Chapter 15

Tunnel Vaults under Seismic Excitation

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Additional information is available at the end of the chapter

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Abstract

This chapter discusses factors that affect the seismic response of tunnels vaults, as the seismic ground motions, the geological condition and rock mechanics properties, and the relevance of numerical analysis, fundamental in the modeling of complex structures and processes, and in regional-scale analysis. As an example, this chapter focuses on the Laboratories of National Institute of Nuclear Physics (INFN) located in a Tunnel within the Gran Sasso mountain (Abruzzo, Italy). In addition to the L'Aquila (2009) earthquake, the chapter refers to observations reported in the literature related to the İzmit earthquake, Turkey (1999); the Chi-Chi earthquake, Taiwan (1999); and the Kobe earthquake (2004); and, as historical event, the Kern County earthquake (1952).

Keywords: tunnel vaults, seismic excitation, seismic ground motion, rock mechanics properties, numerical analysis

1. Introduction

There are two areas of concern in earthquake engineering of tunnel vaults. The first one is related to the values of the peak ground acceleration (PGA) to which the structures may survive by responding in the elastic or the plastic field. The second one is related to the fault movement, to which the structure cannot offer a valuable resistance. The chapter discusses the factors that affect the seismic response of tunnels vaults, as the seismic ground motions, the geological condition and rock mechanics properties, and the relevance of numerical analysis, fundamental in the modeling of complex structures and processes, and in regional-scale analysis. As an example, this chapter focuses on the Laboratories of the National Institute of Nuclear Physics (INFN) located in a tunnel within the Gran Sasso mountain (Abruzzo, Italy). A number of geophysics studies have been devoted to the area [1–7]. A numerical analysis on the INFN Laboratories has been presented in [8]. This chapter collects observations and references on the behavior of tunnel vaults under seismic excitation, with the aim to derive design soil motion for the INFN Laboratories, in view of future installations.

2. Factors affecting the seismic response of tunnel vaults

The response of tunnel vaults under seismic excitation depends on multiple factors. First, the earthquake motion, such as the earthquake intensity and magnitude. Second, the tunnel environment condition, as, that is, the rock condition, the overburden layer depth, the location with respect to the fault zone. Third, the structural condition of the tunnel, the presence of lining, its integrity, and the quality of the construction.

2.1. Role of ground motions

The study presented in [9] observes 71 cases of rock tunnel response to earthquake motions, with diameter varying from 3 to 6 m. Out of 72, 42 cases were damaged. The study in [9] proposes a relationship of the damage level with the earthquake magnitude, intensity and epicenter. The following observations can be drawn: (1) the tunnel has no damage when $PGA < 0.19g$ and peak ground velocity (PGV) is lower than 20 cm/s; (2) the tunnel will have minor damage when $0.19g < PGA < 0.5g$ and $20\ \mathrm{cm/s} < PGV < 80\ \mathrm{cm/s}$; and (3) the tunnel will be severely damaged when $PGA > 0.5g$ and $PGV > 80\ \mathrm{cm/s}$. In these evaluations, the quantities PGA and PGV refer to "free field" conditions, that is the expected quantities at the nearby region, in plane conditions. The study in [10] provides a database containing 192 observations from 85 earthquakes worldwide. Half of the events refer to earthquakes of Richter magnitude higher than 7, and about 75% of damage is observed within 50 km from the epicenter (near-field). Among the 192 cases, no damage is observed with PGA of the horizontal components lower than 0.2 g, in agreement with [9]. In the majority of the cases, important damage has been observed for $PGA > 0.4g$.

2.2. Role of geological condition and rock mechanics properties

A study of tunnel seismic damage in Japan [11] observed that the tunnel sector with thick lining had the biggest damage percentage: 82, 38, and 16%, considering respectively thickness of 40, 30, and 20 cm. However, this observation should be revisited taking into account the nearby geological conditions. In the same study, the authors observe a damage percentage of 16% in hard rock, 40% in soft rock, 44% in joint development rock, and 61% in earth. Based on these observations, the earthquake safety of tunnel is mainly controlled by the natural condition. When the natural condition is poor, to increase lining thickness may increase earthquake forces and be detrimental to the safety of the tunnel. A more effective method could be to reinforce the surrounding rocks. The study concludes that earthquakes do not affect tunnels farther than 50 km from the epicenter.

Literature refers to peculiar applications devoted to rock mechanics. A useful database for rock mechanics properties is provided by Lama and Vutukuri [12] and has been used in [8]. In [13], a 3D dynamic analysis program for saturated porous rocks and soils is presented. The theoretical formulations incorporated in the proposed computer program are the extension of Biot's two-phase theory to nonlinear region. A numerical study shows the effects of pore water on the dynamic response of underground openings in saturated rock masses. It is shown that underground openings in saturated porous media could be significantly more vulnerable to the potential damages associated with high motions and shear failure that those in dry media. The work presented in [14] established that crack-induced stress-aligned shear wave splitting, with azimuthal anisotropy, is an inherent characteristic of most of rocks in the crust. This means that most in situ rocks are characterized by fluid-saturated micro-cracks. The evolution of such stress-aligned fluid-saturated grain boundary cracks and pore throats in response to changing conditions can be calculated, in some cases with great accuracy, using anisotropic poroelasticity (APE).

2.3. Role of fault movement

Fault movement is one of the major areas of concern in earthquake engineering of tunnel vaults. Based on the study in [15], three considerations related to the fault movement can be drawn. First, the ratio between surface displacement and sub-surface displacement has a wide range, between 0.2 and 8. The average sub-surface displacement is calculated from the seismic moment and the rupture area. The study in [15] does not mention the stiffness of the soil surface; however, the highest ratios should be assigned to the most deformable surface soils, and in particular imported backfill and reclaimed land. Second, the amplitude of displacement varies along the length of the fault, like cracks in a concrete structure or pavement. Third, the eventual movement of a fault shall be considered sub-surface movement, and not surface movement, if we consider deeply embedded tunnels. As for the amplitude of the expected displacement, Wells and Coppersmith [15] provide relations between the average displacement, in m, and the moment magnitude. Relation as those presented in [16–18] may be used to express peak ground acceleration as a function of the moment magnitude and of the distance from the epicenter. **Table 1** shows the maximum expected displacement between the fault surfaces, considering the relation in [15] between maximum expected displacement and moment magnitude and the relations in [16–18] between PGA and moment magnitude. Equation from [16–18] is provided in the Appendix A1. **Table 1** indicates that the problem regards the cases with PGA larger or equal to 0.25 g. It is at the border of the present analysis, and consequently it requires a further insight into the expectation of a fault movement.

PGA (g)	Magnitude [16, 17]	Magnitude [18]	Maximum displacement amplitude (m)
0.05	~1	~1	~0
0.15	4.6	4.6	~0
0.25	6.5	6.3	< 0.1
0.35	7.8	7.4	> 1

Table 1. Maximum expected displacement between the fault surfaces, joining the correlation of PGA and M, ([16–18], Appendix A1), and that of M and the amplitude, [15].

3. Relevance of numerical analyses in assessing the seismic response of tunnel vaults

Theoretical analyses of tunnels and lined tunnels have been proposed in the literature [e.g., 19, 20]. However, tunneling engineering is one of the areas of applied soil and rock mechanics in which the numerical methods for stress analysis are frequently adopted in practice [e.g., 21]. Their frequent use depends on several reasons related to the complex characteristics of the tunneling problems. One of the most important is the strong influence of the excavation and construction procedures, and of their technological details, on the stress/strain distribution in the rock surrounding the opening and in its supporting system. This represents a main drawback for the analytical solutions and for simplified methods of analysis, which, in most cases, cannot capture this process with a sufficient level of detail. Another important aspect of tunneling problems captured by numerical analyses is their complex geometrical nature. This includes, among other aspects, (1) the shape of the opening, (2) the presence of discontinuities in the rock mass, and (3) the presence of non-homogenous or non-isotropic layers. The extension to 3D problems is possible, provided the required amount of information and the ability to manage a more complex map of stresses.

Numerical tools are especially useful when dealing with regional-scale analysis. The study in [22] illustrates an application of the HAZUS [23] methodology to the tunnels and bridges of a highway network. The variability in the ground shaking and in the construction characteristics leads to very different probability of failure for different components (i.e., tunnels and bridges) in the network. The resulting damage levels for bridges and tunnels depend on the fragility curves used in the evaluations. They were developed for existing bridge and tunnel structural typologies in the United States. State-of-the-art fragilities with models of capacity and demand have been proposed in [24, 25].

4. Lesson learnt from direct observation of damage

4.1. The İzmit earthquake (1999)

Effects produced by faults movement are reported especially by [26, 27] for the Anatolian Motorway tunnel, Bolu tunnel, in occasion of the M_W 7.4 İzmit earthquake (1999).

4.2. The Chi-Chi earthquake in Taiwan (1999)

Effects similar to those produced by İzmit earthquake are described in [28] for the M_W 7.6 Chi-Chi earthquake of Taiwan (1999). It is reported that out of 57 galleries, 49 have suffered damage. The study is in particular devoted to the covering lining, tunnels, and design documents (see **Figure 1**). The work [29] on the Chi-Chi earthquake shows that tunnels in intensity nine areas were damaged, whereas in low intensity areas, the tunnels were undamaged. In [29], information on seven tunnels affected by the Chi-Chi earthquake are collected, and the

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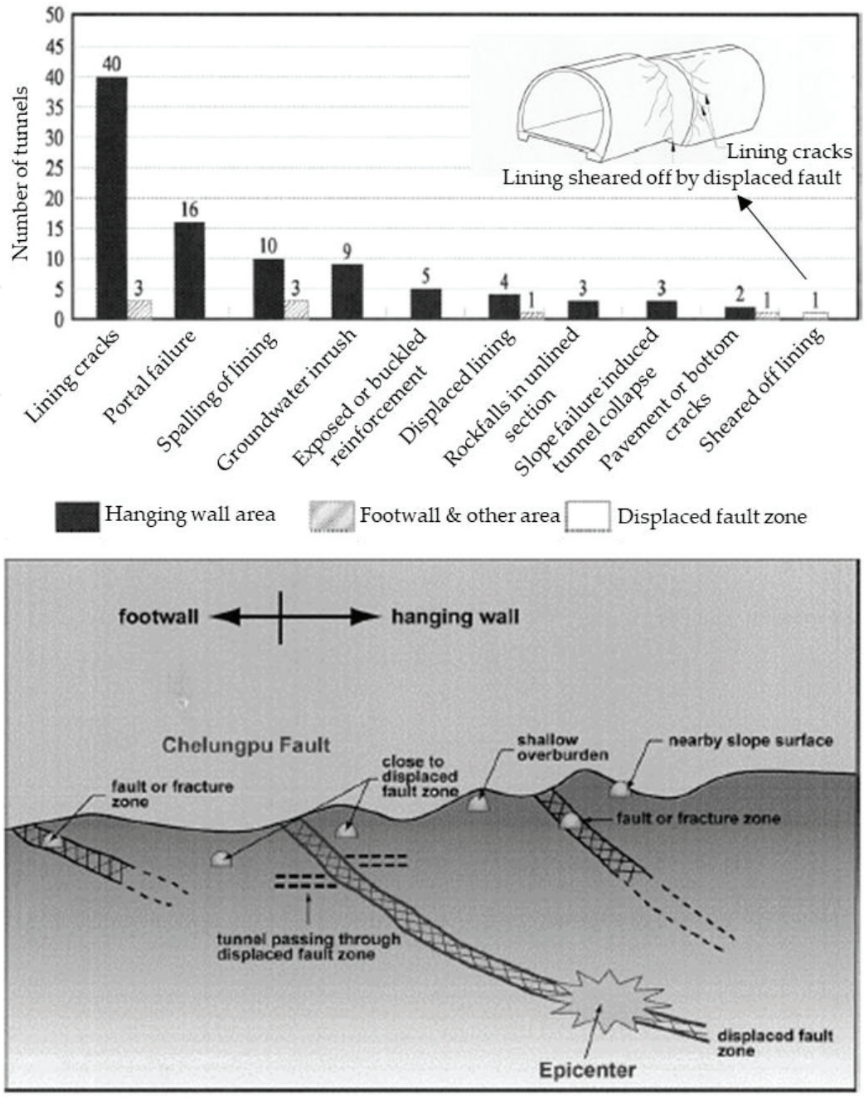

Figure 1. Number of tunnels suffering various type of damage and locations of tunnels with the respect the displaced fault zone (adapted from [28]).

intensity was adjusted according to Chinese intensity. The area intensity is a measure similar to the Mercalli scale. The results presented in [29] are in agreement with the numerical analysis reported in [8].

4.3. The Kobe earthquake (1995)

There were more than a hundred tunnels in the disaster area in the M_W 6.8 Kobe earthquake (1995), [30–34]. The damage of the tunnels has been related to the area intensity. Tunnels in the intensity 10 areas were damaged in different levels, with several tunnels major damaged for crossing fault zones. Many tunnels were damaged in the intensity nine areas, whereas only few tunnels experienced damage in intensity eight areas. No damage was reported for tunnels in intensity seven areas. The previously referred study [29] includes also information on 27 tunnels damaged during the Kobe earthquake. The study in [6] describes two cases, at depth

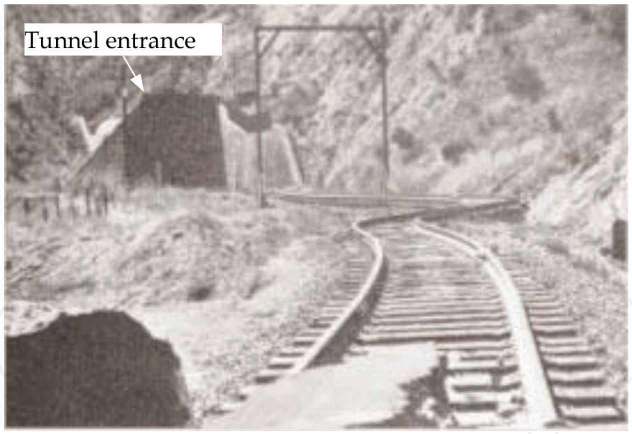

Figure 2. Damage at the tunnel entrance of the tunnel during the 1952 Kern country earthquake (adapted from [37]).

and shallow depth, during the 1995 Kobe earthquake: the collapse of the Daikai Underground Station in the city of Kobe [35, 36], and the damage to the Bantaki Tunnel in the mountains near Kobe. Similar damage pattern was found in the Uonuma Tunnel of the Japanese high-speed train (Shinkansen) network immediately after the 2004 Niigata-ken Chuetsu earthquake.

4.4. The Kern County earthquake (1952)

The study in [37] considers three earthquakes and, in particular, the M_W 7.3 Kern County (1952) earthquake, when a tunnel experienced damages, but just at the entrance (see **Figure 2**). The question arising therefore is whether the earthquake damage in the Bolu tunnel represents an exception, or whether the hypothesis that tunnels are affected by minor seismic risk affecting tunnels should be re-evaluated. The authors examined numerous tunnels in tectonically and seismically active areas concluding that tunnels in such areas are vulnerable not only to seismic shaking, but also to tectonic deformations. The study in [37] refers of old events where tunnels collapsed under the effects of faults. However, beside the historical relevance, these references lack quantitative data. Some useful information on faults movements causing damage are given in [38], however related to a M_W 4.0 seismic event, induced by mining in the Saar District, Germany.

5. Case study: the INFN Laboratories

The Laboratories of National Institute of Nuclear Physics (INFN) are located in a Tunnel within the Gran Sasso mountain (Abruzzo, Italy), **Figure 3**.

5.1. Ground motions during L'Aquila (2009) earthquake

During L'Aquila (2009) earthquake, acceleration records have been collected at plane conditions, at several stations on the Gran Sasso, with values of peak ground acceleration (PGA) between 0.35 and 0.5 g. A few accelerograms have been collected in the gallery, about 1400 m

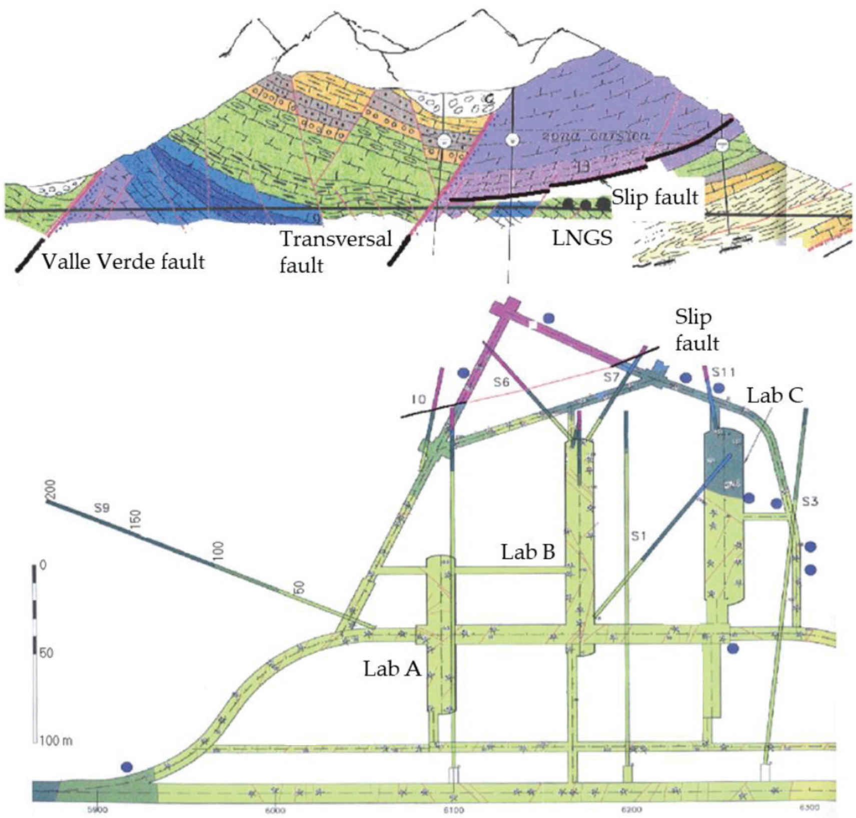

Figure 3. (top) Vertical section of the Gran Sasso mountain, and the rooms of INFN; (bottom) plant of the laboratories of the National Institute of Nuclear Physics, INFN.

below the mountain crest, with values of PGA lower than 0.1 g. This reduction confirms a qualitative result reported by Dowding and Rozen [9], considering 71 earthquakes that affected tunnels. This reduction justified also a large portion of the observations available in the literature, as discussed in this chapter. In the numerical analysis performed in [8], the accelerogram in the gallery has been reproduced, assuming as input data a representative accelerogram collected in plane conditions, with PGA equal to 0.5 g.

5.2. Geological condition and rock mechanics properties

Several reports on the geological conditions of Gran Sasso are available in the literature [1–4]. Following the L'Aquila 2009 earthquake, Amoruso et al. [4] report about significant changes in the hydrogeology of the Gran Sasso carbonate fractured aquifer. These changes are (1) the disappearance at the time of the main shock of some springs located along the surface trace of the Paganica normal fault; (2) an abrupt increase in the discharge of the Gran Sasso highway tunnel drainages and of other springs; and (3) a progressive increase of the water table elevation at the boundary of the Gran Sasso aquifer, in the months following the seismic event. The authors in [4] propose a model of the effect of the earthquake on the Gran Sasso aquifer based on historical data including seismic monitoring, spring discharge, water table elevations, turbidity and rainfall events. This model excludes the effects of seasonal recharge. The short-term hydrologic effects registered immediately after the seismic event have been ascribed to a pore pressure increase related to the aquifer deformation. Mid-term effects observed in the months following the event suggested a change in groundwater hydrodynamics. Additional groundwater flowing towards aquifer boundaries and springs in discharge areas may result from an increase in the hydraulic conductivity in the recharge area, nearby the earthquake fault zone. This increase might be attributed to fracture clearing and/or expansion. Results from numerical simulations of the pore pressure and permeability change with time are in agreement with observed field data.

5.3. Current information about faults presence and movement

Figure 4 shows current information about the presence of faults, collected during the tunnel excavation in the Gran Sasso. Discontinuities in the rock mass, or joints, are names commonly used to catalog faults during the construction phase of galleries.

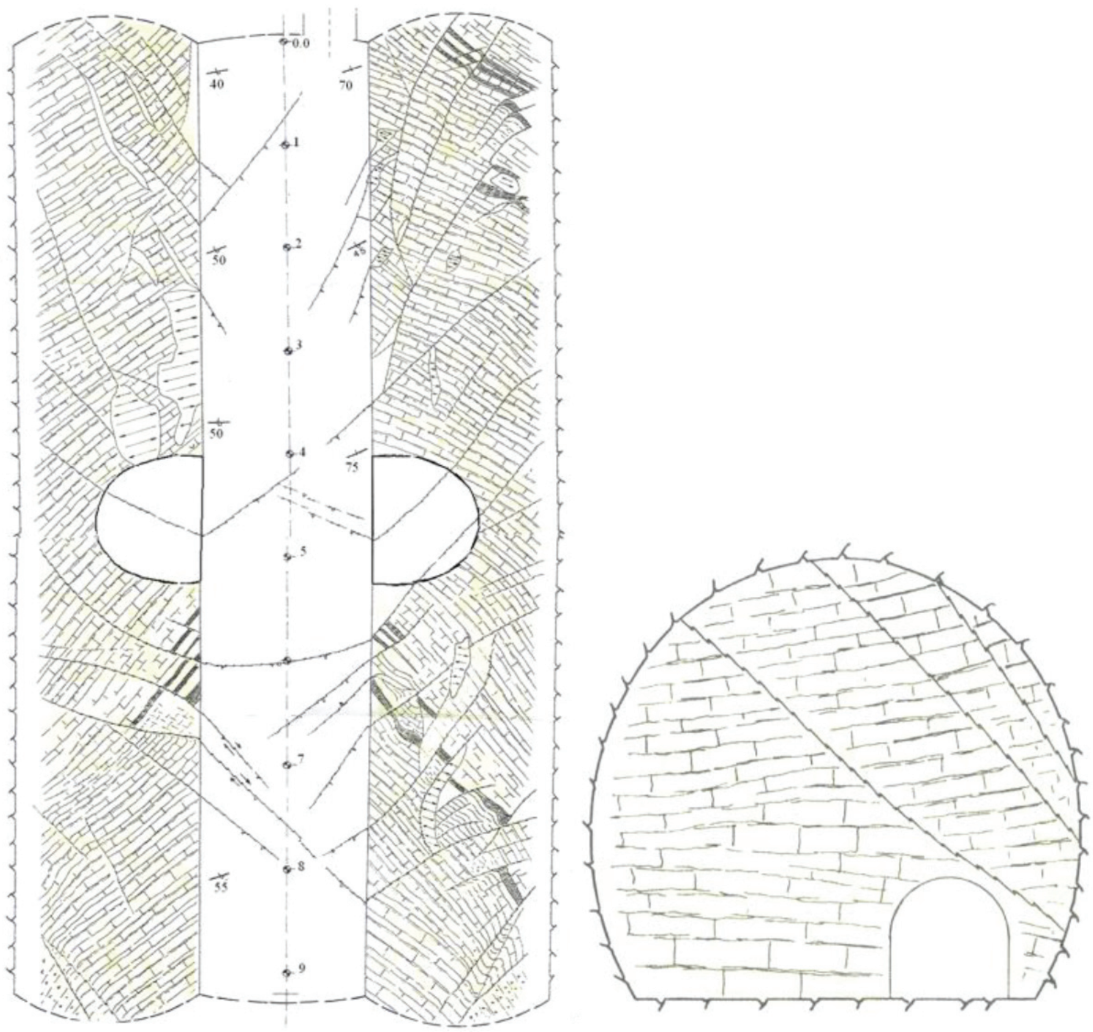

Figure 4. (left) In-plane trace of faults that pertain to the highway gallery of Gran Sasso, recorded during construction; (right) trace of faults in the vertical plane, near the tunnel entrance.

A paper focused on the Apennine geophysical condition has been prepared by Brunori et al. [5]. If a fault shows evidence of having moved at least once in the past 100,000 years, then it should be regarded as a potential source of earthquakes. Another prevailing opinion is that if the fault has moved at least once in the past 5000 years, then it should be considered a potential source of damaging earthquakes to any settlement within a radius of 50 km. Once a major fault has formed, future earthquakes are generated along the same fault line, and after years of movement, increasingly larger vertical and horizontal displacements of land may occur. With reference to the trace of faults shown in **Figure 4**, it is possible to assume two different scenarios. In the first scenario, the seismic motion is originated from a deeply embedded fault, which shows a superficial offshoot. The tunnel is concerned by the offshoot, and it is located within the epicenter area. In the second scenario, the tunnel and the fault crossing it are at some tens of kilometer from the epicenter. The seismic motion is not assigned to an energy release from the fault under object; however, the seismic motion may activate a relative motion at the sides of the fault. In the first scenario, along the fault, an energy has been cumulated, capable to activate the movement. The expected effects are more important, but the event is associated to a lower probability of occurrence, because even if the seismic event occurs, the epicenter should be exactly in correspondence to the crossing. The movement of that fault is at the origin of the earthquake. In the second scenario, along the fault the cumulated energy is not enough to activate the seismic motion, and the relative motion along the fault is an induced motion. The probability of this event is in a fair approximation linked to the probability of the earthquake motion itself, that is, 2‰ per year.

In our case, the earthquake of L'Aquila 2009 has been classified as originated at the Pettino fault, [7], (sometimes at the Paganica fault). The distance from the Gran Sasso INFN Laboratory is about 30–40 km in both cases. Therefore, it falls within the second scenario. The study in [5] focuses the analysis on the Pettino fault, a part of the Late Quaternary segmented system called the Upper Aterno fault system, which is responsible for the evolution of the L'Aquila basin, and likely, for the 1703 A.D. $M_W > 6.0$ earthquake. The Pettino fault appears, at a field survey scale, quite continuous and homogeneous along the trace. We are not aware about studies on the interactions of this fault (or Paganica fault) and the faults crossing the Gran Sasso tunnel. However, Italian seismic history reports numerous examples of cascading activation of faults nearby one to the other, following a strong earthquake. In those cases, the time delay varies from a few seconds, (?Irpinia, 1980; three shakings in 40 s), to 1 day, (Umbria-Marche, 1997), some days, (Emilia, 2012), till a week, (Calabria, 1783), or even years (Nicastro, Southern Calabria 1905, followed by Messina, 1908).

5.4. Tendons along the tunnel vaults

The lining of the tunnel and that of the Lab rooms is anchored to the rock behind by a network of tendons, **Figure 5**. According to Castellani et al. [8], the state of stress in the lining is not meaningful with respect to the existing static stress due to relaxation following the construction. However, the measure of the ovalization of the halls, expressed by a change in length of the diameters reached up to 8 cm. The risk of superficial ruptures and consequence of rocks fall

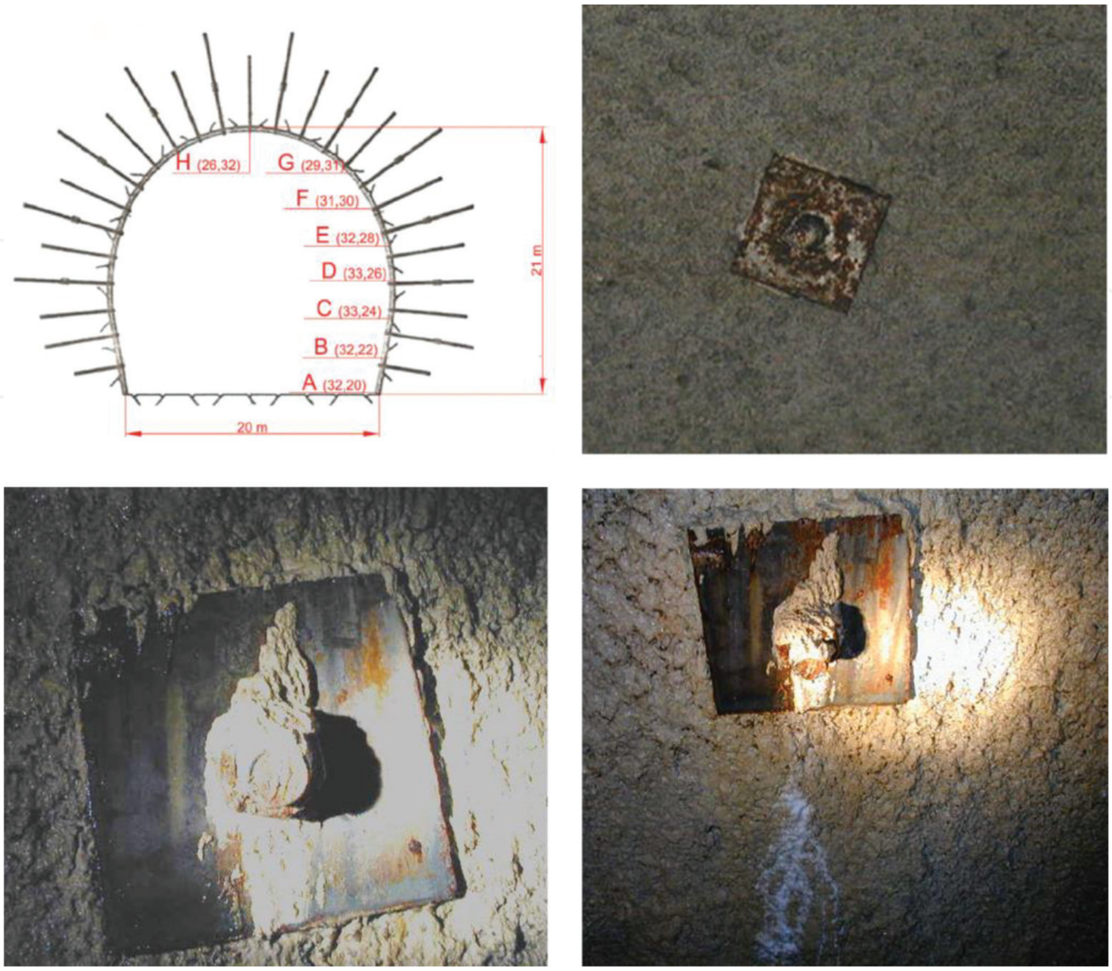

Figure 5. (top left) Tendons on one of the Laboratory rooms at Gran Sasso, recorded during construction; (top right) covering of the walls and roof. Anchor plate and tendon, one every square meter; (bottom left and right) anchor caps, showing water filtering, following the water basin movement, described by Amoruso et al. [4].

should be taken into account. For this reason, the anchors are inserted; however, according to the authors' opinion, they do not affect the overall behavior of the tunnel or the Lab rooms.

6. Conclusion

In addition to the L'Aquila (2009) earthquake, this chapter refers to observations of the response of tunnel vaults under seismic excitation reported in the literature related to (1) the İzmit earthquake, Turkey (1999); (2) the Chi-Chi earthquake, Taiwan (1999); (3) the Kobe earthquake (2004); and (4) the Kern County earthquake (1952).

Common observations are the following:

i. With respect to structures on the surface, or at shallow depth, underground deep structures subjected to dynamic waves vibrate solidly with their surroundings;

ii. Shallow galleries suffer more damage than deep galleries, with 60% of the observed damage referring to galleries of depth lower than 50 m;

iii. Galleries with rectangular cross section, excavated in open air (cut and cover structures) are more vulnerable than deep circular tunnels;

iv. Surrounding soil has the greatest importance. As discussed in [10], among 192 observations, 79% of tunnels excavated in a deformable soil have suffered damage, whereas those excavated in rock soil resulted in lower damage.

As an example, this chapter focuses on the Laboratories of National Institute of Nuclear Physics (INFN) located in a Tunnel within the Gran Sasso mountain (Abruzzo, Italy). The design acceleration at the ground floor of the Laboratory of Physics at Gran Sasso is evaluated, taking into account the ground motion attenuation in the tunnel, measured during the 2009 L'Aquila earthquake. Numerical analysis were able to reproduce such attenuation, based on local data. The survey at the Laboratory, immediately after the earthquake, confirms that the PGA at the Lab has been lower than 0.1 g, and no damage occurred, although PGA at "free field" has been around 0.5 g. This chapter confirms that similar attenuations have been pointed out in the literature of deep galleries. A few exceptions are remarked, but different conditions have been discussed between the Gran Sasso Gallery case and these exceptions. A residual risk should be investigated, connected with a possible interaction among adjacent faults (in the considered case between the Pettino and the Paganica faults).

A.1. Magnitude and peak acceleration at given distances from epicenter

Maps of seismicity are available online (e.g., earthquake.usgs.gov/earthquakes). They are expressed through the epicenters location and the measure of magnitude. In general, the most recent data available online are expressed in terms of magnitude. In order to express these data in a format comparable with for instance [9], the peak ground acceleration *PGA* needs to be related to the magnitude. Studies in [16, 17] provide one of these equations

$$\ln(PGA) = -1.101 + 0.2615M - \ln\left[\left(r^2 + 7.2^2\right)^{0.5}\right] - 0.00255\left[\left(r^2 + 7.2^2\right)^{0.5}\right], \tag{1}$$

where *PGA* is the peak ground acceleration in *g* units, *M* is the moment magnitude, *r* is the distance in *km* of the site from the epicenter. In [18], a similar equation has been proposed

$$\ln(PGA) = -1.562 + 0.306M - \ln\left[\left(r^2 + 5.8^2\right)^{0.5}\right]. \tag{2}$$

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