

# Analysis of tunnels seismic behaviour: consideration of the structure geometry and site conditions

Zakaria Akakza<sup>1</sup>, Amine Samet<sup>1</sup> and Zohra Boutaraa<sup>1\*</sup>

<sup>1</sup> Hassiba Benbouali University of Chlef- 02000, Algeria

**Abstract.** Tunnels are extremely important underground structures, the durability of which is paramount due to the high cost of their construction, which is undoubtedly tricky due to the encountered ground conditions, and which requires careful planning, particularly in seismic zones. These structures are susceptible to be damaged by earthquakes. Consequently, the study of their behaviour under the effect of seismic vibrations is of great importance. Thus, using an analytical method and two earthquake scenarios, this work aims to analyse the seismic behaviour of a tunnel located in northern Algeria, taking into account the geometry of the structure and the site conditions. The results, represented by fragility curves, show that the mechanical characteristics of the soil layers encountered have a remarkable impact on the behaviour of the tunnel under the effect of earthquakes.

## 1 Introduction

Tunnels are underground structures that can be subjected to seismic shocks in seismic zones. For this reason, assessing their seismic vulnerability is an essential task in the design process. The behaviour of a tunnel under earthquakes can be evaluated, or at least assessed, by evaluating its vulnerability to earthquakes. This can be done by developing the structure's fragility curve.

In the event of an earthquake, tunnels are likely to suffer damage of varying degrees, resulting in them being out of service for varying periods of time, which is detrimental to traffic. To this end, the preventive approach consists of assessing the seismic vulnerability of tunnels by developing fragility curves, expressing the probability of tunnel damage as a function of a parameter measuring seismic intensity (PGA, PGD, etc.). Several methods can be envisaged for developing these curves, including empirical methods, those based on expert judgment and analytical methods.

Several types of damage can occur when an underground structure is subjected to a seismic event [1]. Typical earthquake-induced damage to underground structures can be a combination of those listed below: shearing of the liner along intersecting faults or in contact with formations of different rigidity, roof or wall collapse, collapse and failure of the tunnel lining or in unlined sections, spalling of the concrete lining, cracking of the concrete lining (with longitudinal, transverse or inclined cracks), slope instability leading

to tunnel collapse, ruin of the portal (tunnel entrance or exit), crushing of the concrete lining, spalling of the rock around the opening, bending and buckling of reinforcing bars, cracking of the pavement, wall deformation, and local opening of joints and obstruction of opening [2]. The different modes of tunnels deformation under the earthquakes effect can be deformations of tension-compression or bending or ovalization [1].

Fragility curves are a probabilistic tool for assessing the seismic vulnerability of a structure. These curves are an essential component of a probabilistic seismic risk analysis. Fragility curves make it possible to take into account the random nature of an earthquake and the uncertainties associated with the properties of a structure. It expresses the probability of reaching a certain level of damage for a certain level of seismic intensity. Fragility curves are very useful because they assess the vulnerability and reliability of a structure for the full range of loads to which it will be subjected [3]. Fragility curves of a structure can be developed using various approaches, including the empirical approach based on observations of damage caused by an earthquake or on experimental observations. These fragility curves are very rare and difficult to obtain because earthquakes are exceptional events. Only a few examples are available for bridges or buildings [4]. The second approach is the expert judgment based on the opinion and judgment of several experts. These curves are subjective and can vary greatly depending on the experience of the experts and the level of rigor used in the investigations. Fragility curves based on expert

\* Corresponding author: [z.boutaraa@univ-chlef.dz](mailto:z.boutaraa@univ-chlef.dz)

judgment have been developed to assess the seismic vulnerability of hydroelectric structure components in Canada [5], hybrid approaches and analytical methods used when it is not possible to obtain sufficient actual observations of structural damage or historical earthquake data, it is necessary to develop fragility curves using an analytical approach [6]. Diverse approaches allowing the fragility calculation of critical transportation infrastructure subjected to earthquake excitations with considering geotechnical effects have been summarized by scholars [7].

Studies dealing with the assessment of the seismic vulnerability of tunnels are rarer than those carried out for other types of transportation structures. An analytical method for seismic fragility assessment of a rock mountain tunnel based on support vector machine, in which uncertainties of four types in the fragility analysis have been considered, including tunnel depths, ground motions, rock mass and lining thickness has been proposed by Huang et al. [8]. Among others, one can cite the study carried out to evaluate the seismic vulnerability of circular tunnels in soft soil deposits in *Shanghai* subway system [9]. The critical aspects of many methodologies that have been recently proposed to estimate the vulnerability of bored tunnels in rock or alluvial and cut and cover or underground structures have been also discussed by researchers [10].

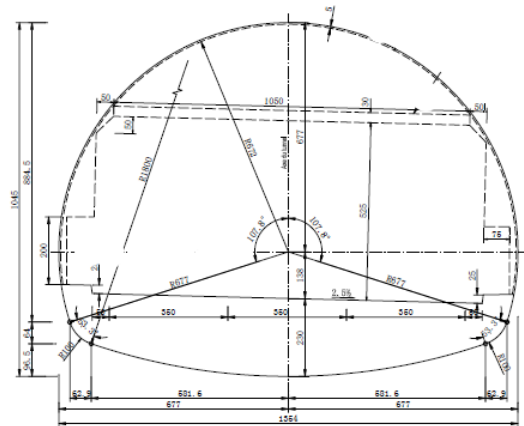
In Algeria, where the northern part is highly prone to seismic activity and tunnels are increasingly being built as part of major road projects launched over the last two decades, especially in the country eastern part, such studies are of great importance. Among them that dealing with the numerical analysis of the influence of the tunnel cover and shape, the thickness of the lining, and the direction of the seismic waves parameters on the behaviour of the soil and the lining of the tunnel of *Djebel El Ouahch* in the province of *Constantine*, the Eastern capital of Algeria [11].

Thus, the aim of this article is to develop fragility curves using the SYNER-G methodology [12], which is an analytical approach for the *Cheffa* road tunnel (Algeria) considering two important parameters, which are the structure type (cross section geometry), and the soil class. 16 profiles are considered in this study. In a second step, two deterministic seismic scenarios, that of *El Asnam* 1980 ( $M_s=7.3$ ,  $PGA=0.296g$ ) and that of *Boumerdes* 2003 ( $M_s=6.9$ ,  $PGA=0.5g$ ) are used as examples to predict the likely damage to the tunnel under study in the event of a major earthquake.

## 2 Studied Case

The case under study is twin circular tunnels with similar cross-sections (2x3 lanes), 11.50 wide and 5.75 height. Each tunnel comprises two tubes. The first tunnel is located 6 km south of *Chiffa* city in the province of *Blida*. The length of the right-hand tunnel is 2.391 km, and that of the left-hand tunnel is 2.375 km. The 2nd tunnel is located in *EL Hemdania* hill, west of *Médéa* province. The length of the right-hand tunnel is 2.423 km, and that of the left-hand tunnel is 2.435 km

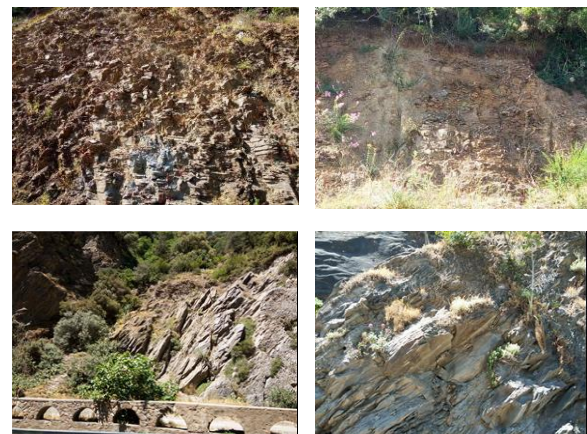
[Data provided by the National Highways Agency]. Figure 2 shows a cross section type of the tunnel.



**Fig.1.** Tunnel cross section

Concerning the site conditions, geotechnical, geological and hydrogeological data are provided by the National Highways Agency, such as the number of joint families in the rock mass, the roughness of joints, their weathering degree and filling material, the hydrological conditions, and the massif tectonic state. The main geological units in the area traversed by the two tunnels are the Neogene of the Mitidja plain, the allochthonous Cretaceous marlstones of the North Blidean Atlas, the Chiffa shales of Lower Cretaceous age and the allochthonous units of Lower, Middle and Upper Cretaceous age.

The area is not very mountainous, the slopes are rough and the morphology is uneven. The ravines are V-shaped and the natural gradient varies from  $30^\circ \sim 50^\circ$ . The minimum altitude on the tunnel axis is 292.13m, and the maximum altitude is 683.13m. In this study, the crucial parameter used to classify the soil profiles thought the crossed site is the *RQD*, defined above. The values of this factor for the 16 considered profiles are given in table 1.



**Fig.2.** Rocky massifs in the tunnel area

**Table 1.** RQD values in the 16 considered soil profiles.

Profile	RQD (%)
1	15
2	15
3	15
4	30
5	15
6	30
7	15
8	25
9	60
10	45
11	15
12	60
13	60
14	65
15	45
16	15

As regards the site seismicity, the geological structure is a layered structure comprising five seismic faults. The principal fault is 5 km long and crosses the two tunnels. It is characterised by breccia and mylonite outcrops. The other four faults are much smaller and are only a few metres in length. The hydrogeological network is well developed, in the form of gullies with permanent flows. The flow rate measured for one of the gullies during this investigation was of the order of 5L/S. A second, smaller gully exists with a flow rate of the order of 1L/S.

### 3 Methodology

The adopted methodology is SYNER-G (Systemic Seismic Vulnerability and Risk Analysis for Buildings, Lifeline Networks and Infrastructures Safety Gain), which is an innovative methodology developed by the Norwegian Geotechnical Institute (NGI). It uses the *PGA* (Peak Ground Acceleration) as a measure of seismic motion. The analytical expression of the fragility curves is given by equation 1 [12].

$$P(D \geq DSk) = \frac{1}{2} \left[ 1 + \operatorname{erf} \left( \frac{\ln PGA - \ln \mu}{\beta \sqrt{2}} \right) \right] \quad (1)$$

Where:

$P(D \geq DSk)$ : is the probability of exceeding the damage degree  $k$  ( $k=2$  for minor damage,  $k=3$  for moderate damage, and  $k=4$  for extensive damage).

$\mu$  and  $\beta$ : are the two fragility parameters depending on the soil class and the tunnel typology (cross-section geometric shape), provided by Table 2.

Once the soil classes of each soil profile are determined via the RQD soil designation and correspondence to EC8 specifications, the fragility parameters  $\mu$  and  $\beta$  are selected from table 3 below for the two considered cases; circular and equivalent rectangular cross section shape. Then, using equation (1) fragility curves are developed for each damage level:  $Ds_2$ ,  $Ds_3$ , and  $Ds_4$ . Two cases of tunnel cross-section geometry are considered: a first case which corresponds to the actual cross-section, which is circular, and a second case which is assumed, in order to compare the results of the damage to be sustained, and which corresponds to a rectangular section having the same width as the diameter of the circular section, from which it is designated by equivalent rectangle.

In a second step, two seismic scenarios are used to compare the damages percentage recorded by the tunnel in both cases. The two scenarios chosen are that of *El Asnam* 1980 with a seismic magnitude ( $M_S = 7.3$ ,  $PGA = 0,296g$ ) and that of *Boumerdes* 2003 with a magnitude ( $M_s = 6.9$ ,  $PGA = 0.5g$ ), according to the post seismic survey [13]. It should be noted that these two earthquakes are the two major seismic events to have occurred in Algeria in the last and current centuries.. The adopted methodology is represented by the flowchart of figure 3.

#### 3.1.Site Geotechnical Characteristics

The soil geotechnical characteristics are estimated using the *RQD* (Rock Quality Designation) parameter, which is fundamental for the dimensioning and design of underground structures. The *RQD* is used to classify the soil crossed layers and to determine their quality (Tab.2). The value of this coefficient is determined on the basis of a core sample, about 50 mm in diameter, taken on site. Based on this value, each soil profile all along the tunnel longitudinal profile is classified in one of the soil classes adopted by EC8 [14].

According to the European code classification, the shear wave velocity  $V_s$  is equal to 360-800 m/s for soil type *B*, 180-360 m/s for soil type *C*, and  $< 180$  m/s for soil *D*. These values are in accordance with those fixed by the Algerian seismic code that classifies type *B* as a dense soil, *C* as a soft soil, and *D* as a very loose soil [15].

**Table 2.** Soil classification based on the RQD factor

RQD (%)	Designation	Corresponding Soil Class
0-25	Very mediocre	<i>D</i>
25-50	Mediocre	<i>D</i>
50-75	Medium	<i>C</i>
75-90	Good	<i>B</i>
90-100	Excellent	<i>A</i>

### 3.2. Fragility Parameters

SYNERG provides the fragility parameters values depending on the soil class and the tunnel typology; cross-section geometric shape (Table 3).

In this work two types of tunnel structure are considered: a circular cross-section, which is the actual case of the tunnel studied, and a second rectangular cross-section, which is assumed in this work for comparison purposes.

**Table 3.** Fragility parameters according to the tunnel typology [16]

Tunnel Typology	Damage	Soil Type					
		B		C		D	
		$\mu$	$\beta$	$\mu$	$\beta$	$\mu$	$\beta$
Circular	Ds2	1.24	0.55	0.55	0.70	0.47	0.75
	Ds3	1.51	0.55	0.82	0.70	0.66	0.75
	Ds4	1.74	0.55	1.05	0.70	0.83	0.75
Equivalent Rectangular	Ds2	0.75	0.55	0.38	0.55	0.36	0.55
	Ds3	1.28	0.55	0.76	0.55	0.73	0.55
	Ds4	1.73	0.55	1.08	0.56	1.05	0.55

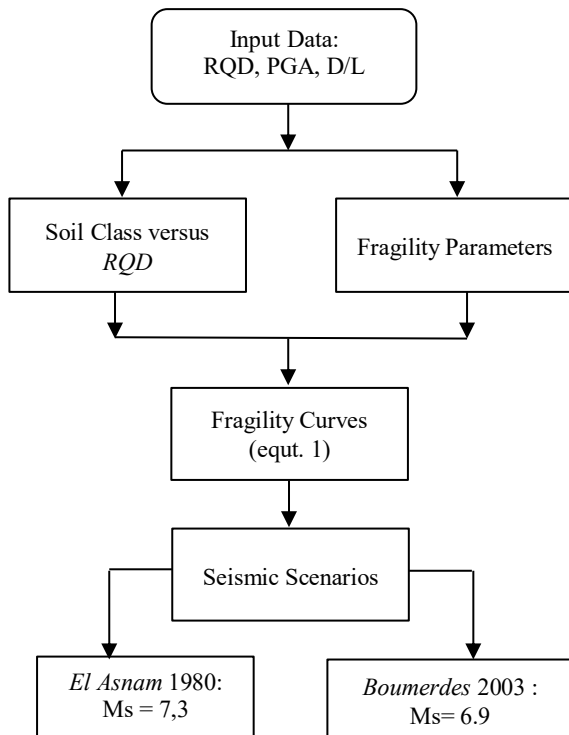
## 4 Results and Discussion

### 4.1. Soil Profiles Classes

The first result consists in the obtained soil classification for each of the 16 profiles considered in this study, according to the Euro code and based on the *RQD* values (Table 4). It can be conclude that 81.25% of the 16 considered soil profiles are composed of low quality soil, since it ranges from soft to very loose.

**Table 4.** Results of the soil profiles classification

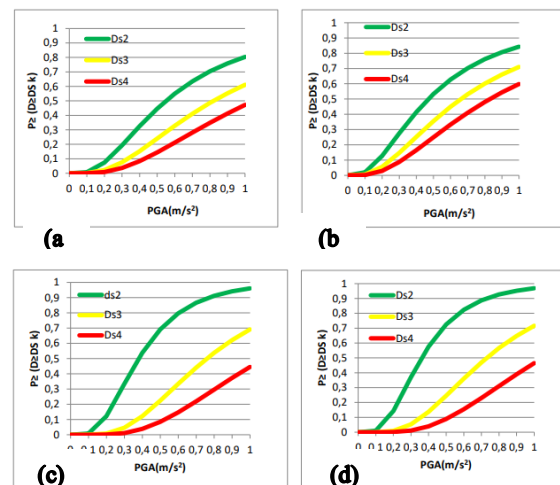
Profile	Soil Class
1	D
2	D
3	D
4	D
5	D
6	D
7	D
8	D
9	C
10	D
11	D
12	C
13	C
14	C
15	D
16	D



**Fig.3.** Followed steps to develop the tunnel fragility curves and seismic scenarios damages

### 4.2. Soil Profiles Classes

The developed fragility curves for the studied case of tunnel are shown in Figure 4 for the different levels of damage (minor DS2, moderate DS3 and extensive DS4) and for the four cases considered in this study, namely: circular tunnel in type C and D soils, and equivalent rectangular tunnel in soil types C and D.



**Fig.4.** Fragility curves: (a) circular tunnel in soil class C, (b) in soil class D, and (c) equivalent rectangular tunnel in soil class C, and (d) in soil class D

In soil class C the circular tunnel suffers less minor and moderate damage and slightly more extensive damage

than the equivalent rectangular tunnel shape. For minor damage the maximum damage value in the former is 96% and 80% in the latter. Concerning moderate damage, the maximum damage level in the equivalent rectangular tunnel shape is 69%, while this value is 61% for the circular tunnel. Then, for extensive damage the maximum damage value is close for the two tunnel shapes (44% in the rectangular tunnel and 47% in the circular tunnel). In soil class "D": both types of tunnels suffer higher damage (13% more than in soil class C).

On the other hand, in soil class D maximum minor damages recorded in the equivalent rectangular tunnel shape are 96% and 84% in the circular tunnel shape. However, the maximum level of moderate damage is 72% for the equivalent rectangular tunnel shape, and 71% for the circular tunnel. About extensive damage, the maximum level of damage expected to be recorded by the two tunnels is close (46% in the equivalent rectangular tunnel and 59% in the circular tunnel). Therefore, the circular shape reduces minor and moderate damage, however, extensive damages remain close whatever soil class.

### 4.3. Seismic Scenarios

Results of the two seismic scenarios used to compare the damages recorded by the tunnel in both cases; circular and rectangular shapes are summarized in Table 5. These results show that circular shape reduces minor damage compared to rectangular shape. But, moderate and extensive damage are increased to some extent. The impact of soil class remains notable, as the percentages recorded for all damage levels are higher in soil class D than in class C. Finally, the PGA has an important impact on the recorded damages; the higher the PGA, the greater the damages.

**Table.5.** Seismic Scenarios Results

Scenario	Tunnel Shape	Soil Class					
		C			D		
		Damage (%)			Damage (%)		
		Ds2	Ds3	Ds4	Ds2	Ds3	Ds4
<i>Boumerdes</i> 2003	Cir.	19.3	7.5	3.6	27.5	14.65	8.7
	Rect.	33.3	4.5	1.1	37	5	1.1
<i>El Asnam</i> 1980	Cir.	44.5	24	14.4	53.2	35	5
	Rect.	69.1	22.3	8.4	72.4	24.5	8.8

The values shown in Table 5 confirm the observations made in section 4.2 above, particularly with regard to the type of structure. Indeed, circular section has a positive effect on reducing the degree of minor damage recorded by the tunnel. On the other hand, for the other two types of damage (moderate and extensive) there is a slight increase in damage in the case of the circular shape compared to the rectangular shape.

The two seismic scenarios considered as examples for the assessment of damage probabilities, and which are major earthquakes of low occurrence, show that the circular tunnel shape will suffer extensive damage four times greater (14.4%) in the event of an earthquake of the same magnitude as that of *El Asnam* 1980 compared with the earthquake of *Boumerdes* which will generate damage of the same type of 4.4%.

In addition, the impact of soil class remains remarkable, in so far as the percentages of damage recorded for the three levels of damage are higher in class D soil than in class C soil.

### 5 Conclusions

This work focused on the study of tunnels behaviour to earthquakes by developing fragility curves using SYNER-G method. Soil classes of the 16 considered profiles were determined versus the RQDs. For the purpose of comparing results, two types of tunnel cross-section have been considered (circular/rectangular). The main results show the following findings:

The circular shape reduces the damage suffered by the tunnel, particularly minor damages, which are the most frequent, given the infrequency of major earthquakes. On the other hand, the soil class has a major impact on the damage sustained by the tunnel. In soil class D: both types of tunnels suffer higher damage (13% more than in soil class C).

Additionally, the introduction of the two seismic scenarios in this study makes it possible to confirm the influence of the ground acceleration recorded during the major earthquakes of *Boumerdes* 2003 and *El Asnam* 1980 on the levels of damage that the tunnel studied may suffer in the event of an earthquake of the same seismic acceleration, and consequently of the same magnitude. The PGA value has a great impact on the recorded damages (the higher the PGA, the greater the damages). Finally, the results study highlights the beneficial effect of the circular tunnel shape adopted for the project, and of course the negative impact of soil class.

### References

1. Y.M.A. Hashash, J. J. Hook, Bi. Schmidt, J. I-Chiang Yao, Seismic design and analysis of underground structures. *Tunnelling and Underground Space Technology* **16**: 247-293 (2011)

2. M. Corigliano, L. Scandella, C.G. Lai and R. Paolucci, Seismic analysis of deep tunnels in near fault conditions: a case study in Southern Italy. *Bull Earth. Eng* (2011). [http://doi.org/10.1007/s10518-011-9249-3\(2011\)](http://doi.org/10.1007/s10518-011-9249-3(2011))
3. T. Kheffache, Modélisation du creusement d'un tunnel en milieu urbain cas de métro d'Alger, Master Thesis, University of Bejaia, Algeria (2007)
4. D. H. Tavares, Évaluation de la vulnérabilité sismique des ponts routiers au Québec à l'aide des courbes de fragilité. Ph. D. Thesis, University of Sherbrooke, Canada, 2012.
5. L. Lin, J. Adams, Lessons for the fragility of Canadian hydropower components under seismic loading. In *Proceedings of the Ninth Canadian Conference on Earthquake Engineering*, June 26-29, (2007).
6. B. G. Nielson, Analytical fragility curves for highway bridges in moderate seismic zones. Ph. D Thesis, Georgia Institute of Technology, Atlanta, Georgia, 2005.
7. S. Argyroudis, S. Mitoulis, A. M. Kaynia, M. G. Winter, Fragility assessment of transportation infrastructure systems subjected to earthquakes. In *Proceedings of Geotechnical Earthquake Engineering and Soil Dynamics V Conference*, Austin, Texas, US, June 10-13, (2018)
8. G. Huang, W. Qiu, J. Zhang, Modelling seismic fragility of a rock mountain tunnel based on support vector machine. *Soil Dyn. & Earth. Eng.*, **102**:160-171 (2017).  
<http://doi.org/10.1016/j.soildyn.2017.09.002>
9. Z.K. Huang, K. Pitilakis, G. Tsinidis, S. Argyroudis, D. M. Zhang, Seismic vulnerability of circular tunnels in soft soil deposits: The case of Shanghai metropolitan system. *Tunnelling and Underground Space Technology*, **98**, 103341(2020).  
<http://doi.org/10.1016/j.tust.2020.103341>
10. G. Tsinidis, A. Karatzetzou, S. Stefanidou, O. Markogiannaki, S. A. Argyroudis, Recent advances in seismic vulnerability assessment of tunnels and underground structures. In *Proceedings of 3rd International Conference on Natural Hazards & Infrastructure: ICONHIC*, Athens, Greece, July 5-7, (2022).
11. A. Berkane, S. Mezhoud, B. Tayeb, T. Karech, A. Noui, Parametric study of shallow tunnel under seismic conditions for constantine Motorway tunnel, Algeria. *Geot. and Geol. Eng.* **40**(8):1-12 (2022).
12. K. Pitilakis, S. Argyroudis, K. Kakderi, A. Argyroudi, SYNER-G: Systemic Seismic Vulnerability and Risk Analysis for Buildings, Lifeline Networks and Infrastructures Safety Gain. Luxembourg: Publications Office of the European Union, (2013).  
<https://publications.jrc.ec.europa.eu/repository/bitstream/JRC84703/lbna26157enn.pdf>
13. Z. Boutaraa, Revelations of the 1980 El Assnam (Algeria) earthquake: urban seismic vulnerability. (Lambert Academic Publishing, Mauritius, 2018).
14. Eurocode 8 EN 1998-2 : Design of structures for earthquake resistance Part 2: Bridges
15. RPOA, Règles parasismique applicables au domaine des ouvrages d'art, Ministère des travaux public, Algérie (2010).