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A probabilistic approach to evaluate the seismic loss of metro tunnels in Shanghai City

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ABSTRACT: Tunnels are crucial lifeline components in the mega cities. This work studies the direct seismic cost of metro tunnels subjected to earthquake events. The degree of tunnel damage and the corresponding direct seismic loss is derived considering various tunnel burial depths. The developed framework is then applied in the metro tunnels located in Shanghai city, China. Specifically, the direct seismic loss of one tunnel ring and the whole Metro Line 10 under different hazard scenario is estimated. Results highlight the significant function of tunnel buried depths towards more efficient seismic loss assessment. The findings of this study constitute useful elements in seismic loss management in terms of lifeline resilience.

Keywords: circular tunnels, seismic vulnerability, cost, infrastructure

1 INTRODUCTION

Tunnels are essential parts of the city's lifeline system, and have high vulnerability to seismic hazards. As a result, they frequently have detrimental effects on society and the economy, including hampered emergency response, potential casualties, and societal and economic losses (Hashash et al., 2001). Examples include the mountain tunnels that collapsed after the 2008 Wenchuan earthquake in China (Wang et al., 2009) and the Daikai subway station that collapsed during the 1995 Kobe earthquake in Japan (Iida et al., 1996). Since the 1990s, tunnel seismic safety has become a significant issue in earthquake-prone regions. In addition, traffic operations and public safety may be impacted by tunnel damage from an earthquake. The time and money needed to repair even slight or moderate damage to tunnels brought on by seismic hazards can ultimately have a detrimental effect on society and the economy. In order to make cities more robust to extreme occurrences like earthquakes, it is crucial to comprehend the vulnerability of vital infrastructures and characterize their resilience. In order to prioritize corrective efforts to increase the resilience of cities, it is crucial to estimate the loss of subway systems.

A series of loss assessment procedures have been developed for surface buildings (Shoraka et al., 2013), various bridge structures (Ghosh and Padgett, 2011), and other important infrastructure (Shahnazaryan et al., 2022). However, the work related to the probabilistic seismic loss assessment of metro tunnels (Selva et al., 2013; Cartes et al., 2021) are quite limited in the

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literature.. However, the available work have not sufficiently investigated the potential impact of tunnel depths on seismic loss analysis. Thus, this is a significant capability gap that needs to be addressed and further researched to enable integrated damage and risk assessment of tunnels.

The objective of this work is to study the direct seismic losses of circular tunnels as subjected to earthquake events. To this end, a practical approach for estimating the seismic losses of circular tunnels is proposed and applied to individual tunnel segments and to tunnel elements representative of Shanghai Metro Line 10, considering various degrees of seismic intensities. The results of this work are useful to engineers and city infrastructure operators involved in resilience-based management of crucial facilities.

2 PROBABILISTIC SEISMIC LOSS ASSESSMENT FRAMEWORK

The paradigm for probabilistic seismic loss assessment of tunnels presented in this paper is shown in Figure 1. There are three typical steps in the framework: (1) Seismic hazard assessment, which could be carried out using existing hazard curves for the studied tunnel site. (2) Seismic vulnerability assessment, which indicates the state of seismic damage in the tunnel for various degrees of seismic intensity. (3) Seismic loss assessment, which entails calculating expected mean seismic damage for the studied tunnels. It should be emphasized that the study's definition of the seismic direct economic loss, which is defined as a percentage of the damaged tunnel element's original construction cost, relates to the cost of repairs made after an earthquake occurrence. The following sections provide more information on these three steps.

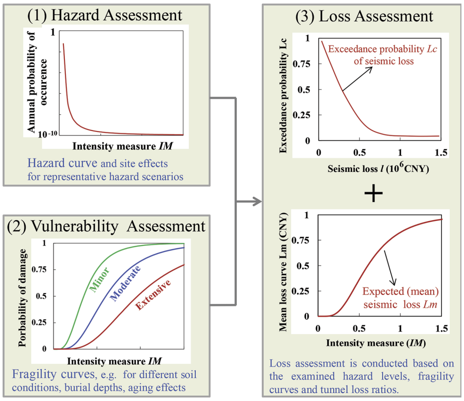


Figure 1. Procedure to evaluate the seismic loss of tunnels.

2.1 *Seismic hazard assessment*

Seismic hazard is represented here in terms of so-called seismic hazard curves. Remember that the annual exceedance frequency as a function of a seismic *IM* is plotted on the seismic hazard curves (e.g., peak ground acceleration *PGA*). The main objective of this analysis is to define the corresponding seismic hazard scenarios for a tunnel site, which can subsequently be utilized to assess the anticipated losses of the investigated tunnel for these given scenarios (steps b and c).

2.2 *Seismic vulnerability assessment*

Fragility functions, which can be generated from expert opinion, empirical techniques, and numerical approaches, can be used to evaluate the seismic vulnerability of structures (in this example, tunnels). The conditional likelihood that a structure would sustain damage equal to or greater than a specific level under a given seismic load *IM* is provided by fragility functions. In the majority of research, fragility functions for tunnels have been represented as fragility curves using a lognormal prob-ability distribution:

$$P[ds \geq ds_i|IM] = \phi\,[\frac{In(IM) - In(IM_{mi})}{\beta_{tot}}] \tag{1}$$

where *P*[-] is the conditional probability of exceeding a damaged state (*ds*) under a specific *IM*; Φ(-) is distribution function; IM_{mi} is the median value of *IM* corresponding to the i_{th} *ds, and* β_{tot} is the standard deviation, indicating the uncertainties from fragility analysis. The fragility curves are usually derived for minor (ds_1), moderate (ds_2), and extensive (ds_3) damage. The punctual probability w_i for each damage state (ds_i) can be derived based on the corresponding fragility curves.

2.3 *Seismic loss assessment*

The potential damage states of the tunnels under consideration based on fragility functions and the associated repair costs for each damage state (*ds*) under various levels of seismic loading *IM* could be used to estimate the seismic losses of infrastructures. Based on existing data from repairs of comparable structures in previous earthquakes or expert judgment, the repair costs for each damage stage can be estimated. A tunnel repair model (Table 1) was proposed by Werner et al. (2006) based on data gathered in the state of California. This model is based on the mean loss ratio (*LR*), which is defined as the proportion of the cost of repairs to the cost of the tunnel element's initial construction (*ICC*) for each damage state (ds_i). According to Werner et al., the equivalent LR_i in this study for no damage, minor damage, moderate damage, and significant damage are considered to be 0, 0.10, 0.25, and 0.75, respectively.

Table 1. Tunnel damage condition definitions and related loss ratio (Werner et al., 2006).

Damage states (*ds*)	Descriptions	Loss ratio (*LR*)
None damage, ds_0	No cracking of the lining	0.00
Minor damage, ds_1	Minor cracking of the lining	0.10
Moderate damage, ds_2	Moderate cracking of the lining	0.25
Extensive damage, ds_3	Extensive cracking of the lining	0.75

In general, the length, the initial construction cost (*ICC*) of a single tunnel segment (per unit length), as well as the *LR* described above for different damage states ds_i, may be used to estimate the projected cost to repair a specific damaged tunnel element under a specific damage condition, as shown below:

$$C_i = ICC \cdot LR_i \cdot n \tag{2}$$

where *n* is the length of the analyzed tunnel element, index I denotes the i_{th} damage state, C_i denotes the estimated cost under that damage state, and LR_i denotes the corresponding loss ratio in fixing that damage state. The beginning construction cost is set at 1,000,000 CNY for this work's examination of a typical circular tunnel liner with a longitudinal length of 1 m built using the shield tunneling method.

A random variable is the damage condition of a structure for a specific level of IM. As a result, it is important to use a sample of damage states for the tunnel part under examination when introducing a stochastic analysis, such as a Monte Carlo (MC) stochastic simulation (by Equations 3-5). A sample of the anticipated cost C_i can be generated using this process. The steps that make up the Monte Carlo stochastic simulation are as follows: (i) The analyzed tunnel element's w_i is compared to a random number between 0 and 1 to determine a specific damage state *i*. (ii) Based on the created random damage scenario for each MC realization, the seismic loss of the entire analyzed tunnel system is calculated by summing the estimated cost C_i for each tunnel element, as shown below, assuming that the examined tunnel comprises k elements.

$$l = \sum_{k=1}^{k} C_i \tag{3}$$

For a particular level of $IM = im$, a large sample of potential total losses can be acquired by running the MC simulation for numerous trials, such as 10,000 times or more. As a result, the following formula can be used to determine the exceedance probability Pl of seismic loss for a given level of $IM = im$:

$$Pl(im, w) = p(l > x | im, w) \tag{4}$$

where w is the punctual probability that accounts for the effect of the examined structure's seismic vulnerability. Based on the description above, the seismic hazard level and the chosen fragility functions may be used to calculate the exceedance probability Pl.

The expected mean seismic loss Lm, which is determined using Equation 5 (assuming that the analyzed tunnel contains k elements), is adopted in this work as an extra loss measure of the examined tunnel systems in addition to the exceedance probability Pl of seismic loss:

$$Lm(im, w) = \sum_{k=1}^{k} \sum_{i=0}^{4} C_i^k \cdot w_i \tag{5}$$

where k stands for the total number of tunnel elements, C_i^k represents the estimated cost to repair a specific tunnel element under a specific damage state ds_i, and w_i stands for the punctual probability of each damage state (ds_i).

3 SEISMIC LOSSESS ASSESSMENT OF TUNNELS

The next sections look at representative circular tunnels' seismic losses under various seismic conditions. Two case studies are included in this analysis: a generic single tunnel lining section with a unit length and the Shanghai Metro Line 10.

3.1 *Description of the adopted fragility functions*

This study made use of a set of fragility curves created by the authors in earlier research to examine the impacts of tunnel burial depth on tunnel seismic loss calculations (Huang et al., 2020). In Figure 2, these fragility curves are displayed. Table 2 provides a summary of the parameters needed to plot the fragility curves, including the median values of *IM* for minor, moderate, and extensive damage, as well as the total standard deviation β_{tot}.

3.2 *Seismic loss assessment of a single tunnel segment*

The seismic loss assessment framework is initially implemented on a single tunnel lining segment with a unit length taking into consideration various soil-tunnel configurations by adopting the fragility curves specified in Table 2 and the tunnel repair model of Table 1. Regarding the soil-tunnel configurations examined by Huang et al. (2020), the assessment made here applies to the tunnel segments matching to those configurations. As an example, a tunnel

Table 2. Parameters of the adopted fragility curves in this study (Huang et al., 2020).

Tunnel typology	Minor IM_1 (g)	Moderate IM_2 (g)	Extensive IM_3 (g)	β_{tot}
Shallow tunnel, burial depth h =9 m, diameter d= 6.2 m	0.350	0.604	0.968	0.533
Moderately deep tunnel, burial depth h =20 m, diameter d= 6.2 m	0.427	0.836	1.491	0.580
Deep tunnel, burial depth h =30 m, diameter d= 6.2 m	0.635	1.231	2.177	0.613

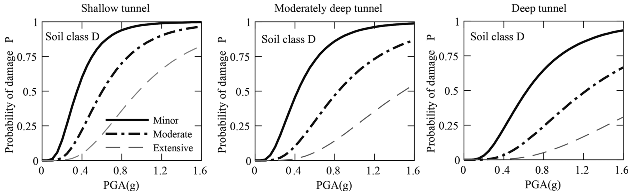
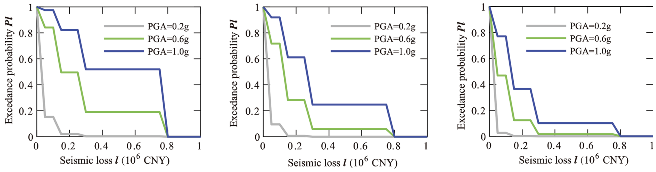


Figure 2. Fragility curves of tunnels: with different buried depths developed by Huang et al. (2020).

segment implanted at various burial depths of soil class D is employed, along with the researchers' proposed fragility curves, as shown in Figure 2.

Figure 3 displays the tunnels under examination's seismic losses exceedance likelihood. For all of the analyzed burial depths, it is discovered that the exceedance probability *Pl* falls as the seismic losses rise. Additionally, when the seismic danger level rises, the likelihood that a certain threshold of seismic damage will be exceeded increases. The possibility of the tunnel under examination exceeding a specific level of seismic risk and seismic loss decreases as the tunnel burial depth rises (i.e., from shallow tunnel to deep tunnel). With a *PGA* of 1.0 g and a seismic loss of l=0.6·10^6 CNY, the exceedance probability of the tunnel is 0.520, 0.247, and 0.102 for the shallow, moderately deep, and deep tunnels, respectively. The predicted exceedance probability varies by up to 400% for the analyzed tunnels, which are buried at various depths.



(a) Shallow tunnel in soil class D

(b)Moderately deep tunnel in soil class D

(c)Deep tunnel in soil class D

Figure 3. Exceedance probability *Pl* of seismic loss for tunnels with different buried depths.

The mean seismic loss *Lm* for the shallow, moderately deep, and deep tunnels are shown in turn in Figure 4. Naturally, *Lm* steadily rises as earthquake intensity increases. For deeper tunnels than for shallower ones, mean seismic losses are calculated at lower values. When there are greater earthquake intensities (*PGA*>0.5 g), the changes on *Lm* are greater. In contrast, the impact of burial depth on the mean seismic loss is less significant for *PGA* levels up to 0.2 g. For the analyzed tunnels with various burial depths, the predicted mean seismic loss value, for example, is equal to 0.018·10^6, 0.011·10^6, and 0.004·10^6 CNY, respectively, if a *PGA* of 0.2 g. In general, the shallower tunnel case seismic losses *Lm* are shown to rise, particularly for higher seismic intensities (i.e., for *PGA* > 0.2 g).

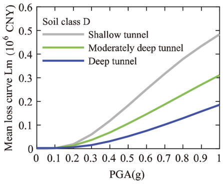


Figure 4. Expected mean seismic loss *Lm* for tunnels with different buried depths.

3.3 *Seismic loss assessment of Shanghai Metro line 10*

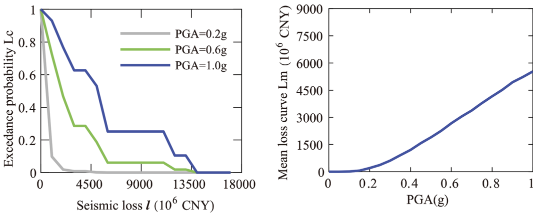
The paradigm presented in Section 2 is applied to the study of an actual subway system, namely Line 10 of the Shanghai Metro, to further assess the seismic losses of subway lines in a city. The full length of the investigated subway line is subjected to the methodology.

The Shanghai Metro Line 10 under consideration was constructed on soft soil, generally known as soil class D in accordance with Eurocode 8 (CEN, 2004). Additionally, the tunnel linings share the same mechanical characteristics and dimensions as those examined by Huang et al. (2020)., with a tunnel diameter of 6.2 m and a lining thickness of 0.35 m. A representative map of the Shanghai Metro Line 10 is shown in Figure 5.

Figure 5. Examined Shanghai Metro Line 10.

In Shanghai, the Metro Line 10 was built in 2010. There are 19 stations along the 17,452 m long, under consideration Metro line, which runs from Hongqiao Road Station to Xin-jiangwancheng Station. Figure 5 depicts the 18 tunnel elements that were evaluated, numbered from ① to ⑱. The tunnels on Line 10 are often categorized as either shallow (2,733 m total length), moderately deep (12,464 m total length), or deep (a total length of 2,255 m). For example, although tunnel elements ⑦ and ⑧ are deep tunnels, tunnel elements ①, ④, and ⑱ belong to shallow tunnels. Additionally, it has been found that the other tunnel components are all reasonably deep tunnels. In this context, the following analysis made use of the fragility functions for shallow, moderately deep, and deep tunnels created by Huang et al. (2020).

Figure 6 displays the mean seismic loss *Lm* and the exceedance probability *Pl* for the metro line under consideration. It is discovered that as seismic loss grows, the exceedance probability *Pl* would decrease. Additionally, at a given level of seismic losses, the exceedance probability *Pl* rises as the magnitude of the seismic hazard does (i.e., as *PGA* increases from 0.2 g to 1.0 g). For the Shanghai Metro Line 10, the corresponding exceedance probability *Pl* for *PGA* of 0.2, 0.6, and 1.0 g is equal to 0.007, 0.286, and 0.626, respectively, assuming a scenario of seismic losses l=4·10^9 CNY.



(a) Exceedance probability *Lc* of seismic loss (b) Expected (mean) seismic loss *Lm*

Figure 6. Seismic loss assessment of Shanghai Metro Line 10.

The mean seismic losses *Lm* for Shanghai's Metro Line 10 are shown in Figure 6(b) for different levels of hazard intensity. *Lm* would logically rise as seismic intensity did. For Shanghai Metro Line 10, the mean seismic loss value is equal to $1.203 \cdot 10^9$ CNY when the *PGA* is 0.40 g. Nevertheless, the mean seismic loss will grow by more than double, or $4.158 \cdot 10^9$ CNY CNY, when a *PGA* rises to 0.80 g. The aforementioned findings indicate that a powerful earthquake occurrence may cause a significant economic loss.

Furthermore, depending on the burial depth, soil conditions, or lengths of the studied sections, the seismic loss estimation for various tunnel segments within the same metro line may differ. Figure 7 displays the distribution of the calculated expected mean seismic losses *Lm* along various tunnel components of Shanghai Metro Line 10 using seismic intensity *PGA*= 0.6 g as an example. Additionally, it should be noted that Line 10's tunnel components—which are classified as shallow, moderately deep, and deep tunnels, respectively—are all buried in the same types of soil. Their tunnel element length and burial depths, as was previously mentioned, are the main factors that affect their seismic loss. Furthermore, the findings in Figure 7 show that tunnel element ⑫ experiences the biggest seismic loss, or $396.03 \cdot 10^6$ CNY, among other reasons because it has the longest tunnel length of 2777 m. However, compared to the other tunnel elements, tunnel element ⑮ has the lowest seismic loss, at $61.32 \cdot 10^6$ CNY.

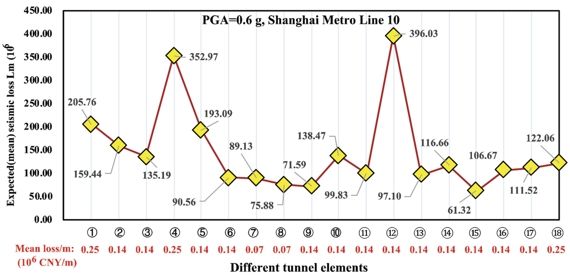


Figure 7. Mean seismic loss *Lm* of Shanghai Metro Line 10 under a hazard intensity *PGA*= 0.6g.

4 CONCLUSION

This work studied the seismic losses of tunnel under ground shaking. A practical probabilistic method for seismic loss assessment of circular tunnels was proposed and demonstrated by the case study of single tunnel segment and the Shanghai Metro Line 10, considering different degrees of seismic intensities. Some conclusions have been drawn as below:

(1) The results indicated that the seismic loss of the tunnels decrease as the seismic hazard intensity decreases.
(2) The tunnel with deeper burial depth is found to have a lower direct seismic losses compared to tunnel embedded in shallower burial depth. Therefore, the tunnel burial depth can be used as an effective factor to control the seismic loss.
(3) The findings of this work can be beneficial to seismic risk mitigation, and further improve the resilience of city infrastructure.

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