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ORIGINAL PAPER

# Parametric Study of Shallow Tunnel Under Seismic Conditions for Constantine Motorway Tunnel, Algeria

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**Abstract** When designing tunnels, it is advisable to pre-estimate several tunnel parameters such as the depth (cover), the lining thickness, and the shape of the tunnel cross section. This condition is important in order to limit deformations during construction of the tunnel, and to ensure good tunnel resistance under seismic load conditions. In this context, the present paper is devoted to the analysis of the influence of some test parameters (the cover of the tunnel, the thickness of the lining, and the shape of the tunnel and the direction of the seismic waves) on the behaviour of the soil and the lining of a shallow tunnel built in soft ground subjected to seismic loading. The reference model for this parametric study is a real case, which happens to be the tunnel of Djebel El Ouahch (East-West motorway) in the province of Constantine/Algeria. The study is performed in three dimensions (3D) using a finite difference calculation method based on the FLAC3D calculation code. The results are presented in terms of shear strain induced in the soil around the tunnel, surface settlement, and vertical displacement of soil under the raft foundation, and also shear stress, bending moment, and shear strain, induced in the tunnel lining. The results show that the increase in thickness of the lining causes a reduction in shear force, and shear strain, while the circular or oval shape of the tunnel cross section results in low values of strain in the lining and ground displacement. It has been also pointed out that bending moment and shear strain induced in the lining are relatively low in comparison with the other forms. On the other hand, the direction of the seismic waves has a great influence on the behaviour of the lining and the surrounding soil. These results demonstrate that the strongest and most stable tunnel is the deepest tunnel with circular or oval section with a large thickness of the tunnel lining under the effect of compressive seismic waves. The results of the present study will be useful in the design of such a case by understanding the effects of various influencing parameters that control the stability of the tunnel in soil with bad characteristics.

**Keywords** Shallow tunnel · Earthquake · Tunnel depth · Shape · Lining thickness

## 1 Introduction

The study of the seismic behavior of tunnels has become in recent years a major concern for geotechnicians, after the collapse of many structures hitherto assumed to be safe from seismic risk as long as the structure did not pass through a fault plane or major

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geological fault. On the other hand, recent studies have confirmed that various tunnels could be damaged by earthquakes (Chen et al. 2012). Some of these studies are summarized in the following section: (1) The Kanto 1923 earthquake (local Magnitude 8.16) damaged 82 rail tunnels out of a total of 116 structures affected in the area impacted by the earthquake. The damage mainly concerned the tunnel entrances, transverse and longitudinal cracking in the coatings linked to excessive deformation (Hashash et al. 2001); (2) In 1995, in Hyogo-ken Nanbu (Kobe, Japan) the earthquake caused the collapse of the Daikai subway station. The station was located about 20 km from the epicenter of the magnitude 6.9 earthquake (Uenishi and Sakurai 2000); (3) The Chi-Chi earthquake in central Taiwan on September 21, 1999 caused extensive damage to the tunnels dug in the mountain. The 7.3 magnitude earthquake was related to the Chelungpu fault located 60 km from the structures. It was found that, among the 57 impacted tunnels, 49 of them were damaged (Wang et al. 2001); (4) Chen et al. (2012) studied a total of 81 mountain tunnels damaged by 10 major earthquakes. The damage has been classified into six typical characteristics; (1) skin cracks, (2) skin shear failure, (3) tunnel collapse caused by slope failure, (4) portal crack, (5) leak and (6) wall deformation/reverse damage.

Indeed, in the literature several authors correlate the seismic vulnerability of a tunnel to certain relevant factors such as: the tunnel cover, the type of soil, the maximum acceleration of the ground, the magnitude of the earthquake, the distance of the epicenter, the ground-tunnel interface conditions, the coating thickness, and the shape of the tunnel. Khoshnoudian (1999) studied the influence of tunnel depth on internal forces (bending moments and shear forces) induced in the tunnel lining, three configurations H/D = (1, 2; 1.8 and 2.4) which correspond respectively to a tunnel close to the ground surface was examined. Calculations were made for the first three frequencies. He observed an increase in these forces with depth for the first and third loading frequency, but a decrease for the second frequency. These results are in agreement with those presented by Owen and Scholl (1981). Sliteen (2013) examined the effect of depth, the numerical simulations carried out for two values of the tunnel depth corresponding respectively to a shallow tunnel and a deep tunnel. The results obtained confirm that the depth effect is important for the normal force, this influence is less significant for the bending moment and the shearing force. Patil et al. (2018) studied the influence of tunnel anchoring rate, on the behavior of the shallow tunnel in soft ground under seismic conditions, they were observed that the distortion in the tunnel lining depends on the anchoring depth and the flexibility ratio of the tunnel. It can be seen that the ovality (in a circular tunnel) and the shelving (in a rectangular tunnel) decrease considerably when the anchoring rate is greater than 2. Berkane and Karech (2018), studied the influence of the tunnel anchoring rate (depth), on the behavior of the shallow tunnel in a soft rock (argillite), it was observed that the decrease in depth of the tunnel increases the risk of instability of the ground-tunnel system, and increasing this depth contributes to its stability. The research of Aicha and Mezhoud (2021) include a parametric study to assess the effect of several parameters on the behavior of the tunnel and the surrounding soil such as the tunnel anchoring depth, the tunnel-soil interface rate and the form of a tunnel the Cross section. The results show that the strongest and most stable position is the mid-deep tunnel with a circular section, with a non-slip interface between the tunnel and the ground.

In addition, some authors studied the tunnel deformation due to earthquake. Owen and Scholl (1981) have showed the three types of deformations which express the seismic response of underground structures as follows: (a) Compression and axial extension: When the compression waves propagate parallel to the axis of the tunnel, the shear stresses transferred between the ground and the structure cause alternating compressive and tensile stresses. These forces are limited by the shear strength of the interface between the tunnel surface and the surrounding soil; (b) Longitudinal bending: If the seismic waves propagate obliquely with respect to the axis of the tunnel, the components of the seismic waves producing movements of particles perpendicular to the longitudinal axis. These movements subject different parts of the structure to out of phase displacements. The result is a compression-rarefaction-longitudinal wave propagating in the tunnel; (c) Deformation of ovality: These deformations develop under the effect of a propagation of shear waves normal or almost normal to the axis of the tunnel.

Regarding the methods used for the seismic analysis of tunnels and design, they can be classified according to the following approaches (Okamato et al. 1973;

Wang 1993): (1) free-field strain approach; (2) soil-structure interaction approach; and (3) dynamic earth pressure method. The free-field approach describes soil deformations or deformations caused by seismic waves without the structure being introduced into the analysis. The general behavior of the tunnel lining is similar to that of an elastic beam subjected to deformations and stresses imposed by the surrounding soil. Tunnel deformations can be overestimated or underestimated depending on the tunnel stiffness with respect to the ground. In the second method, called the interaction method, we consider the interaction between the ground and the tunnel. On the other hand, the use of the dynamic approach of land pressure for tunnels and underground structures comes up against several limitations (Okamato et al. 1973). Therefore, in this paper, the focus will be only on the soil-structure interaction and due to the complex nature of the interaction problem, it is necessary to use numerical techniques such as: the difference method (FDM) to model the interaction of the tunnel lining with the surrounding soil, using the FLAC3D computer code (Itasca 2013). Previous studies (Jiang et al. 2009; Li et al. 2010) have studied the seismic response in tunnels under the effect of Rayleigh waves, which consist respectively of combining the horizontal and vertical seismic components (S waves) and (P waves), overground. The results of the studies showed that Rayleigh waves could be significant in the case of very shallow underground distribution tunnels.

Despite these literature reviews, researches regarding to the dynamic behavior of tunnel under seismic conditions are almost overlooked. In addition, most of these authors have devoted their work to the latter type of deformation linked to the distortion of the cross section of the tunnel lining and generated by shear waves propagating perpendicular to the axis of the tunnel, but the studies concerning the axial deformation and flexural strain are almost neglected. For this reason, the main purpose and results of this work is to study the seismic response due to the shear waves and the effect of the compression waves which propagate in the plane parallel to the axis of the tunnel. It is important also to evaluate the influence of certain parameters (tunnel cover, coating thickness, tunnel shape and direction of seismic waves) on the dynamic behavior of the tunnel lining and the surrounding soil. Furthermore, this work aims to evaluate the dynamic behavior of shallow tunnel under seismic conditions in order to be useful in the design of such a case by understanding the effects of various influencing parameters that control the stability of the tunnel in soil with bad characteristics.

## 2 Description of the Case Study

The T1 tunnel in Constantine province (Algeria) was chosen as case study. This tunnel is part of the construction of the Maghreb Unity Motorway (AUM), approximately 7000 km in length, crossing Algeria with a length of 1200 km. The damaged tunnel belongs to Sect. 4.1 of this highway (Berkane et al. 2018). It crosses Djebel El-Ouahch mountain in the northeast of the province of Constantine and includes two practically parallel tubes with a total length of 1909 m. Several authors (Mezhoud et al. 2017, 2018; Samy et al. 2019) indicated that the motorway at this location suffered by several geotechnical problems in addition to tunnel collapse, like soil sliding and ground swelling by decompression which caused the appearance of serious reflective cracking, during construction and after commissioning the motorway.

The section chosen for the dynamic study is located in the most critical zone (shallow depth zone), corresponding to the kilometer point of [PK: 205 + 407.5 up to 205 + 476 for the straight tube, and PK: 205+ 393 up to 205 + 461.5] for the left tube, in the vicinity of Sounding S4-LT-2NP. The geometry of this section which is taken as the reference for the modeling is presented in Fig. 1a. The average tunnel depth at this section is 17 m. In addition, the studied part of the T1 tunnel passes through argillite or Mudstone. The mechanical and geological characteristics of the natural terrain comprising the studied section are summarized in Table 1 and presented in Fig. 1b.

The depths considered for calculation are: H = 17 m (the reference value), H + 5 and H-5 (depending on the topology of the tunnel) with a tunnel length of 50 m (according to the literature study, the seismic effect is taken into account only in the first 50 m from the entrance or exit of the tunnel) (Fig. 1a, b); the lining thicknesses are: t = 0.4 m (reference value), t = 0.2 m, and t = 0.8 m (Fig. 1c); the shapes of the tunnel considered are: the reference shape (Fig. 1a), circular shape, and rectangular shape as presented in Fig. 1c, d. Regarding to types of the seismic waves, the compression and shear waves are considered (Fig. 1e, f).

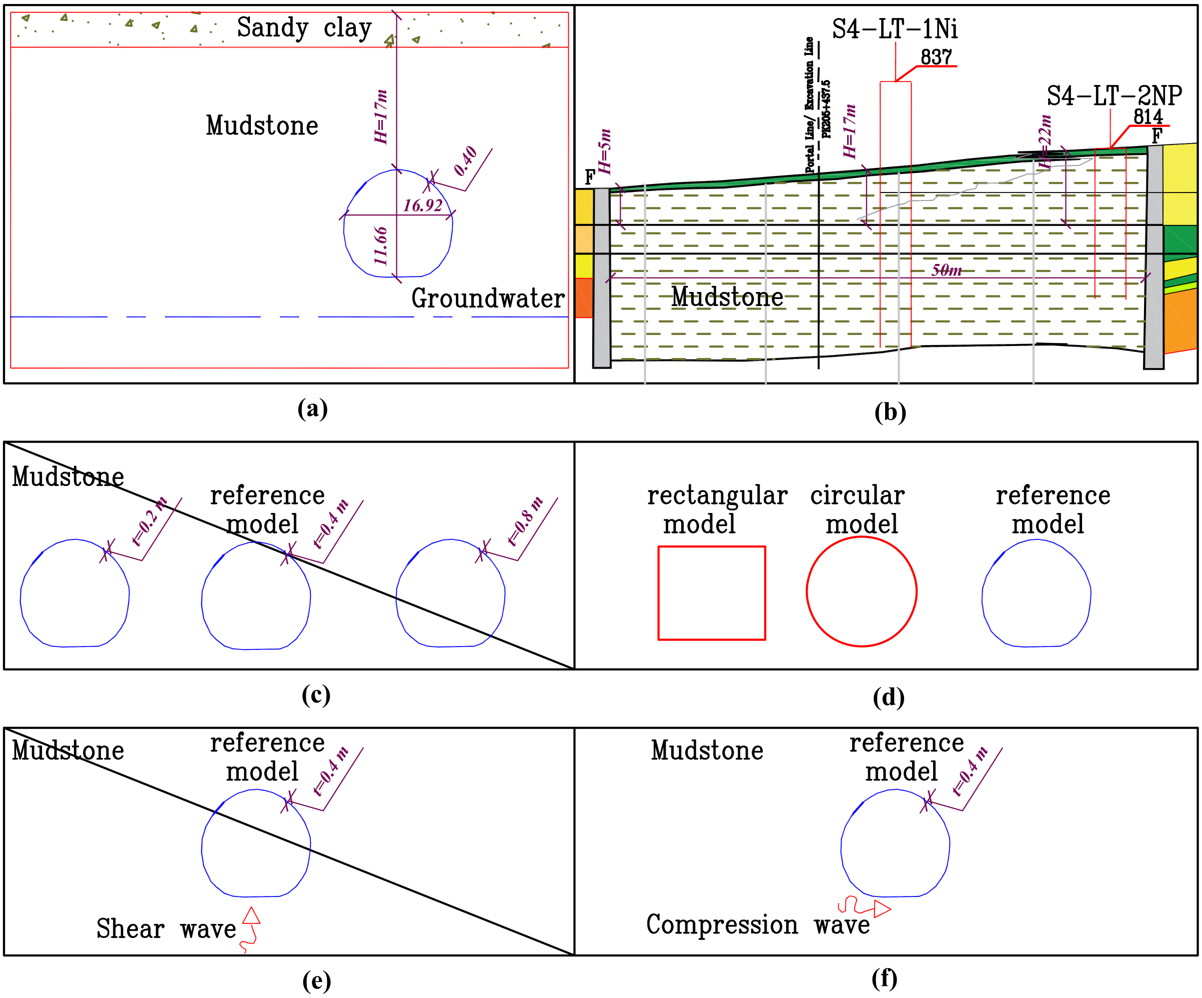


**Fig. 1** **a** Cross section of the model reference *with* (*L* = 50 m); **b** Longitudinal section of the model; **c** The thickness of the different models; **d** Different shapes of models cross section; **e** Model with shear waves; **f** Model with compression waves

**Table 1** Geotechnical characteristics of the soil

| Soil nature | γ (kN/m$^3$) | γsat (kN/m$^3$) | C (kN/m$^2$) | φ(°) | E (kN/m$^2$) | υ | Gmax (kN/m$^2$) | Vs (m/s) |
|---|---|---|---|---|---|---|---|---|
| Sandy clay | 19.05 | 21.60 | 0.29 | 19.5 | 2.0 E4 | 0.33 | – | – |
| Mudstone | 25.10 | 25.58 | 200 | 25.0 | 1.0 E5 | 0.35 | 9E6 | 1900 |

## 3 Numerical Modeling

### 3.1 Soil Model Used to Represent the Behavior of the Soil

The cyclic behavior of the soil is represented by the combination of two models: a hysteretic damping model of Hardin/Drnevich and an elastoplastic model of Mohr-Coulomb (Hardin and Drnevich 1972).

The Mohr-Coulomb model has a constant tangent elastic shear modulus $G_{max}$, and a constant yield strength $\tau_m$. The modulus reduction technique is applied in the elastic range while natural damping is applied in the plastic range. The inclusion of hysteretic damping reduces the shear modulus from the initial value $G_{max}$, and increases the damping ratio. The latter increases monotonically with the magnitude of the shear strain. As a result, the efficiency level of the hyperbolic law must be greater than the Mohr Coulomb breaking stress. The Hardin/Drnevich model is used to ensure the energy dissipation in the elastic domain and not to simulate the efficiency using a hyperbolic plasticity model.

### 3.2 The Earthquake Adopted for the Dynamic Study

In order to study the dynamic effect on the behavior of the tunnels, our calculation is based on the Boumerdes Earthquake (magnitude of 6.8), considered the most important in Algeria during the last twenty years, the most violent earthquake in Algeria occurred in Chlef (Ex. Asnam) on October 10, 1980, with a magnitude of 7.3. On May 21, 2003, the region of Boumerdes about 70 km East of the capital Algiers suffered an earthquake of magnitude order of 6.8 determined by the USGS (US Geological Survey). The recorded amplitude is given by the Dar El Beida station (0.52 g). The earthquake lasted 27.67 s. maximum acceleration is 556.79 cm/s$^2$ (0.57 g) at 7.70 s. In the response spectrum, the seismic acceleration corresponds to nearly 3 Hz and 6 to 8 Hz (Fig. 2).

We adopted one of the most dangerous earthquakes in Algeria, and Constantine could have known the same intensity in order to put the tunnel in the worst case.

### 3.3 Numerical Modeling of the Tunnel

The study is carried out in 3D by a finite difference calculation using the FLAC3D calculation code (Fast Lagrangian Analysis of Continua in 3D). The calculation code (FLAC3D) for this study uses the combined Hardin/Drnevich hysteretic damping model with the Mohr-Coulomb elastoplastic model to simulate the behavior of the soil under seismic stress. The earthquake is modeled by a load applied to the base of the massif in the horizontal direction in the form of a sinusoidal harmonic load of varying amplitude (see Eq. 1). The wave has a frequency of 6 Hz with an amplitude equal to the maximum earthquake speed = 27.28 cm/s.

$$\mathrm{Sinwave} = 4.07.e^{-\frac{t}{6}\sqrt{55^{e^{-5.5t}}}}.t^{12}.\sin(2\pi.\mathrm{f}.\mathrm{t}) \qquad (1)$$

with f: frequency and t: time.

A Rayleigh damping of 5% is considered in this calculation. The lateral boundaries of the model are stressed by the movement of the ground in a free field. Figure 3 presents a three-dimensional model of the case studied in a Cartesian coordinate system (o, x, y, z), where (x) is the horizontal direction, (y) the longitudinal direction and (z) the vertical direction. The dimensions of the model are: length Lx = 90 m, longitudinal depth Ly = 50 m and height Lz = 40 m. The base of the tunnel is 10 m from the substratum. The height of the cover above the tunnel is 17 m.

The finite difference analysis of the tunnel seismic response is carried out in three stages:

- Establishment of the initial stress field before the excavation work of two tunnel tubes, with the coefficient of the ground at rest $k_o = 0.5$.
- Establishment of the stress field after the excavation and the installation of the tunnel lining.
- Dynamic calculation.

### 3.4 Verification of the Numerical Modelling

During the design phase of tunnel constructions, advanced finite element models are a convenient tool to predict and reduce the impact of settlement or earthquake at the level of the infrastructure. These models can only deliver realistic results if, on the one hand, the level of detail of the model is high enough and, on the other hand, the model parameters have been well calibrated and validated. Since the tunnel and its surrounding soils are subjected to large parameter uncertainties, the determination of the model parameters is quite challenging. In addition, measurement data which is continuously recorded through sensors or several experimentations, is quite necessary for validation process. However, in this case of tunnel collapse, we are dealing with a real case of damage tunnel, which is not possible to make experimentations or field investigation. In addition, there are loss of records and suitable data or experimental results for model validation, therefore it is difficult to undergo a validation process in this case, and the analysis results of this tunnel pathology are considered as suggestions on further improvement of the numerical tunnel modelling.

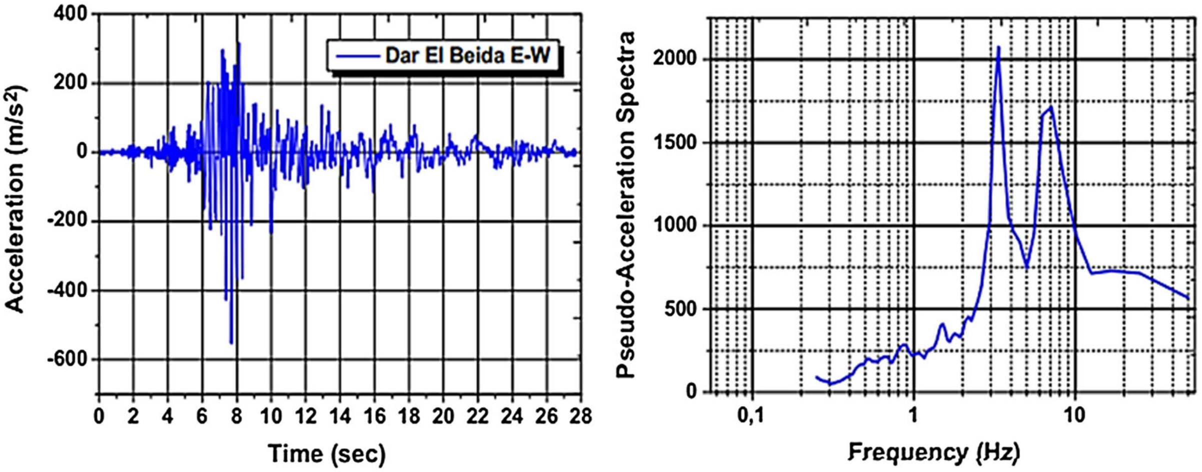


**Fig. 2** Accelerometer signal East–West at Dar El Beida station and the corresponding response spectrum

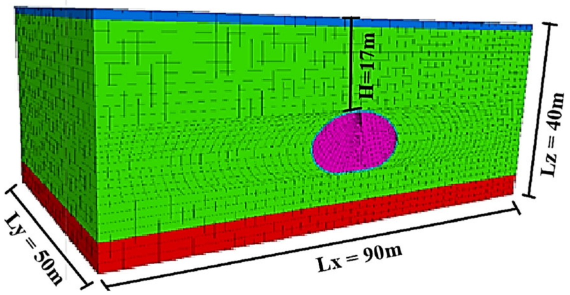


**Fig. 3** 3D mesh of the reference model

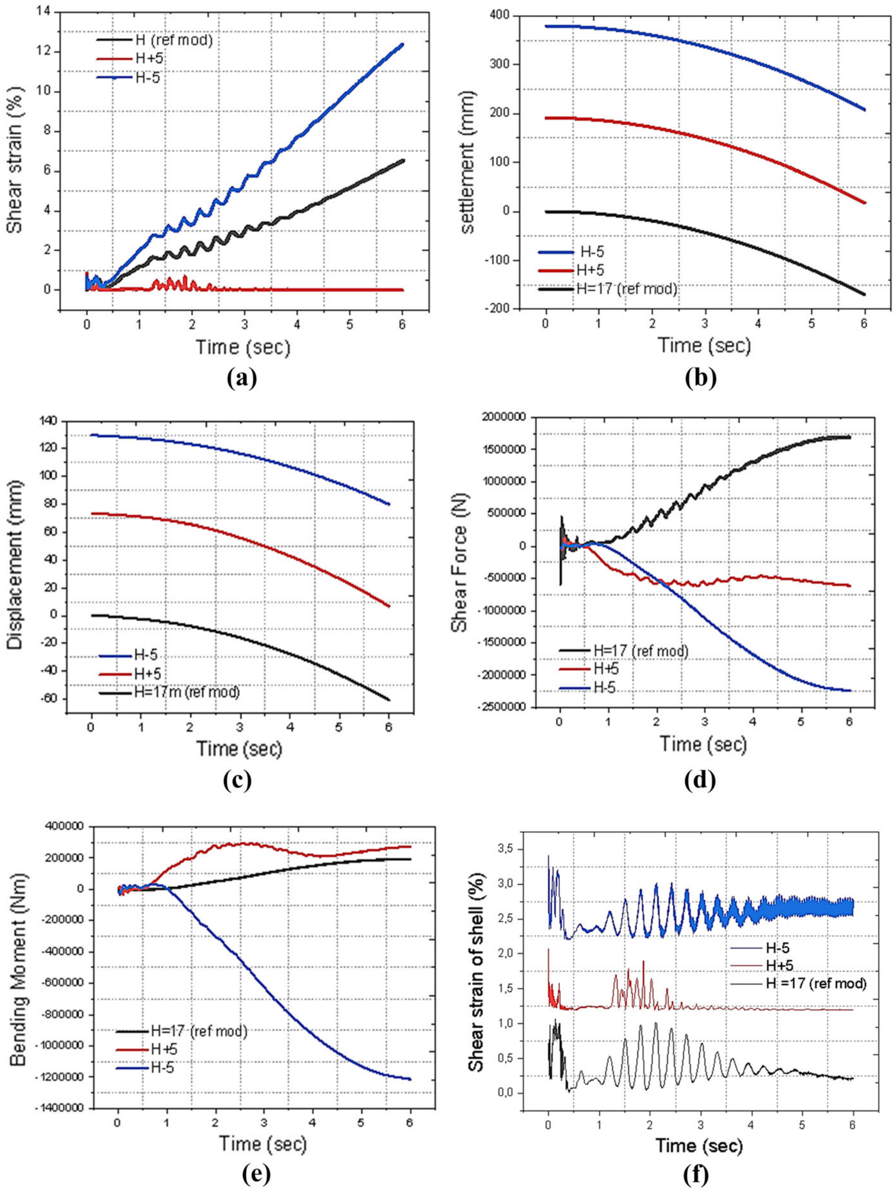
## 4 Results and Discussion

### 4.1 Effect of Tunnel Depth

The effect of the tunnel depth (the coverage) (H) is the subject of this part. The results of the numerical simulation are presented in the Fig. 4a–f. The influence of the tunnel depth (H) on soil behavior is considered through three values located above the keystone of the tunnel. Additionally, to the real depth of the tunnel at this location (H = 17 m), two other tunnel depths are considered, H+5, and H-5. The choice of the three depths was done according to the longitudinal section of the tunnel. The results obtained are compared in order to detect the most stable tunnel's location given that the soil at these locations have the same geological and geotechnical characteristics in case of seismic loading.

The comparison between the three curves of shear deformation (Fig. 4a), the settlement at the free surface of the soil above the tunnel (Fig. 4b), and vertical displacement under the tunnel raft (Fig. 4c) shows that the shear strains appearing in the soil around the left tunnel tube cavity increase with decreasing depth, and vice versa. In addition, the high shear strain in the soil can lead to a reduction in the shear strength of the soil and consequently a reduction in the bearing capacity and therefore the risk of increased cracking in the mass of the soil (Berkane et al. 2021). The accentuated deformations were due to several factors such as: convergence due to high tunnel depth, the case of the deep tunnel, and low compressive strength of argillite in the case of shallow tunnel (Berkane and Karech 2018). On the other hand, the settlement at the free surface of the soil for three different depths of the tunnel, and the vertical displacement of the soil under the base of the left tunnel tube are highly variable and inversely proportional to the depth of the tunnel. As mentioned in results H+5 (22 m) position gives the lower shear strain, settlement, and displacement. Therefore, it can be said that the deepest tunnel contributes to the stability of the ground around the tunnel.

In addition, it is also apparent from Fig. 4d-f that the shear force induced in the tunnel lining (Fig. 4d), the bending moment (Fig. 4e), as well as the shear deformation (Fig. 4f) appearing in the tunnel lining are inversely proportional to the depth, these values increase strongly with change of signs in the case of a decrease in depth, and become less important in the case of an increase in depth. Increasing the values of these terms can lead to a decrease in the shear strength



(a) (b) (c) (d) (e) (f)

**Fig. 4** Effect of tunnel depth variation: **a** Induced shear strain in the ground around the tunnel cavity; **b** Settlement at the soil surface above the tunnel; **c** Vertical displacement under the tunnel raft; **d** Shear force induced in the tunnel lining; **e** Bending moment induced in tunnel lining; and **f** shear strain induced in the tunnel lining

and consequently to the appearance of openings and cracks in the tunnel wall due to the low tensile strength of the concrete. These results are in conformity with those of Patil et al. (2018), which indicated that the tunnel lining tends to distort more at a shallow depth. Distortion in the tunnels that are buried at a deeper depth shows less ovaling in case of a circular tunnel and racking in case of a rectangular tunnel. So, it can be seen once more that the most resistant tunnel is the deepest tunnel.

### 4.2 Effect of Tunnel Lining Thickness

The results of the numerical simulation in relation with the effect of the tunnel lining are presented in Fig. 5a–f. The shear strains induced in the soil around the tunnel

(Fig. 5a), and the vertical displacements under the tunnel raft (Fig. 5c), vary inversely with the variation in tunnel thickness. While the effect of this parameter is negligible on the term of settlement at the soil surface above the tunnel (Fig. 5b). Therefore, it can be seen that the thickness of the tunnel lining is important in the stability of the ground around the tunnel, and it is necessary to increase the rate of reinforcement of the tunnel (the thickness of the shotcrete) to reduce the deformation of the ground in conformity with the design threshold.

In addition, Consulting Fig. 5d–f shows that: The effect of varying the thickness of the tunnel lining is important on the variation in Shear force (Fig. 5d),

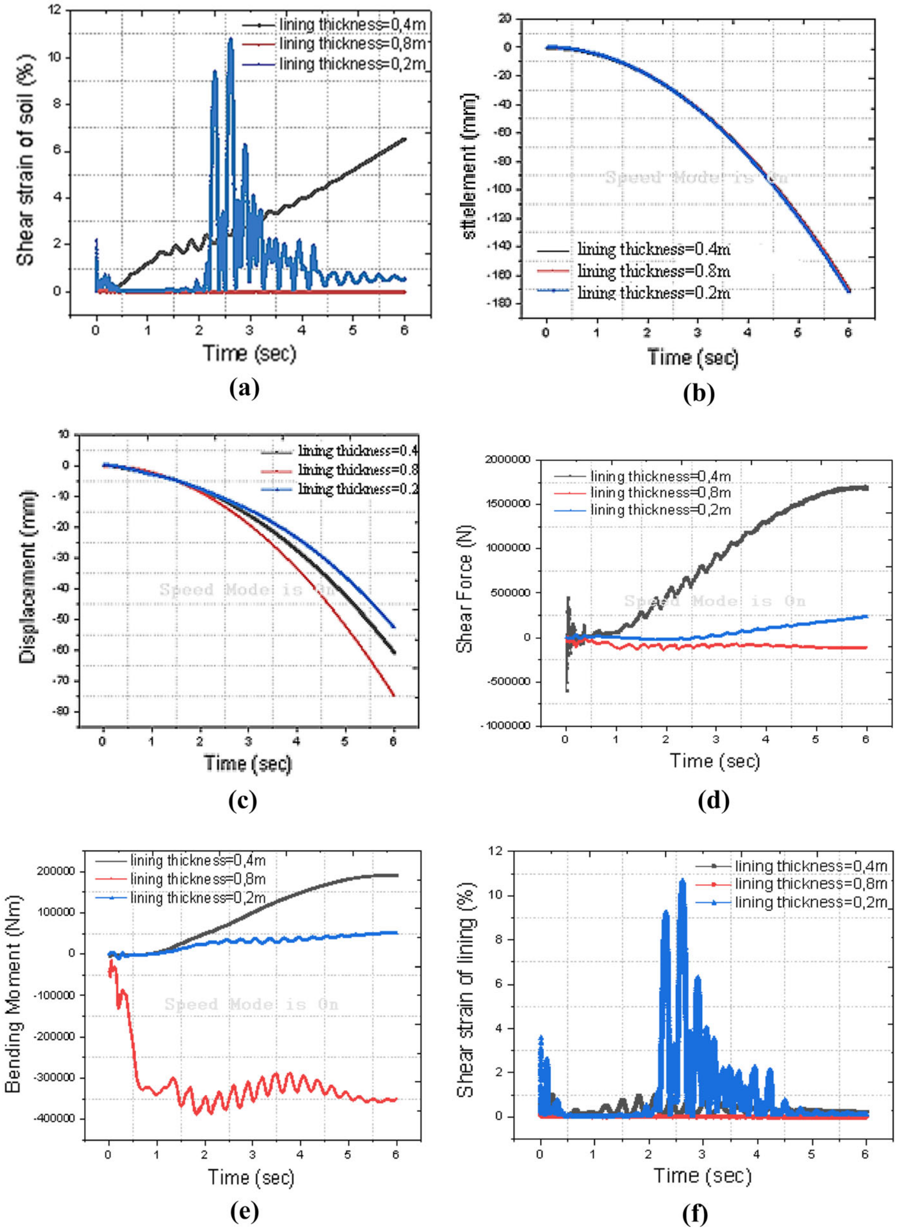


**Fig. 5** Effect of tunnel lining thickness: **a** shear strain induced in the soil around tunnel lining; **b** Settlement at the soil surface above the tunnel; **c** Vertical displacement of the soil under the tunnel raft; **d** Shear force induced in the tunnel lining; **e** Bending moment induced in tunnel lining; and **f** shear strain induced in the tunnel lining

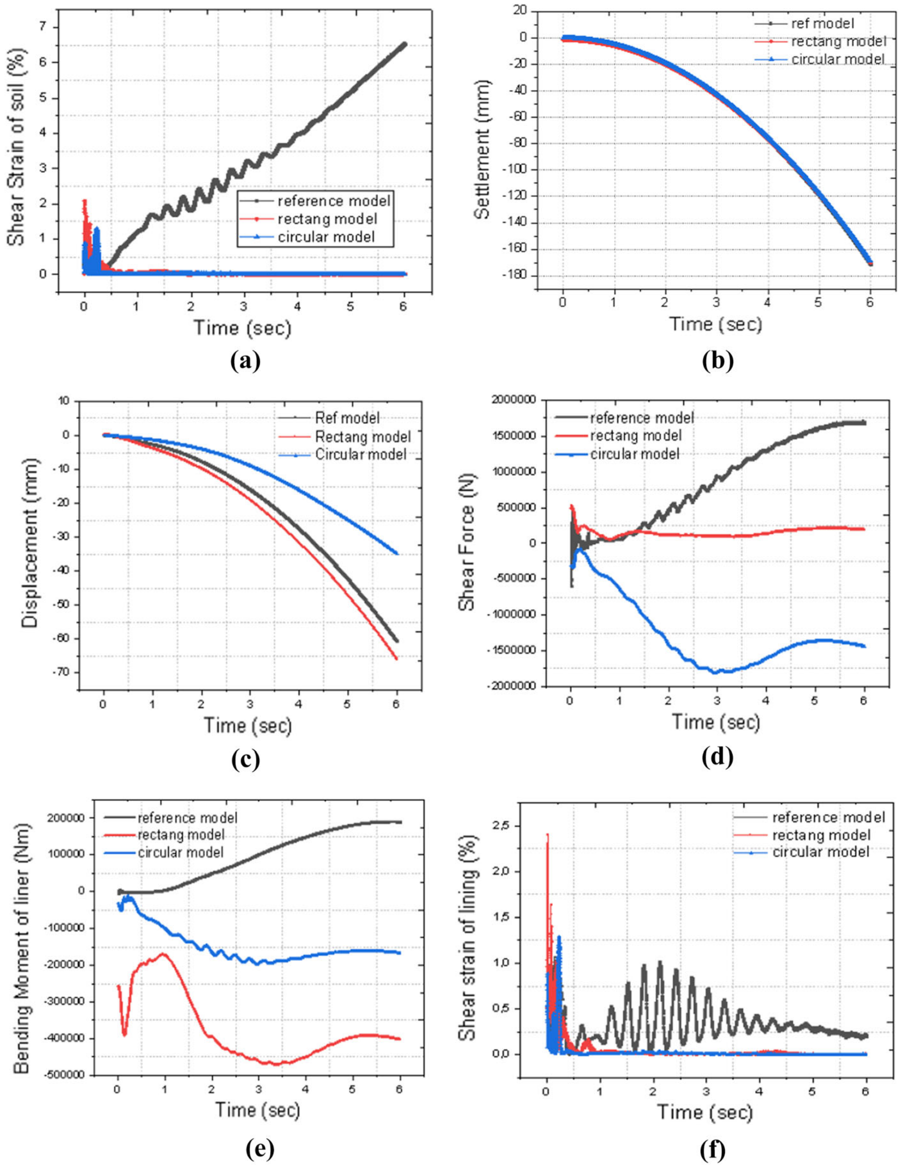
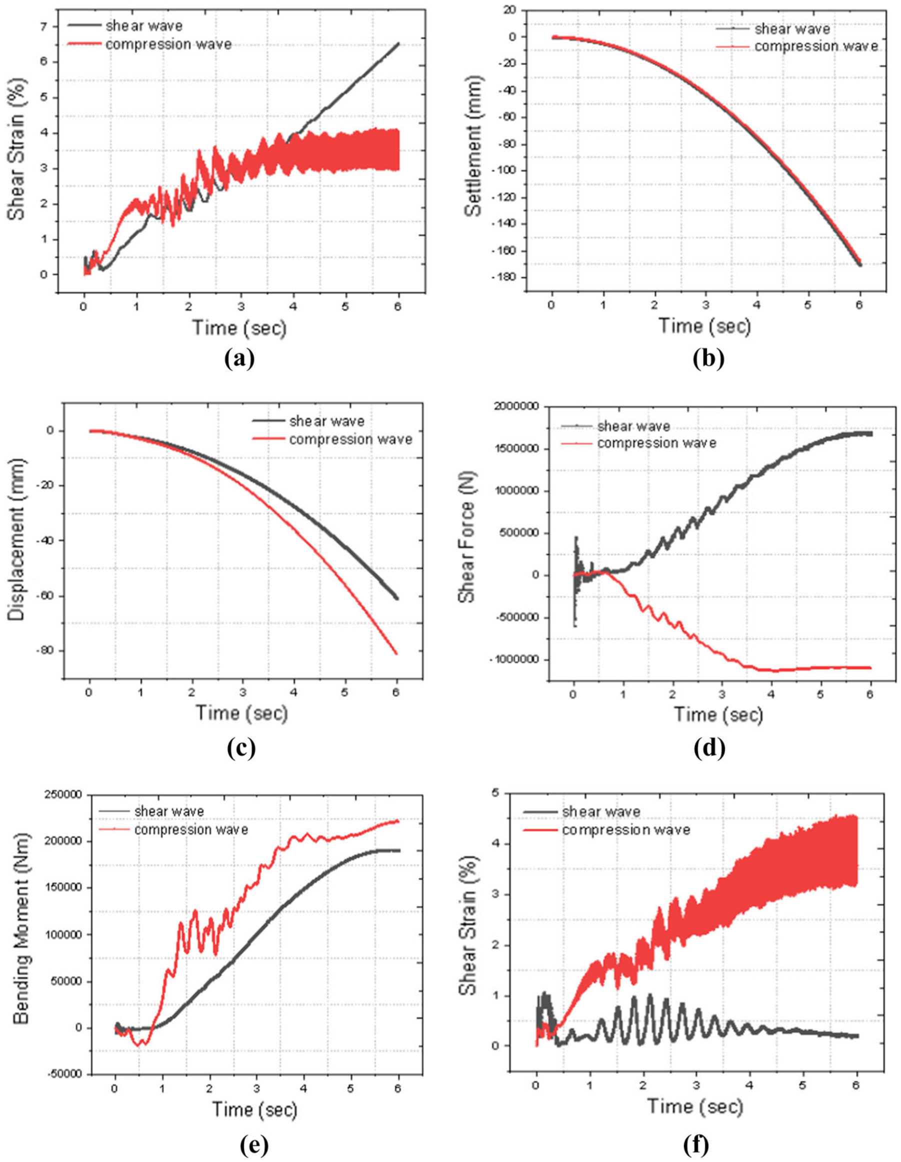


**Fig. 6** Effect of tunnel shape: **a** shear strain induced in the soil around tunnel lining; **b** Settlement at the soil surface above the tunnel; **c** Vertical displacement of the soil under the tunnel raft; **d** Shear force induced in the tunnel lining; **e** Bending moment induced in tunnel lining; and **f** shear strain induced in the tunnel lining

bending moments (Fig. 5e), and shear strain (Fig. 5f) produced in the tunnel lining. While the increase in this thickness generates a significant increase in moments, and a remarkable decrease in the other terms, so it can be seen that the shear strains are inversely proportional to the thickness of the tunnel (Fig. 5f). it is important in these conditions to increase the thickness of the lining of the tunnel to avoid deformation and cracking of the tunnel concrete, i.e., the tunnel becomes more resistant.

### 4.3 Effect of Tunnel Shape

The results of the simulation (Fig. 6a–f) show that the effect of the variation in tunnel shape is considerable on the shear strain induced in the soil around the tunnel lining (Fig. 6a), the settlement at the soil surface



(a) (b) (c) (d) (e) (f)

**Fig. 7** The effect of the Seismic wave type: **a** shear strain induced in the soil around tunnel lining; **b** Settlement at the soil surface above the tunnel; **c** Vertical displacement of the soil under the tunnel raft; **d** Shear force induced in the tunnel lining; **e** Bending moment induced in tunnel lining; and **f** shear strain induced in the tunnel lining

above the tunnel (Fig. 6b), and on the vertical displacements induced in the soil under the tunnel raft (Fig. 6c), it should be noted that the the circular shape of the tunnel make it possible to obtain minimum values of shear deformation, and of displacement, while the maximum values of the latter appear in the ground under the rectangular tunnel base. The effect of shape is almost negligible on soil surface settlement above tunnel.

In addition, the examination of curves belonging to Fig. 6d–f indicates that the minimum values of the shear force are located in the rectangular tunnel lining (Fig. 6d). The other shapes give almost the same values with opposite signs. On the other hand, the low values of bending moments (Fig. 6e) and shear strains (Fig. 6f) appearing in the oval or circular tunnel lining, and the high values are induced in the rectangular tunnel lining. Consequently, it is preferable to have a tunnel in the circular or oval shape, in order to ensure its stability. These results are in conformity with those of Patil et al. (2018), Mandal et al. (2020), and Aicha and Mezhoud (2021).

### 4.4 Seismic Wave Type Effect

The assessment of the results of the shear strain induced in the soil around tunnel lining (Fig. 7a), the settlement at the soil surface above the tunnel (Fig. 7b) and the vertical displacement of the soil under the tunnel raft (Fig. 7c) shows that the propagation of seismic shear waves generates a maximum shear strain, and minimum vertical displacement, on the other hand the impact of the type variation of the seismic waves on the soil settlement is negligible. This observation demonstrate that the effect of seismic shear waves is more important and dangerous on the stability of the tunnel and the surrounding soil.

In addition, the exploration of the Fig. 7d–f indicates that the propagation of the compression waves generates a strong bending moment (Fig. 7e), and a very high shear strain (Fig. 7f) with a less important shearing force (Fig. 7d) induced in the tunnel lining. It can therefore be said that the impact of seismic compression waves is greater than the seismic shear waves on the behavior and resistance of the tunnel lining.

## 5 Conclusions

This paper presents a study of the effect of certain parameters like tunnel depth, coating thickness, shape of the tunnel cross-section, and direction of seismic waves on the behavior of the shallow tunnel in a loose soil under seismic conditions. The numerical simulations are made by a finite difference calculation using the Flac-3D calculation code which makes it possible to take into account the three-dimensional aspect of the problem. The behavior of the ground is described by the combined model of the hysteretic damping of Hardin / Drnevich with an elastoplastic model of Mohr-Coulomb. The analysis is made in terms of horizontal stresses, shear stresses, horizontal displacements, and shear strains as a function of time induced at the level of the tunnel lining, and in the surrounding soil.

From the results of this study, the following conclusions can be listed:

- The more the tunnel depth decreases, the more the shear strain, settlement, vertical displacement, appearing in the mass of the soil, and the shear force, the bending moment, and the shear strain induced in the tunnel lining are also increasing and in a remarkable way.
- The increase in the thickness of the tunnel lining causes the significant reduction in the values of shear deformation, and of vertical displacement, appearing in the soil around and below the tunnel, and also a decrease in the values in terms of shear force, and shear strain induced in the coating.
- The circular shape of the cross section of the tunnel generate low values of shear deformation, vertical displacement in the ground, and thus of bending moment, low shear deformation induced in the coating, in comparison with the rectangular shape.
- The direction of the seismic waves has a great influence on the behavior of the coating and the surrounding soil, particularly the impact of the compression waves which can generate strong shear deformation in the ground under the base of the tunnel, and a significant evolution of the bending moment, with shear strain induced in the tunnel lining.
- The influence of the following parameters: the thickness, the cross-sectional shape of the tunnel, and the direction of the seismic waves on the soil settlement above the tunnel is negligible.

The very high deformations and stresses appearing in the soil mass, and induced in the tunnel lining, can reduce the shear resistance of the soil mass, and of the support system (lining), and consequently lead to the failure of the tunnel. ground-tunnel system, and therefore the risk of tunnel instability increases.

Then we can conclude that the strongest and most stable tunnel are the circular or oval shape tunnels, the deepest and thickest under the effect of seismic shear waves. The results of the present study will be useful in the design of such a case by understanding the effects of various influencing parameters that control the stability of the tunnel in soil of weak characteristics.

### Declarations

**Conflict of interest** On behalf of all authors, the corresponding author states that there is no conflict of interest.

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