as the most relevant natural hazard, affecting embedded structures (Tsinidis et al., 2020). Analytical methodologies for the derivation of fragility functions have been proposed to assess the vulnerability of mountain tunnels in rock, as well as bored tunnels and underground rectangular structures (e.g., cut & cover tunnels, subways etc.) in alluvial, focusing mainly on the effects of ground seismic shaking in the transversal direction. The vulnerability assessment of embedded structures against seismically induced ground failures has received less attention. In the frame of research project INFRARES (www.infrares.gr) a thorough review on recent advances in vulnerability assessment of tunnels and underground structures has been conducted and a detailed up-to-date database of available seismic fragility functions has been developed (Tsinidis et al., 2022), to facilitate the selection and application of existing empirical and analytical fragility functions by end users, i.e., design engineers, stakeholders, operators and catastrophe risk analysts. This paper discusses critical aspects of the methods employed in the seismic vulnerability assessment of embedded structures based on the literature review and presents the novel database. Acknowledged gaps in the literature are highlighted, while a procedure to select fragility functions, using the database developed within INFRARES, is discussed.

FRAGILITY FUNCTIONS

Fragility functions (i.e., fragility curves or surfaces) are functional forms linking the probability of exceeding a predefined level of damage due to the examined hazard, with the measure selected to describe the hazard severity. The level of structural damage is commonly expressed by a set of discrete *Damage States (DS)*, defined by means of values (i.e., thresholds) of a parameter used to describe the structural performance, commonly referred as *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)*. Fragility functions (e.g., Fig. 1) for tunnels and underground structures are commonly expressed by a lognormal probability distribution (Argyroudis & Pitilakis, 2012), as follows:

$$P_f(LS \geq LS_i|IM) = \Phi\left[\frac{1}{\beta_{tot}} ln\left(\frac{IM}{IM_{mi}}\right)\right] \tag{1}$$

where $P_f(.)$ is the probability of exceeding a given limit state, for a given level of seismic intensity (the latter expressed via an IM), Φ is the standard cumulative probability function, IM_{mi} is the median threshold value of the intensity measure, required to cause the i^{th} limit state and β_{tot} is the total lognormal standard deviation, describing uncertainties related with the definition of the fragility function. β_{tot} is commonly estimated, as follows (HAZUS, 2014):

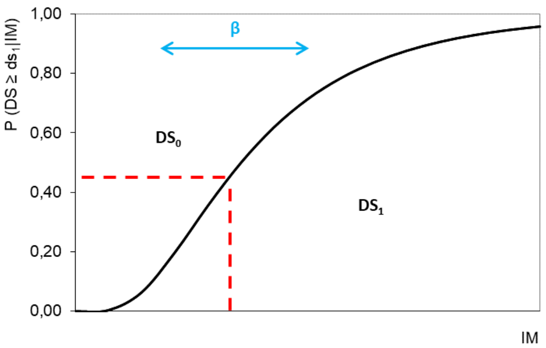

Figure 1. *Fragility curve representing the probability of exceeding damage state DS1 (D' Ayala et al., 2015) (β: total variability, dashed lines correspond to an example of application of the fragility curve).*

$$\beta_{tot} = \sqrt{\beta_c^2 + \beta_d^2 + \beta_{DS}^2} \tag{2}$$

where: β_c is the uncertainty related with the definition of structural capacity (e.g., modelling uncertainties, variability of mechanical and/or geometric properties), β_d is the uncertainty associated with the seismic demand (e.g., variability of ground seismic motion), and β_{DS} is the uncertainty associated with the definition of thresholds of *EDP* in defining damage levels.

Fragility functions are constructed based on data obtained from post-earthquake observations or expert judgement (empirical fragility functions). In addition, a variety of methodologies have been proposed recently to develop fragility functions based on results of numerical or experiment studies.

Two methods are commonly employed in treating data to develop fragility functions. The first one includes least-squares regression analyses, conducted on data sets of *EDP-IM*, commonly in the log-log space (Baker, 2007). The second method is the *maximum likelihood method* (Shinozuka et al., 2000), which is based on assigning binary values (i.e., 1 when the examined structure is damaged, 0 when the structure remains intact) to a vector of damage states for each fragility curve referring to a predefined damage state. The method is more suitable for the cases where discrete damage states may be defined.

In addition to fragility functions, *vulnerability curves* were developed by employing fragility functions and setting relevant vulnerability indexes e.g., ratio of cost of repair to cost of replacement (Huang et al., 2020).

VULNERABILITY ASSESSMENT FOR GROUND SEISMIC SHAKING

Numerical models and constitutive models used in analytical studies

Most analytical methodologies for the assessment of embedded structures against ground seismic shaking in the transversal direction employed 2D numerical models of ground-structure configurations. These models were used to calculate the structural demand for an increasing level of ground shaking. The models were developed assuming plane strain conditions and were used to perform either full dynamic time history analyses or static analyses. The seismic loading was simulated in the latter case, in a pseudo-static manner, by means of adequate displacement patterns induced on the boundaries of the models. Fig. 2 presents the numerical codes employed in studies assessing the vulnerability of mountain tunnels in rock, bored or segmental tunnels in alluvial and cut & cover (C&C) tunnels or subways in alluvial. The general-purposed finite element (FE) code ABAQUS was employed in most studies to perform the analyses (e.g., Avanaki et al., 2018). Other FE codes, such as PLAXIS 2D (e.g., Argyroudis & Pitilakis, 2012), MIDAS (Osmi et al, 2015) and SAP2000 (Nguyen et al., 2019) were also used. In addition, researchers used finite difference (FD) codes oriented to geotechnical problems, such as FLAC 2D (Andreotti & Lai, 2019) and FLAC 3D (Huang et al., 2017), while the DEM (discrete element method) code UDEC was also employed to examine the vulnerability of mountain tunnels in fractured rock (Sarkar & Pareek, 2021).

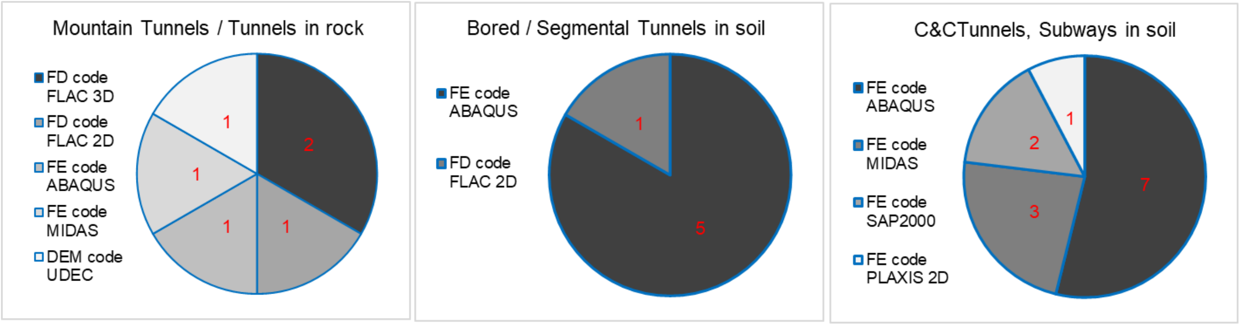

Figure 2. *Distribution of analytical studies on vulnerability assessment of various types of embedded structures subjected to ground seismic shaking in the transversal direction per numerical code.*

For the analytical studies, various constitutive models were used to simulate the response of ground subjected to seismic shaking (Fig. 3). In the simplest case, a linear elastic model (Huang et al., 2017) or approaches that are based on the *equivalent linear approximation* in simulating the effect of nonlinear response of ground under ground shaking (e.g., Avanaki et al, 2018) were adopted. Nonlinear models that employ a Mohr Coulomb yield criterion were also used widely (e.g., Andreotti & Lai, 2019). In some studies, the Mohr Coulomb models were calibrated by adjusting the stiffness and damping of the examined ground based on results of separate 1D soil response analyses, aiming to a more realistic simulation of the ground response under lower earthquake-induced strains (e.g., Argyroudis & Pitilakis, 2012). The validity of this approach has been tested in studies examining the seismic response of tunnels (e.g., Tsinidis et al., 2015). More advanced models were also employed in some studies; for instance: the hardening soil model with small strain embedded in PLAXIS (Fabozzi & Bilotta, 2017), a visco-elastic constitutive model proposed by Zhuang et al. (2007) used in Jiang et al (2021), and a nonlinear model with multi-nested yield surfaces used in Zhuang et al. (2021).

Most methodologies, assume total stresses and undrained conditions in the ground response analysis. The seismic vulnerability of embedded structures in drained conditions and specifically the response associated with pore pressure built-up due to ground shaking or liquefaction phenomena has not received significant attention to date. Studies investigating the response and vulnerability of embedded structures in liquefiable soils are deemed necessary (Tsinidis et al., 2020).

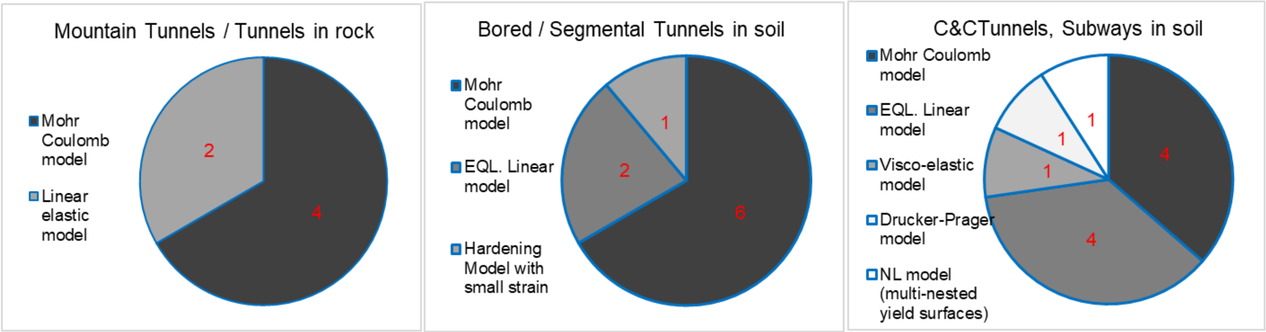

Figure 3. *Constitutive models used to simulate the ground response in vulnerability assessment studies of various types of embedded structures subjected to ground seismic shaking in the transversal direction.*

Regarding the response of the lining, most of the studies for mountain tunnels in rock or bored tunnels in alluvial employed a linear elastic model (e.g., Huang et al., 2017) (Fig. 4). 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. Concentrated plasticity models were used by some researchers to account for the nonlinear seismic response of tunnel liners, i.e., by using inelastic zones / hinges (e.g., Andreotti & Lai, 2019). In case of large rectangular embedded structures (e.g., subways), more advanced nonlinear models were used to simulate the response of concrete of liners. For example, the damage plasticity model proposed by Lubliner et al. (1989) was adopted in Zhang et al. (2021), while the plastic-damage constitutive model of Lee & Fenves (1998) was used in Zhuang et al., 2021. The latter models were accompanied in some cases by nonlinear models to simulate the response of steel reinforcement; for instance, a bilinear relationship with alterative isotropic hardening introduced by Guirguis & Mehanny (2012) was applied in Zhang et al (2021).

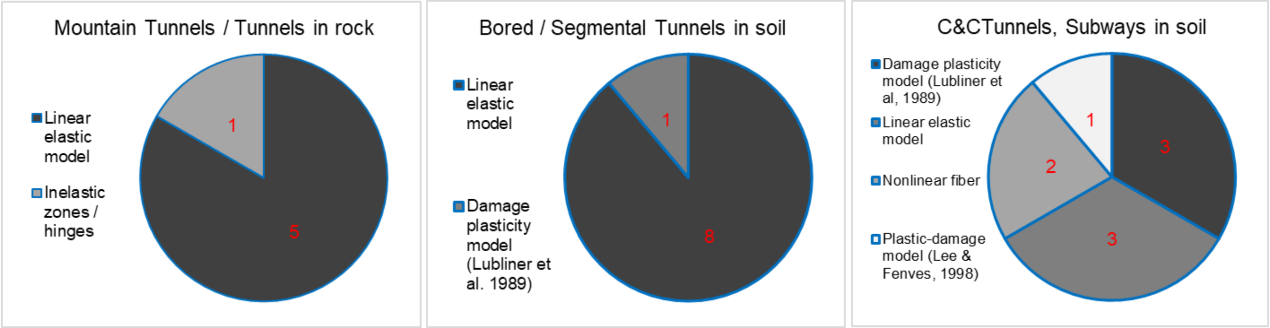

Figure 4. *Constitutive models used to simulate the response of lining in vulnerability assessment studies of various types of embedded structures subjected to ground seismic shaking in the transversal direction.*

To the Authors' knowledge, only one analytical study has focused on the seismic vulnerability of bored segmental tunnels subjected to ground shaking in the longitudinal direction (Dong et al., 2021). In this study, an *elastic beam on soil springs* model was employed to calculate the response of a tunnel for increasing levels of ground shaking. Tunnel segments were simulated using a linear elastic model, since emphasis was placed on the connection elements (i.e., joints) of the segments.

EDPs and definitions of damage states

Fig. 5 summarizes the *EDPs* proposed for assessing the performance of various types of embedded structures in relevant vulnerability assessment studies, focusing on the effect of ground shaking in the transversal direction. Argyroudis & Pitilakis (2012) 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 used in many studies as shown in Fig. 5. The capacity bending moment was commonly estimated based on section analyses of the examined liners conducted separately, for various levels of axial loading. The definition of damage states thresholds in these studies (Table 1) was based on engineering judgement, following Argyroudis & Pitilakis (2012).

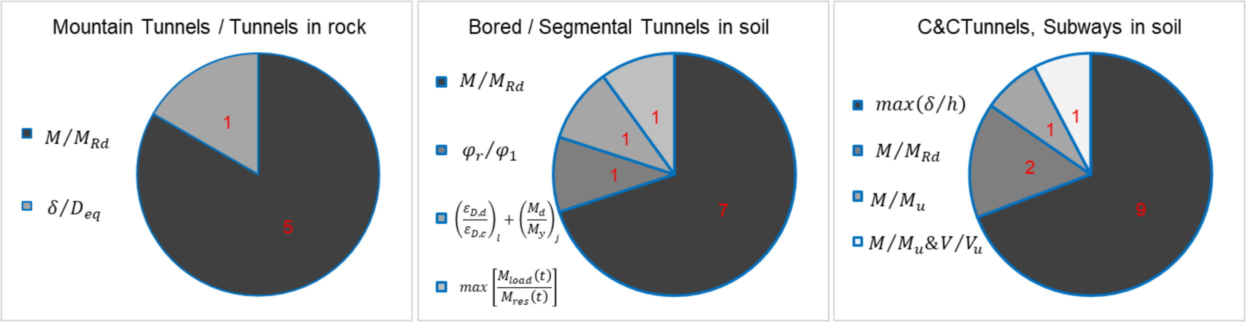

Figure 5. *EDPs used by various studies on vulnerability assessment of embedded structures subjected to ground seismic shaking in the transversal direction.*

Table 1. *Definition of damage states for the assessment of tunnels proposed by Argyroudis & Pitilakis (2012).*

Damage state (ds_i)	**Range of damage index (DI)**	**Central value of damage index**
ds_0: *None*	$M/M_{Rd} \leq 1.0$	-
ds_1: *Minor/slight damage*	$1.0 < M/M_{Rd} \leq 1.5$	1.25
ds_1: *Moderate damage*	$1.5 < M/M_{Rd} \leq 2.5$	2.00
ds_1: *Extensive damage*	$2.5 < M/M_{Rd} \leq 3.5$	3.00
ds_1: *Collapse*	$M/M_{Rd} > 3.5$	-

Despite the simple and straightforward definitions of *EDP* and damage states thresholds, the uncoupled approach proposed to compute the lining capacity and, hence, the *EDP*, does not capture accurately the variation of capacity with time during ground shaking, associated with the variation of axial forces acting on the liner during ground shaking. Moreover, the linear elastic model employed by these studies does not replicate cracking and/or yielding phenomena on the liner associated with the response at higher levels of ground shaking. De Silva et al (2021) presented an analytical method for the analysis of liners accounting for the effect of axial load time dependency on the resistance bending moment of the lining and therefore on the computation of the damage to capacity ratio. However, the definition was made for one damage state and a linear elastic model was used for the lining.

In addition to M/M_{Rd}, Fabozzi & Bilotta (2017) proposed the use of φ_r/φ_1 (i.e., the ratio of the permanent rotation of the joints connecting the segments, φ_r, over the first critical rotation of the joints, defined as $\varphi_1 = Nl^2/6EI$) as an additional *EDP* focusing on the response of the joints of segmental tunnels. The researchers provided separate analytical fragility curves using the aforementioned *EDPs*. Avanaki et al. (2018) suggested the use of a damage index that accounts for potential damage of the segments or the joints, thus, composed of two ‘parts’, i.e., lining part and joint part:

$$DI = \left(\frac{\varepsilon_{D,d}}{\varepsilon_{D,capacity}}\right)_{lining} + \left(\frac{M_d}{M_y}\right)_{joint} \tag{3}$$

where $\varepsilon_{D,d}$ is the diametric strain-demand on the lining, defined as the ratio of maximum diametric deformation due to a given seismic intensity over the lining diameter and $\varepsilon_{D,capacity}$ is the diametric strain capacity of the lining, calculated based on closed form solutions proposed for circular tunnels by Wang (1993). M_d and M_y stand for the demand bending moment and yielding bending moment of the joints defined on the basis of appropriate tests of the joints.

Andreotti & Lai (2019) introduced *inelastic zones* on the linings to simulate the lining nonlinear response of mountain tunnels and defined the damage index based on the damage accumulated due to ground shaking in all zones. This index was then correlated with the ratio of the relative displacement between the crown of arch and the inverted arch over the equivalent diameter of the tunnel lining cross-section (δ/D_{eq}), which was used as *EDP* in the fragility analysis.

Several studies proposed the use of *maximum drift ratio* (i.e., maximum relative interstory displacement over height of structure, *max(δ/h)*) as an adequate *EDP* for the assessment of rectangular tunnels and subway stations (e.g., Zhuang et al., 2021; Zhang et al., 2021). Pushover analyses of the examined structures were employed to define the thresholds of damage states. In some studies, only the structure was modelled as a frame subjected to deformation patterns replicating the ground shaking effect e.g., Zhong et al. (2020), while other studies proposed the use of 2D numerical models of the ground-structure configurations (e.g., Jiang et al., 2021), accounting also for the effect of vertical component of ground shaking. Du et al. (2021) performed a series of pushover analyses using 3D numerical models of actual subway stations in real sites to estimate the interstory drift thresholds for distinct performance (limit) states. The analysis approaches that employ also the ground are considered more efficient in replicating soil-structure interaction effects on the response and, hence, on the vulnerability of tunnels and embedded structures (e.g., distributions of earth pressures acting on the structure, effect of soil yielding on the structure). In this context, the definition of thresholds of damage states based on such analyses might be more rigorous; however, these approaches are associated with a much higher computational effort.

The only available study on the vulnerability of embedded structures subjected to ground seismic shaking in the longitudinal direction is the one by Dong et al. (2021). In this study, the joint opening between rings and the dislocation between segments were used as *EDPs*, while the definition of damage states and relevant thresholds were based on performance criteria, associated with the strength of bolds connecting the segments, and watertightness design requirements.

Optimal intensity measures

Ground motion characteristics, such as amplitude, frequency and energy content and duration, affect the response and therefore the vulnerability of embedded structures. However, describing all ground motion characteristics using only one parameter is not possible (Baker & Cornell, 2005); therefore, several studies focused on identifying the optimal intensity measures (*IMs*) for assessing the seismic performance of structures by performing various tests on the examined *IMs*. The most common tests refer to the *efficiency* and *sufficiency* of examined *IMs* (Shome et al., 1998; Luco & Cornell, 2000). An *efficient IM* results in reduced variability of the *EDP* computed for a given level of seismic intensity (i.e., for a given value of *IM*) (Shome et al., 1998). The efficiency of a seismic *IM* may be quantified based on the computed dispersion of the regression analyses of *EDP-IM* data, with the most efficient *IM*, revealing the lowest dispersion among the tested ones. The use of a *sufficient IM* leads to a computed response that is conditionally independent of the characteristics of ground motions, e.g., earthquake magnitude (M), epicentral distance (R); hence, allowing for a free selection of ground motions in the analytical framework employed to compute the vulnerability of an examined structure. The sufficiency of a seismic *IM* is evaluated based on the statistical significance of the residuals trend (i.e., the arithmetic differences between the computed values of *EDP* from the numerical analyses and the *EDP* values predicted from the regression fitting curve of the *EDP-IM* data) and the characteristics of the ground motions, i.e., magnitude or epicentral distance of the seismic event. The *p-value* test is often used as a quantitative measure of the statistical significance of regression estimates with sufficient *IMs* leading to high *p-values*.

Additional tests have been proposed for identifying optimal intensity measures for structures, e.g., the *proficiency test, the practicality test, the effectiveness test, the robustness test, and the hazard computability* (e.g., Padgett et al, 2008).

Peak Ground Acceleration (*PGA*) and Peak Ground Velocity (*PGV*) have been used widely as *IMs* to develop fragility curves for tunnels and embedded structures subjected to ground seismic shaking in the transversal direction (Fig. 6). Various assumptions were made by researchers regarding the position where the above metrics refer (i.e., outcrop conditions, bedrock, or ground surface at free-field conditions).

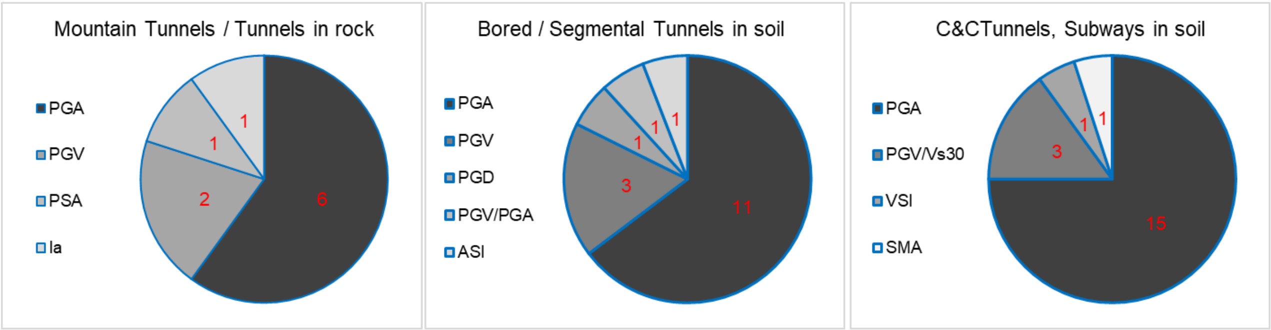

Figure 6. *IMs used by various studies on vulnerability assessment of embedded structures subjected to ground seismic shaking in the transversal direction.*

Some analytical studies have tested various *IMs* to identify the optimal ones for the seismic assessment of tunnels and subway stations. Andreotti & Lai (2019) reported a lower correlation of the computed response of examined mountain tunnels with *PGA* compared to *PGV*. To identify optimal *IMs* for bored tunnels in soft soil, Huang et al. (2021) tested the *correlation*, *efficiency*, *practicality*, and *proficiency* of 18 *IMs* based on regression analyses between the *IMs* (estimated at free-field conditions) and the dynamic response of the examined tunnels (expressed through an *EDP*) computed via a series of full dynamic analyses. A better performance of *PGA* (referring to ground surface) was reported for the examined case of a shallow tunnel, whereas in the cases of a moderately deep or a deep tunnel, *PGV* (at ground surface) was found the optimal *IM* among the tested ones. A similar study was conducted by Huang & Zhang (2021), who tested 15 *IMs*. For the examined ground-tunnel configurations, *PGA* at ground surface was reported as the optimal *IM*, with *PGV* and acceleration spectrum intensity (*ASI*), following.

Comparing the regression analyses of *EDP* against *PGA* and *PGV* referring to ground surface or bedrock conditions, de Silva et al. (2021) found that *PGV* at ground surface captured better the seismic response of tunnels compared to *PGA*. In addition, a better performance in capturing the response of tunnels was reported for the intensity measures referring to ground motions, i.e., at bedrock conditions. The latter observation was attributed to the response of the sites under ground shaking and the relevant effects on the values of tested *IMs* computed at ground surface.

Huang et al. (2021) proposed a methodology based on Artificial Neural Networks for developing a Performance Seismic Demand Model (PSDM) for bored tunnels in soft soil. In this study, various *IMs* were tested, including, *PGA*, *PGV*, *PGD*, *PGV/PGA* and *Arias Intensity* (I_a). Comparing the standard deviation of correlations of each *IM* with the computed *EDP* of the examined tunnel, the higher efficiency of *PGV* for the examined configuration was reported.

Higher research interest has been reported the last few years in identifying the optimal *IMs* for the assessment of rectangular embedded structures, particularly, for subways. Nguyen et al. (2019) used *PGA*, *PGV* and PGV/V_{s30} (V_{s30}: is the averaged shear-wave velocity to 30 m depth) as *IMs* to develop fragility curves. Lower dispersions were reported from least-square regression analyses between *EDP* and *PGV* or PGV/V_{s30} compared to *PGA*, revealing a better performance of these metrics for rectangular tunnels. He & Chen (2020) found a better performance of *PGA* compared to *PGV* in the case of a rectangular tunnel in stiff ground site. A relatively large scatter was reported for *PGA* in the case where the structure was assumed to be embedded in softer soil deposit. In a study assessing the vulnerability of the Daikai subway station in Kobe, Japan, that collapsed during the 1996 Great Hanshin earthquake, Zhong et al. (2020) examined the *efficiency* of a series of intensity measures, i.e., *PGA*, *PGV* and I_a, estimated at various positions, including the bedrock, ground surface and at the depth of the station. Their analysis yield in a superior performance of *PGA* at ground surface and at the depth of structure, compared to the other examined measures. Zhuang et al. (2021) tested a series of intensity measures to identify the optimal one for the assessment of rectangular underground structures in soft soil. In their study, the researchers examined *PGA*, *PGV*, I_a, and *PBA*, as well as the peak relative lateral displacement *(PRLD)* of the site, by employing the efficiency test, practicality test, proficiency test, and comparing correlation factors (R^2) of relevant regression analyses of the *EDP-IM* datasets. Their analysis revealed a better performance of *PGA* and *PRLD* compared to the other tested *IMs. PGA, PGV, PGD, spectral acceleration at fundamental frequency* $S_a(T_1)$ and *PRLD*, computed at ground surface, bedrock and at the burial depth of the structure were tested by Zhong et al. (2021) to identify the optimal ones for the assessment of subway stations. The *IMs* were tested for their *efficiency*, *practicality*, and *proficiency*, with *PGA* and *PGV* at ground surface being reported as optimal ones. Finally, a similar study was presented by Zhang et al. (2021) who tested 21 *IMs* using the criteria of efficiency, practicality, proficiency, and sufficiency. To reduce the number of required analyses the *Spearman Rank Correlation Coefficient (SRCC)* was used to evaluate the grade of interdependency among the examined *IMs* in the logarithmic space. Different *IMs* were proposed as optimal ones for distinct soil conditions examined within the study.

PGA, PGV, PGD, spectral acceleration S_a, *Arias Intensity* I_a, and the *root-mean square acceleration (RMSA)* were tested by Dong et al (2021), using the criteria of correlation, efficiency, practicality, and proficiency to identify the optimal ones for the assessment of a circular segmental tunnel subjected to ground seismic shaking in the longitudinal direction. The researchers reported *PGV* as the optimum measure for the examined ground-tunnel configurations and proposed relevant *PGV*-based curves for this purpose.

The use of optimal *IMs* is essential in the vulnerability assessment of any infrastructure asset; however, *hazard computability*, i.e., the ability to obtain information about *IM* after an event is of great importance particularly in case of extended structures, such as tunnels.

Uncertainties in vulnerability assessment against ground seismic shaking

In most analytical studies the uncertainties associated with the vulnerability assessment of examined tunnels and underground structures were treated as per Equation 2. More specifically, the uncertainties related with the definition of capacity of the examined element, β_c were calculated through the lognormal standard deviation estimated via least-square regression analyses of the *EDP-IM* datasets in the log-log space. For the definition of the uncertainties related to demand (β_d) and definition of damage states and EDP thresholds in defining damage levels (β_{DC}), most studies followed relevant proposals of HAZUS (2004), as proposed by Argyroudis & Pitilakis (2012). Given that the latter definitions are based on limited empirical data, research in this field seems necessary.

On the development of PSDM

A PSDM builds a relationship between the *EDP* and hazard *IM*, which is used to define optimal *IMs*, failure probability and/or the parameters of the fragility functions. It is worth noting that PSDMs are critical components for performance-based design of structures, as well. Most analytical studies introduced least-squares regression analyses on data sets of *EDP-IM*, in the log-log space to establish the PSDM (Baker, 2007). 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 have been recently proposed for the development of PSDM (e.g., Huang et al., 2017; Huang et al., 2021), 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.

Effect of ageing phenomena

Ageing phenomena, e.g., corrosion of the lining, are expected to degrade the performance of embedded structures, leading to increased vulnerability against seismic loading. This topic has not been studied thoroughly yet. Argyroudis et al. (2017) examined the effect of ageing of the lining due to corrosion of the reinforcement, on the vulnerability of bored circular tunnels subjected to ground seismic shaking. An uncoupled numerical framework, similar to Argyroudis & Pitilakis (2012) was proposed, and the effect of corrosion on the capacity of tunnel liners was considered for various scenarios in the section analysis by means of loss of reinforcement area with time. The latter was estimated based on relevant studies referring to aboveground structures. The procedure resulted in a series of fragility curves developed for distinct corrosion scenarios (i.e., 0, 50, 75, 100 years of life of examined ground-tunnel configurations).

VULNERABILITY ASSESSMENT AGAINST SEISMICALLY INDUCED GROUND FAILURES

The vulnerability assessment of embedded structures against seismically induced ground failures has received less attention compared to ground seismic shaking; indeed, to the Authors' knowledge only one study examined the vulnerability of bored segmental tunnels by means of centrifuge tests (Kiani et al., 2016). According to Andreotti & Lai (2019) this is partially attributed to the 'nature' of the specific seismic effects. Taking fault deformation acting on an embedded structure as an example; this constitutes a complex 3D problem characterized by large uncertainties, which require site specific investigation. At the same time, it affects a very limited part of the examined structure, which is commonly identified (at least for known faults) during the design phase; therefore, appropriate countermeasures to mitigate the high risk are applied beforehand. In this context, limited research efforts have been made toward identifying and computing the vulnerability of embedded structures and tunnels against fault displacements.

SELECTION OF FRAGILITY FUNCTIONS IN VULNERABILITY ASSESSMENT STUDIES

Available empirical and analytical fragility functions are applicable in case of tunnels/underground structures with similar typologies, geometries and materials and ground conditions, with those adopted to develop these functions. The selection of adequate fragility functions, should be always made carefully, employing calibration procedures with data collected from maintenance management systems of tunnels or underground structures (Cartes et al., 2021). Rossetto et al. (2014) proposed a systematic method for selecting a suitable fragility curve (Fig. 7). The method classifies fragility functions (i.e., curves) based on their relevance with the characteristics of the examined structures and their quality. The relevance criterion depends on the ability of each curve to represent damage states of an examined element for a given range of hazard intensities. The quality criterion accounts for the rationality of the modelling approach and the quality of input data used to develop the fragility functions, as well as for the quality of technical documentation used to calibrate the fragility curves.

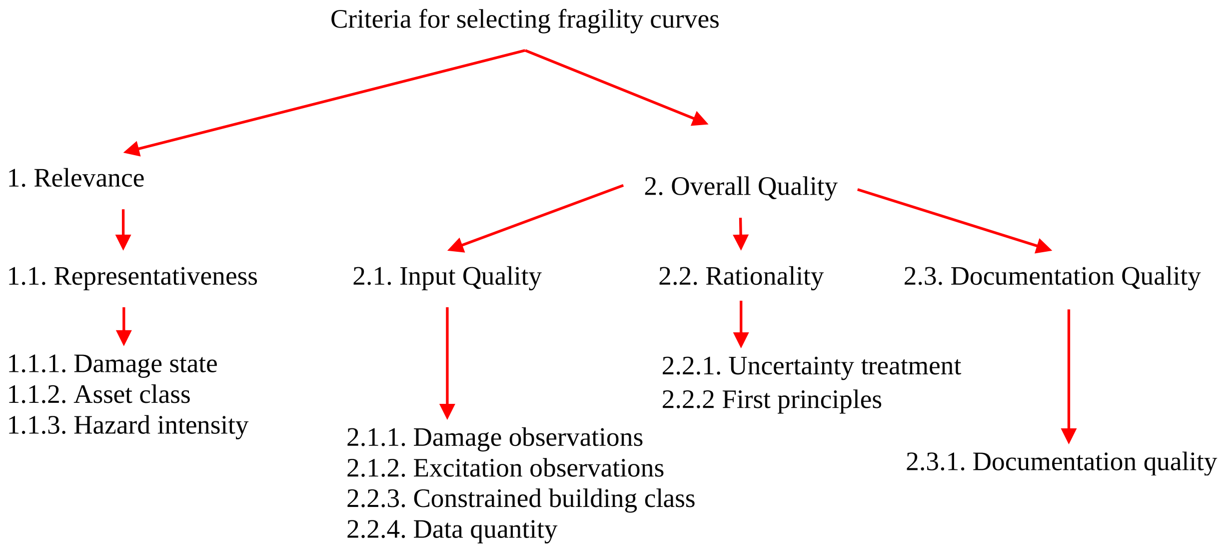

Figure 7. *Criteria for selecting fragility functions, after Rossetto et al (2014) and Cartes et al (2021)*

Following this approach, Cartes et al. (2021) presented a framework for the selection of fragility curves for the seismic vulnerability assessment of tunnels in Chile. The framework included: (i) the selection of available fragility curves using as criterion the employed seismic *IM*, (ii) the selection of fragility curves referring to tunnel- or embedded structure-ground configurations with similar characteristics to the ones of the examined cases, (iii) the evaluation of the chosen fragility curves based on the criteria set out by Rossetto et al. (2014). Each criterion was evaluated based on three scores, i.e., “high” (score 3), “medium” (score 2), and “low” (score 1), with the final score resulted from the sum of the qualifications for each criterion. The fragility curve with the highest final score was selected. In cases, in which more than one fragility curves with similar scores are identified, it was proposed to combine these curves, as follows:

$$E[P(DS \geq ds_i|A)] = \sum_{j=1}^{n} w_j \times P_j\,(DS \geq ds_i|A) \qquad (4)$$

where n is the number of fragility curves with same score, $P_j\,(.)$ represents each fragility curve, $E[P(.)]$ is the combination of fragility curves and w_j is a weighted factor expressing the probability that j fragility curve is the most accurate one among the n curves combined, estimated, for instance, based on expert judgement.

Databases of existing empirical and analytical fragility functions, summarizing the soil conditions, the characteristics of the tunnel/embedded structure, the *IM* and *EDP* used to develop the curves, the damage states definitions, and the definitions of relevant thresholds, facilitate the selection and evaluation procedure presented above. A novel database, containing all information required to select, evaluate, and apply available fragility functions was developed within the research project INFRARES (www.infrares.gr). Fig. 8 presents an example of the page set up of this database (Tsinidis et al, 2022a, Tsinidis et al, 2022b). Each page of the database refers to a study and contains information about the typology of the ground-structure configuration examined, information regarding the used *IM* and *EDP* as well as the definition of damage states, information about the parameters required to plot the fragility functions, as well as the methodology (analytical, empirical, or experimental) employed to develop the fragility functions. A graphical presentation of fragility functions is provided allowing for a quick check of the ‘shape’ of functions. Finally, the full reference of the relevant publication is provided.

CONCLUSIONS

The paper discussed critical aspects and assumptions of methodologies on the seismic vulnerability assessment of embedded structures, based on a thorough review of the state-of-the-art. Additionally, an up-to-date database of available fragility functions for the seismic vulnerability assessment of tunnels and underground structures, developed within research project INFRARES, was presented.

Despite the recent advances in the field, more research is deemed necessary in topics related to the seismic response and vulnerability of embedded structures under drained soil conditions, the response and vulnerability of embedded structures against ground shaking in the longitudinal direction, as well as seismically induced ground failures. Also, in the development of time-dependent fragility functions accounting for potential cumulative effects due to sequence of earthquakes and/or aftershocks, as well as ageing effects of the lining on the seismic vulnerability. The research project INFRARES contributes in some of the topics mentioned above toward more accurate and comprehensive resilience assessments of underground structures.

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1. Zhong et al. (2021)

Reference / Link:

Zhong, Z., Shen, Y., Zhao, M., Li, L., Du, X. (2021). Seismic performance evaluation of two-story and three-span subway station in different engineering sites. *Journal of Earthquake Engineering*, doi: 10.1080/13632469.2021.1964647.

Typology: Two-storey, three span subway station in soft soils sites

Dimensions: 21.2 × 12,49 (m), thicknesses: t_w = 0,70 m, t_B = 0,80 m, t_R=0,70 m, t_{iw} = 0,80 m; burial depth, h = 10 m

Soil properties: site I: V_s = 300-600 m/s, site II: V_s = 180-500 m/s, site III: V_s=120-250m/s (increasing with depth)

Method: Analytical

Function: Lognormal

Engineering Demand Parameter:

θ_{max}: maximum interstory drift ratio of the i-th floor

Limit / Damage states:

d_{s0}: No damage	$\theta_{max} \leq 0.08\%$
d_{s1}: Minor/slight	$0.08\% \leq \theta_{max} \leq 0.34\%$ (central value 0.21%)
d_{s2}: Moderate	$0.34\% \leq \theta_{max} \leq 0.62\%$ (central value 0.48%)
d_{s3}: Extensive	$0.62\% \leq \theta_{max} \leq 0.95\%$ (central value 0.79%)
d_{s4}: Collapse	$0.95\% \leq \theta_{max} \leq 1.00\%$* (central value 0.98%)

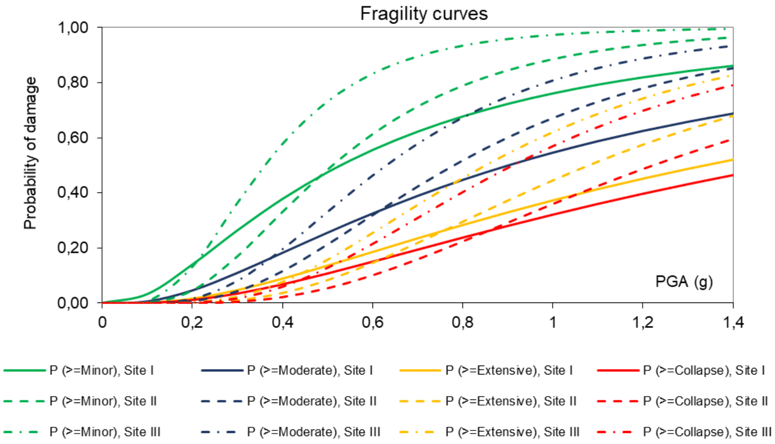
** based on engineering judgement*

Parameter (s) of intensity: PGA, PGV at ground surface (PGA, PGV, PGD at ground surface and of input motion were tested as potential optimal IMs)

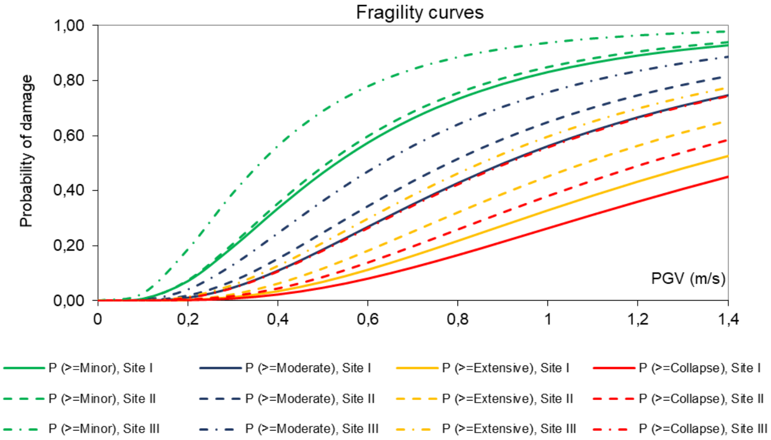
Modeling: 2D dynamic analyses of soil-tunnel configurations, IDA, linear elastic approximation of soil, nonlinear linings

Seismic excitations: 21 real ground motions, scaled from 0,03g to 1,20 g

Fragility curves (PGA-based) – Ground shaking



Fragility curves (PGV-based) – Ground shaking



Uncertainties/Parameters:

Two-storey, three span subway station	**PGA-based - Damage state**				
	Median, μ (g)				**β_{tot}**
	Slight	**Moderate**	**Extensive**	**Collapse**	
Site I	0,53	0,90	1,34	1,52	0,90
Site II	0,51	0,78	1,08	1,22	0,56
Site III	0,36	0,63	0,85	0,91	0,53
Two-storey, three span subway station	**PGV-based - Damage state**				
	Median, μ (g)				**β_{tot}**
	Slight	**Moderate**	**Extensive**	**Collapse**	
Site I	0,53	0,90	1,34	1,52	0,66
Site II	0,51	0,78	1,08	1,22	0,65
Site III	0,36	0,63	0,85	0,91	0,66

Comments: -

Figure 8. *Example of page setup of database of fragility functions for embedded structures developed in the frame of research project INFRARES.*

REFERENCES

Andreotti G. & Lai CG. (2019). Use of Fragility Curves to Assess the Seismic Vulnerability in the Risk Analysis of Mountain Tunnels. Tunnelling and Underground Space Technology, 91, 103008.

Argyroudis SA. (2022). Resilience metrics for transport networks: a review and practical examples for bridges. Proceedings of the Institution of Civil Engineers-Bridge Engineering, https://doi.org/10.1680/jbren.21.00075.

Argyroudis SA. & Pitilakis KD. (2012). Seismic fragility curves of shallow tunnels in alluvial deposits. Soil Dynamics and Earthquake Engineering, 35, pp. 1-12.

Argyroudis S., Tsinidis G., Gatti F., Pitilakis K. (2017). Effects of SSI and Lining Corrosion on the Seismic Vulnerability of Shallow Circular Tunnels. Soil Dyn. Earthq. Eng., 2017, 98, pp. 244-256.

Avanaki MJ., Hoseini A., Vahdani S., de Santos C. (2018). Seismic Fragility Curves for Vulnerability Assessment of Steel Fiber Reinforced Concrete Segmental Tunnel Linings. Tunnelling and Underground Space Technology, 78, pp. 259-274.

Baker JW. (2007). Probabilistic Structural Response Assessment Using Vector-Valued Intensity Measures. Earthquake Engineering and Structural Dynamics, 36(13), pp. 1861-1883.

Baker JW., Cornell CA. (2005). A Vector-Valued Ground Motion Intensity Measure Consisting of Spectral Acceleration and Epsilon. Earthquake Engineering & Structural Dynamics, 34, pp. 1193-1217.

Cartes P., Chamorro A., Echaveguren T. (2021). Seismic Risk Evaluation of Highway Tunnel Groups. Natural Hazards, 108, pp. 2101-2121.

D' Ayala, D., Gehl P. et al. (2015). Fragility Functions Matrix, Deliverable 3.2, Novel indicators for identifying critical INFRAstructure at RISK from Natural Hazards.

de Silva F., Fabozzi S., Nikitas N., Bilotta E., Fuentes R. (2021). Seismic Vulnerability of Circular Tunnels in Sand. Géotechnique, 71(11), pp. 1056-1070.

Dong Z., Kuo C., Yin J., Wen S., Ganzhi L., Gou Y. (2021). Examination of Longitudinal Seismic Vulnerability of Shield Tunnels Utilizing Incremental Dynamic Analysis. Frontiers in Earth Science, 9, 779879.

Du X., Jiang J., El Naggar H.M., Xu C., Xu Z. (2021). Interstory Drift Ratio Associated with Performance Objectives for Shallow-Buried Multistory and Span Subway Stations in Inhomogeneous Soil Profiles. Earthquake Engineering & Structural Dynamics, 50, pp. 655-672.

Fabozzi S. & Bilotta E. (2017). A Numerical Study on Seismic Vulnerability of Tunnel Linings: III Conference on Performance Based Design in Earthquake Geotechnical Engineering. Vancouver, Canada.

Guirguis J. & Mehanny S. (2012). Evaluating Code Criteria for Regular Seismic Behavior of Continuous Concrete Box Girder Bridges with Unequal Height Piers. Journal of Bridge Engineering, 18 (6), pp. 486-498.

He Z. & Chen Q. (2020). Vertical seismic effect on the Seismic Fragility of Large-Space Underground Structures. Advances in Civil Engineering, 9650294

Huang G., Qiu W., Zhang J. (2017). Modelling Seismic Fragility of a Rock Mountain Tunnel Based on Support Vector Machine. Soil Dynamics and Earthquake Engineering, 102, pp. 160-171.

Huang ZK., Pitilakis K., Tsinidis G., Argyroudis S., Zhang DM. (2020). Seismic Vulnerability of Circular Tunnels in Soft Soil Deposits: The Case of Shanghai Metropolitan System. Tunnelling and Underground Space Technology, 98, 103341.

Huang ZK. & Zhang, DM. (2021). Scalar- and Vector-valued Vulnerability Analysis of Shallow Circular Tunnel in Soft Soil. Transportation Geotechnics, 27, 100505.

Huang ZK., Argyroudis S., Pitilakis K., Zhang D., Tsinidis G. (2021). Fragility assessment of tunnels in soft soils using artificial neural networks. Underground Space, doi: 10.1016/j.undsp.2021.07.007.

Huang ZK., Pitilakis K., Argyroudis S., Tsinidis G., Zhang D.-M. (2021). Selection of Optimal Intensity Measures for Fragility Assessment of Circular Tunnels in Soft Soil Deposits. Soil Dynamics and Earthquake Engineering, 145, 106724.

Jiang J., El Nggar H., Xu C., Zhong Z., Du X. (2021). Effect of Ground Motion Characteristics on Seismic Fragility of Subway Station. Soil Dynamics and Earthquake Engineering, 143, 106618.

Kiani, M., Ghalandarzadeh, A., Akhlaghi, T., Ahmadi, M. (2016). Experimental evaluation of vulnerability for urban segmental tunnels subjected to normal surface faulting. Soil Dynamics and Earthquake Engineering, 89, pp. 28-37.

Lee, JH. & Fenves GL. (1998). Plastic-damage Model for Cyclic Loading of Concrete Structures. Journal of Engineering Mechanics, 124(8), pp. 892-900.

Lubliner J., Oliver J., Oller S., Onate E. (1989). A Plastic-damage Model for Concrete. International Journal of Solids and Structures, 25(3), pp. 299-326.

Luco N., Cornell C.A. (2007). Structure-specific Scalar Intensity Measures for Near-Source and Ordinary Earthquake Ground Motions. Earthquake Spectra, 232, pp. 357-392.

Nguyen D-D., Park D., Shamsher S., Nguyen V.-Q. Lee T.-H. (2019). Seismic Vulnerability Assessment of Rectangular Cut-And-Cover Subway Tunnels. Tunnelling and Underground Space Technology, 86, pp. 247-261.

Osmi SKC., Ahmad SM. (2016). Seismic Fragility Curves for Shallow Circular Tunnels Under Different Soil Conditions. World Academy of Science, Engineering and Technology. International Journal of Civil and Environmental Engineering, 10(10), pp. 1351-1357.

Padgett JE., Nielson BG., DesRoches R. (2008). Selection of Optimal Intensity Measures in Probabilistic Seismic Demand Models of Highway Bridge Portfolios. Earthquake Engineering & Structural Dynamics, 37, pp. 711-725.

Rossetto T., D'Ayala D., Ioannou I., Meslem A. (2014). Evaluation of Existing Fragility Curves. In: SYNER-G: Typology Definition and Fragility Functions for Physical Elements at Seismic Risk, Geotechnical, Geological and Earthquake Engineering; Pitilakis K et al., Eds., Springer: Dordrecht, Volume 27, pp. 47-93.

Sarkar R. & Pareek K. (2021). Influence of Stratification and Assessment of Fragility Curves for Mountain Tunnels. Geotechnical Engineering, 174(3), pp. 279-290.

Shinozuka M., Feng MQ., Kim HK., Uzawa T., Ueda T. (2003). Statistical Analysis of Fragility Curves. Technical Report MCEER-03-0002, State University of New York, Buffalo, USA.

Shome N., Cornell CA., Bazzurro P., Carballo J.E. (1998). Earthquakes, Records, and Nonlinear Responses. Earthquake Spectra, 14, pp. 469-500.

Tsinidis G., Pitilakis K., Madabhushi G. Heron C. (2015). Dynamic Response of Flexible Square Tunnels: Centrifuge Testing and Validation of Existing Design Methodologies. Géotechnique, 65(5), pp. 401-417.

Tsinidis G., De Silva F., Anastasopoulos I., Bilotta E., Bobet A. Hashash, YMA., He C., Kampas G., Knappett J., Madabhushi G., Nikitas N., Pitilakis K., Silvestri F., Viggiani G., Fuentes R. (2020). Seismic Behavior of Tunnels: From Experiments to Analysis. Tunnelling and Underground Space Technology, 99, 103334.

Tsinidis G., Karatzetzou A., Stefanidou S., Markogiannaki O. (2022a). State of the Art Report Regarding Methodologies for Multi-hazard Vulnerability Assessment of Tunnels. Deliverable D3.1. INFRARES. Towards resilient transportation infrastructure in a multi-hazard environment.

Tsinidis G., Karatzetzou A., Stefanidou S., Markogiannaki O. (2022b). Developments in Seismic Vulnerability Assessment of Tunnels and Underground Structures. Geotechnics, 2(1), 209-249.

Wang J.N. (1993). Seismic Design of Tunnels: A Simple State of the Art Design Approach; Parsons Brinckerhoff Inc.: New York.

Zhang C., Zhao M., Zhong Z., Du X. (2021). Seismic Intensity Measures and Fragility Analysis for Subway Stations Subjected to Near-Fault Ground Motions with Velocity Pulses. Journal of Earthquake Engineering, doi: 10.1080/ 13632469.2021.1994056.

Zhong Z., Shen Y., Zhao M., Li L., Du X., Hao H. (2020). Seismic Fragility Assessment of the Daikai Subway Station in Layered Soil. Soil Dynamics and Earthquake Engineering, 132, 106044.

Zhong Z., Shen Y., Zhao M., Li L., Du X. (2021). Seismic Performance Evaluation of Two-story and Three-Span Subway Station in Different Engineering Sites. Journal of Earthquake Engineering, doi: 10.1080/13632469.2021.1964647.

Zhuang, H, Chen G, Liang Y, Xu M. (2007). A developed Dynamic Viscoelastic Constitutive Relation of Soil and Implementation in ABAQUS Software. Rock and Soil Mechanics, 28(3), pp. 436-442.

Zhuang H., Yang J., Chen S., Dong Z., Chen G. (2021). Statistical Numerical Method for Determining Seismic Performance and Fragility of Shallow-Buried Underground Structure. Tunnelling and Underground Space Technology, 116, 104090.