UNDRAINED
seismic response of underground structures

Colección Ingeniería
Investigación

Sandoval, Eimar
Undrained seismic response of underground structures / Eimar Sandoval, Antonio Bobet. -- Cali : Programa Editorial Universidad del Valle, 2020.
262 páginas ; 24 cm. -- (Colección Ingeniería - Investigación)
1. Ingeniería sísmica - 2. Control de respuesta sísmica - 3. Control sísmico 4. Drenaje - 5. Construcciones subterráneas – 6. Estructura de suelos.
624.1762 cd 22 ed.
S218
Universidad del Valle - Biblioteca Mario Carvajal

Universidad del Valle
Programa Editorial
Title: Undrained Seismic Response of Underground Structures
Authors: Eimar Andrés Sandoval, Antonio Bobet
ISBN: 978-958-5144-53-8
ISBN-PDF: 978-958-5144-54-5
DOI: 10.25100/peu.442
Collection: Ingeniería-Investigación
First edition

Rector of the Universidad del Valle: Édgar Varela Barrios
Vice-rector for Research: Héctor Cadavid Ramírez
Director of the Editorial: Omar J. Díaz Saldaña

Cover design: Isabella Manjarrés Melo
Layout: Eimar Sandoval

Cali, Colombia, September 2020

Eimar Andrés Sandoval • Antonio Bobet

UNDRAINED
seismic response of underground structures

Colección Ingeniería
Investigación

PREFACE

This book is the result of over five years of research conducted by the first author, under the advising and support of the second author. The basis for the research stemmed from our interest on the better understanding of earthquake engineering, soil dynamics, and soil-structure interaction. Progress has been made in the last few years in understanding the soil-structure interaction mechanisms and the stress and displacement transfer from the ground to underground structures during a seismic event. It seems well established that the most critical demand to the structure is caused by shear waves traveling perpendicular to the tunnel axis. These shear waves cause distortions of the cross section that result in axial forces and bending moments, whose magnitudes depend on the relative stiffness between the ground and the liner (expressed by the flexibility ratio, F). Nevertheless, the studies have concentrated on structures placed in linear-elastic ground, and there is little information regarding the behavior of buried structures placed in nonlinear ground, especially under undrained conditions, i.e., when excess pore pressures generate and accumulate during the earthquake. Thus, the target of the book is to help to fill this gap by investigating the seismic response of underground structures when undrained conditions apply. For comparison purposes, the drained response is also evaluated.

Due to the complexity of the load-transfer mechanism and stresses and strains demand on underground structures produced by the ground, as it deforms during seismic events, in-depth studies usually involve numerical analyses. The seismic response of the tunnels in this book is evaluated through full dynamic numerical analyses using FLAC 2D. For a complete understanding of the phenomenon, the undrained response of tunnels is studied for three different types of analyses: (i) linear-elastic ground; (ii) nonlinear elastoplastic ground, but without including the excess pore pressures accumulation that occurs with cycles of loading; and, (iii) nonlinear elastoplastic ground including excess pore pressure accumulation during cyclic loading. In the first two cases, excess pore pressures are produced by the inability of the material to change volume, and so they are directly related to the change in normal stresses caused by the presence of the tunnel. As a result, and considering that far-field earthquakes can be effectively approximated as a simple shear, the excess pore pressures are only produced at the tunnel diagonals and do not accumulate during the seismic/cyclic loading. For the third case, excess pore pressures generate and accumulate all around the tunnel with cycles of loading.

A new cyclic nonlinear elastoplastic model for the ground, to simulate the nonlinear behavior and excess pore pressures accumulation with cycles of loading, is written, incorporated in FLAC and verified. Upon completion of the verification, the effect of input frequency on the distortions of the tunnel is evaluated for linear-elastic and nonlinear ground, under drained and undrained loading (without and with excess pore pressures accumulation). Afterwards, excess pore pressures, shear stresses, and stiffness degradation of the nonlinear ground are investigated for two extreme conditions of relative stiffness, namely a very flexible tunnel and a very stiff tunnel. A parametric study is also conducted to evaluate the effect of the flexibility ratio on the distortions and loading in the liner. The effect of increasing the amplitude of the dynamic input on the tunnel distortions is also investigated for select cases. Finally, cyclic pseudo-static analyses are conducted to compare results with those obtained from the full dynamic numerical analyses.

The book supports the statement that pseudo-static analyses can be conducted to investigate the seismic response of tunnels located far from the seismic source, even when nonlinear ground and excess pore pressures accumulation are included. The book also highlights the importance of considering the nonlinear behavior and excess pore pressures accumulation in the ground (if applicable), when evaluating the seismic response of underground structures. Performance criteria are discussed, which depend on the relative stiffness between the liner and the ground, as well as on the drainage conditions and the magnitude of excess pore pressures. For some cases, axial forces and bending moments may control response while the distortions of the cross section are small. For other cases, both loading on the liner and distortions of the cross section may be important. In specific situations, the performance is largely determined by the distortions of the cross section, while the axial forces and bending moments are almost negligible. We believe that the readers of the book will understand better the interplay that exists between the flexibility ratio, the drainage loading condition and the magnitude of excess pore pressures during seismic loading. With our contribution, we hope that underground structures will be safely designed, and their damage prevented or at least minimized during seismic events.

Eimar Sandoval
Antonio Bobet
Cali (Colombia), May 2020

CONTENTS

Chapter 1

INTRODUCTION

1.1 Problem statement and motivation

Underground structures must be able to support static overburden loads, as well as to accommodate additional deformations imposed by seismic motions. While there is a general good agreement of the scientific and practicing communities, regarding the design considerations for static loads, that is not the case for seismic loads. There has been, for quite some time, the perception that underground structures are safe during an earthquake. The argument has been based on the idea that, during earthquakes, underground structures follow the deformation of the surrounding ground and, because the structure is confined, no damaging stresses are produced. Indeed, underground structures are safer than aboveground structures for a given intensity of shaking, as it has been confirmed by a number of cases reporting overwhelming damage to structures placed on the ground compared to those placed underground. However, damage has been reported in the literature for more than 40 years (Dowding & Rozen, 1978; Owen & Scholl, 1981; Power, Rosidi, & Kaneshiro, 1998; Sharma & Judd, 1991) and has been observed in recent earthquakes around the world. For example, in Japan (1995), Taiwan (1999), and China (2008), as reported by Asakura and Sato (1996), W. Wang et al. (2001), and Yu, Chen, Bobet, and Yuan (2016), respectively. The continues evidence of tunnel damage demonstrates that these structures are also vulnerable to earthquakes.

The effect of earthquakes on underground structures can be divided into fault slip, ground failure and ground shaking. For the first case, avoiding active faults or correcting localized damage are usually the best solutions.

For the second case, the ground can be improved against a potential failure (Kuesel, 1969). Ground shaking, the vibration of the ground due to propagation of seismic waves, has been of great interest among the engineering community. Progress has been made in the last few years in understanding the soil-structure interaction mechanisms and the stress and displacement transfer from the ground to the structure during the ground shaking.

For most tunnels, with the exception of submerged tunnels, it seems well established that the most critical demand to the structure is caused by shear waves traveling perpendicular to the tunnel axis (Bobet, 2003; Hendron & Fernández, 1983; Merritt, Monsees, & Hendron, 1985; J.-N. Wang, 1993). These shear waves cause distortions of the cross section (ovaling for a circular tunnel, and racking for a rectangular tunnel) that result in axial forces (thrusts) and bending moments. The previous work has shown that the most important parameter determining the distortions of a cross section of a tunnel is the relative stiffness between the medium and the liner (expressed by the flexibility ratio, F), and that the depth and shape of the structure have second-order effects (Bobet, 2010). While all this has been well-studied for structures placed in linear-elastic ground under drained loading conditions, there is little information regarding the behavior of buried structures placed in nonlinear ground, especially under undrained loading conditions, i.e., when excess pore pressures are generated and accumulated during the earthquake.

Due to the rate of the loading during an earthquake, excess pore pressures may accumulate in fine-grained and some coarse-grained soils. A number of cases of liquefaction in shallow layers of fine sands has been observed after different earthquakes (e.g., Niigata, 1964; Loma Prieta, 1989; Christchurch, 2011). Regarding sand-gravel composites, Kong, Xu, and Zou (2007) reported that liquefaction occurred in Haicheng (1975) and Tangshan (1976) in China, and in Borah Peak (1983) in the United States. For soils with large grain sizes, or purely gravelly soils, even though liquefaction could not be reached in shallower layers (due to the high hydraulic conductivity and small drainage distances), numerical investigations have shown that at depths of 10 m or lower, excess pore pressures up to 50% or 60% of the initial confinement can be reached in loose to medium deposits, with hydraulic conductivity between 0.001 and 0.01 m/s (Pender, Orense, Wotherspoon, & Storie, 2016). The numerical analyses have shown that those excess pore pressures can be produced for input frequencies between 0.2 and 3 Hz, which cover most of the range of far-field motions, the target of this research. For deeper gravels deposits, where drainage is restricted, either due to long drainage distances, or by the presence of deposits with low hydraulic conductivity overlying the gravels deposits, very large excess pore pressures can be generated, even to liquefaction. The excess pore pressures generation in gravely soils has also been verified through laboratory tests on samples with size up to 40 mm conducted in medium scale triaxial or cyclic simple shear devices. Thus, it seems that soils with even moderately large permeability and grain size develop excess pore pressures during earthquakes, particularly those that are buried several meters below the surface.

1.2 Research objective and scope of the work

The objective of the research is to investigate the undrained seismic response of underground structures placed in nonlinear ground, when excess pore pressures accumulate with cycles of loading. For comparison purposes, the response of tunnels placed in nonlinear ground under drained loading, and of tunnels placed in linear-elastic ground for both drainage loading conditions, are also investigated. The research is aimed at the understanding of soil-structure behavior during an earthquake rather than providing design guidelines for any specific case. The objective is achieved by conducting explicit dynamic numerical analyses with the commercial package FLAC 7.0. For the numerical analyses, a nonlinear elastoplastic constitutive model is developed and verified.

The scope of the work is:

1. Development and verification of a constitutive model that captures the ground behavior observed in laboratory tests at different scales, under drained and undrained loading.
2. Evaluation of the effect of earthquake frequency content on the distortions of the tunnels.
3. Investigation of the effect of the flexibility ratio on the distortions and loading in the liner, as well as on the excess pore pressures, shear stresses and stiffness in the ground.
4. Evaluation of the effect of dynamic amplitude on the distortions of tunnels, under drained or undrained loading.
5. Determination of conditions under which a pseudo-static analyses is acceptable.

1.3 Outline

This book includes research performed to evaluate the undrained seismic response of underground structures subjected to ground shaking, using dynamic numerical analyses. The commercial package FLAC 7.0 has been used in all the simulations. The document contains six chapters, in addition to this introduction. The outline of the document is as follows:

Chapter 2 presents the background. It includes information about the effect of earthquakes on underground structures, the approaches commonly used to evaluate tunnel behavior under seismic loading, relevant studies found in the literature for both drained and undrained loading, constitutive models that have been used to predict the stress-strain behavior of soils, models to predict the excess pore pressures accumulation during cyclic loading, and some evidence of excess pore pressures generation in soils with relatively large size and hydraulic conductivity.

Chapter 3 contains the cyclic nonlinear elastoplastic constitutive model adopted in the research. The model is based on previous work by Jung (2009) and by Khasawneh (2014). The new model includes a modified "proportional" rule, after Tatsuoka, Masuda, Siddiquee, and Koseki (2003), to update the scaling factors in the hysteresis loop when the octahedral shear strain amplitude changes with respect to the octahedral shear strain amplitude in the previous cycle; includes a new formulation for cyclic plane strain tests; considers a plastic multiplier and plastic potential function for a non-associated flow rule, to calculate plastic strains. One of the most important contributions to the model is the incorporation of coupling of the shear and the volumetric strains to estimate the excess pore pressures accumulation during undrained loading. The implementation of the model in FLAC is also discussed in Chapter 3.

Chapter 4 includes the verification of the constitutive model. This is done through comparisons between the model simulations and results from other numerical analyses and from laboratory tests at different scales and stress paths, under drained and undrained loading. Three types of comparisons are made. First, the stiffness degradation for a drained cyclic simple test is compared with typical values in sands. Results of a monotonic plane strain compression test and of dynamic simulations with 1-D codes (DEEPSOIL, SHAKE) are compared with predictions with the model. Second, results of drained and undrained cyclic laboratory tests are compared with the simulations. More precisely, simple shear, triaxial compression, and plane strain for drained loading, and simple shear for undrained loading, are used for the verifications. Third, results of a centrifuge test with excess pore pressures generation, conducted on sand, are predicted with the constitutive model. Accelerations and excess pore pressures in the soil at different depths are compared. Results of another plane strain centrifuge test on a deep tunnel placed in dry sand, exposed to dynamic loading are also simulated. Ground accelerations at different depths, as well as axial forces and bending moments in the tunnel obtained with the simulations are compared with the experiments.

Chapter 5 presents the evaluation of the effect of input frequency on the seismic response of underground structures. Dynamic numerical analyses under different input frequencies of the dynamic loading (between 0.1 and 15 Hz) are conducted. The dynamic analyses are performed using as input a sinusoidal velocity at the bottom of the discretization. Linear-elastic and nonlinear ground under drained and undrained loading (with and without excess pore pressures accumulation) are investigated. Results for the different input frequencies are compared in terms of distortions of the tunnel cross section, normalized with respect to the distortions in the free field.

Chapter 6 includes parametric studies. The following scenarios are included: (i) Linear-elastic ground, to investigate the effect of relative stiffness on the distortions of circular and rectangular tunnels; and (ii) Nonlinear ground and circular tunnels, with and without excess pore pressure accumulation, to study the effect of relative stiffness on the distortions and loading in the liner (thrusts and bending moments), as well as the excess pore pressures, stiffness degradation and shear stresses in the ground. Also, the effect of increasing the amplitude of the dynamic input is assessed for drained and undrained loading with excess pore pressures accumulation. In addition, results from cyclic pseudo-static numerical analyses are compared with the full dynamic numerical analyses. The objective is to evaluate whether the seismic response of underground structures can be estimated through a static analysis.

Chapter 7 presents a summary of the work conducted, the main conclusions reached in the research, and recommendations for future work.

CHAPTER 2

BACKGROUND

2.1 INTRODUCTION

The most critical demand due to ground shaking is caused by shear waves traveling perpendicular to the tunnel axis, which cause distortions of the cross section. There are two approaches used to evaluate the response of underground structures under these conditions. One is the free field approach (Hendron & Fernández, 1983; Kuesel, 1969; Merritt et al., 1985; Newmark, 1967), which assumes that the structure follows the free field deformations of the ground, and therefore accommodates them without loss of its integrity. The other is the soil-structure interaction approach (Bobet, 2003, 2010; Huo, Bobet, Fernández, & Ramírez, 2006; Penzien, 2000; J.-N. Wang, 1993), which states that the underground structure modifies the free field deformation of the ground around it such that demand and response depend on the relative stiffness between the ground and the tunnel support. Two dimensionless coefficients have been proposed to consider soil-structure interaction, namely the flexibility and the compressibility ratios (Einstein & Schwartz, 1979; Peck, Hendron, & Mohraz, 1972).

The flexibility ratio is a measure of the resistance of the system to change shape (distort) under a state of pure shear, and so it is the main parameter controlling the seismic response of underground structures. Both analytical closed-form solutions and numerical analyses have been used to evaluate the seismic response of underground structures. The analytical solutions, and some pseudo-static numerical analyses, have been based on the premise that no stress amplification due to inertia force is present in tunnels located far from the seismic source (Hendron & Fernández, 1983; Merritt et al., 1985;

Monsees & Merritt, 1991; Mow & Pao, 1971; Paul, 1963; Yoshihara, 1963). In most studies, a drained condition, i.e., when no excess pore pressures are generated, and homogeneous, isotropic, elastic medium have been assumed.

This chapter presents the main aspects involved in the seismic response of underground structures, including some important studies that have been performed to understand better this problem. Constitutive models that have been used to predict the soil behavior and models to evaluate excess pore pressures accumulation are also described. More precisely, the different effects and the most critical demand of earthquakes on underground structures are presented in Section 2.2. The reported damage to underground structures during seismic events, including an actual tunnel collapse, is described in Section 2.3. In Section 2.4, a summary of fundamental studies carried out to evaluate the seismic response of underground structures under drained conditions is presented. In this section, the free field approach and the soil-structure interaction approach are explained separately. The few studies found involving the seismic response of tunnels under undrained conditions are described in Section 2.5. Given than in-depth studies should require numerical analyses, a brief description of some constitutive models used to predict the behavior of geological materials is presented in Section 2.6. The models are divided into commonly used models, and advanced complex models. The theoretical fundamentals and experimental evidence of the coupling between shear and volumetric strain, which produces excess pore pressures during undrained loading, are described in Section 2.7. Some examples of models proposed to evaluate such ground behavior are described in that section. In Section 2.8, results of numerical analyses and laboratory tests showing excess pore pressures generation of gravely soils, with hydraulic conductivity up to 0.01 m/s and maximum grain size up to 40 mm, are presented. A summary and discussion of the background described in the chapter is presented in Section 2.9.

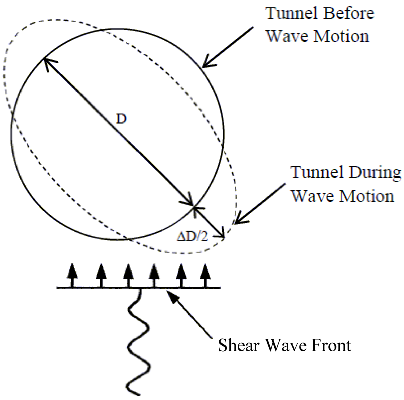
2.2 Effect of earthquakes on underground structures

The earthquake damage to underground structures can be divided into three main sources: fault slip, ground failure, and ground shaking. Fault slip includes direct shearing displacements of the ground and, even though the associated damage may be important, it is limited to a relatively narrow zone adjacent to the fault. It is not usually feasible to prevent faulted-induced displacements to an underground structure. Avoiding active faults or accepting the displacement and providing the means to facilitate a localized damage are the best solutions (Kuesel, 1969). Ground failures refer to ground instabilities such as rock slides, landslides, ground squeezing, soil liquefaction and soil subsidence. The best way to control this risk is by improving ground conditions against this type of failure. Ground shaking, the vibration of the ground due to propagation of seismic waves without large permanent displacements, is a common source of damage to underground structures, included those situated far from the epicenter of the earthquake. Dowding (1985) defined a point as ”far” from the epicenter, when the distance is larger than 10 km; that is, where the seismic loading usually has a frequency content between 0.1 and 10 Hz. This case deserves special attention, and is the seismic effect studied in this research.

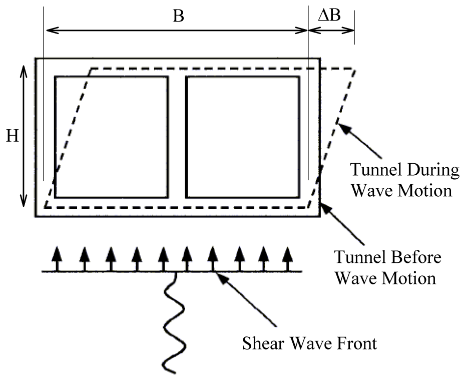
2.2.1 Effect of ground shaking on underground structures

Ground shaking motions are composed of body waves (longitudinal P-waves or transverse shear S-waves), and surface waves (Rayleigh or Love waves). The ground deformation, due to the interaction of the different seismic waves, is a complex phenomenon. However, for engineering purposes, the effect is usually separated and the deformation response of tunnels to ground shaking motions can be divided into three types: (i) axial or compression-extension, (ii) curvature or longitudinal bending, and (iii) distortions of the cross section (ovaling for circular tunnels and racking (sideways) for rectangular tunnels). The axial and curvature deformations are produced when seismic waves propagate in the longitudinal direction along the tunnel axis, i.e., parallel or oblique to the tunnel. For the latter, the largest axial deformation occurs when the angle of incidence is 45°. The ovaling and racking distortions are produced when the seismic waves propagate perpendicular, or nearly perpendicular, to the tunnel axis, i.e., in the transverse direction (Owen & Scholl, 1981). It has been well established that the most critical demand on underground structures, due to ground shaking, consists of distortions of the cross section caused by shear waves traveling perpendicular, especially vertically propagating, to the tunnel axis (Bobet, 2003; Hendron & Fernández, 1983; Merritt et al., 1985; J.-N. Wang, 1993). These waves transmit the greatest proportion of the earthquake energy and are the predominant source for earthquake loading. The design considerations for tunnels apply to the transverse direction and the behavior can be simulated as plane strain on any cross section perpendicular to the tunnel axis.

The seismic response of underground structures is a displacement-driven problem, and the main interest is to evaluate the distortions of the cross section caused by the ground shear deformations induced by the shear waves. Depending on the stiffness of the ground and the structure, such distortions could result in important axial forces and bending moments on the liner, additional to those produced by the geostatic stresses (St John & Zahrah, 1987). Distortions are usually expressed as the diametric strain ($\Delta D/D$) for circular liners, and as the difference between the horizontal displacement of the top and bottom slab normalized by the height of the tunnel ($\Delta B/H$), for rectangular structures (J.-N. Wang, 1993). Figure 2.1 shows the ovaling and racking distortions for circular and rectangular supports.



(a) Ovaling deformation.

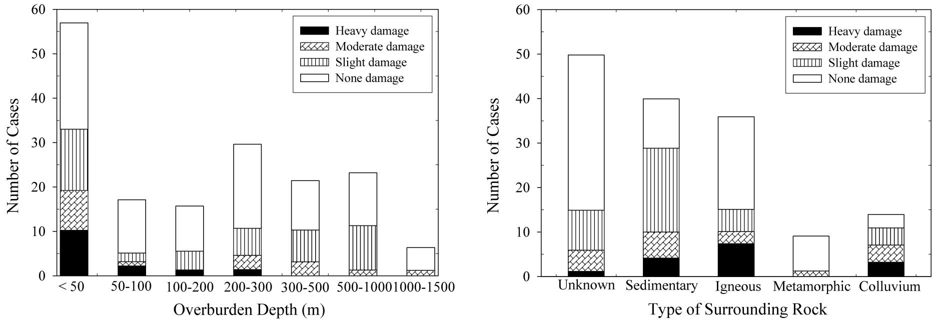


(b) Racking deformation.

Fig. 2.1. Ovaling and racking deformation of the tunnel cross section (adapted from Owen & Scholl, 1981).

2.3 Reported damage to underground structures during seismic events

Damage to underground structures due to seismic loading has been reported in the literature for more than 40 years. Dowding and Rozen (1978) evaluated the behavior of 71 tunnels under seismic loading. The database was expanded by Owen and Scholl (1981) with 56 additional cases. Later, Sharma and Judd (1991) increased the number to 192 tunnels. Power et al. (1998) provided a further update for a total of 217 case histories. Cases included in the database contain information about the effect of overburden cover, ground type, earthquake parameters, among others. Figure 2.2 shows the number of cases reported by Sharma and Judd (1991) for different types of overburden depths (2.2-a) and surrounding material (2.2-b). During the earthquake, 94 of the 192 cases (49% of the total) reported by Sharma and Judd (1991) suffered damage at different levels. It can be seen that damage occurred mostly for depths lower than 50 m, and that the less competent material (colluvium) had the higher percentage of damage, compared to the number of cases reported. The damage reported in the databases was obtained for peak ground accelerations larger than 0.15g. The damage ranged from some cracking to collapse and closure of the opening.



(a) Overburden depth (m). (b) Type of surrounding rock.

Fig. 2.2. Effect of overburden depth and surrounding material on damage of tunnels (adapted from Sharma & Judd, 1991).

Regarding different tunnels affected by the same earthquake, two cases of mountain tunnels, i.e., those situated deep within ground layers, are discussed in this book. The first case is the Hyogoken-Nambu earthquake (also known as the Kobe earthquake), which occurred in Japan in 1995. The second one is the Chi-Chi earthquake that took place in Taiwan in 1999.

Asakura and Sato (1996) summarized the survey carried out on 111 tunnels located in the hazard area of the Hyogoken-Nambu earthquake; 32 tunnels (29% of the total) suffered damage during the earthquake. The damage ranged from some cracks to spalling and collapse of the liner. Figure 2.3 shows the reported damage, for different overburden depths. For comparison purposes, the figure shows the same ranges of overburden depths reported by Sharma and Judd (1991) (Figure 2.2-a). Similar to the database shown in Figure 2.2-a, the major damage was observed for overburden depths smaller than 50 m; it must be noted however that damage was reported even for overburden depths larger than 300 m. Although the epicentral distance was not specified by the authors; based on location and geology provided by the authors, it can be inferred that most of the tunnels were far from the epicenter

(> 10 km) and/or did not cross a fault. Figure 2.4 shows damage in two of the mountain tunnels reported by Asakura and Sato (1996). Figure 2.4-a shows cracks in the side wall of Rokko tunnel and Figure 2.4-b illustrates the lining failure at the Bantaki tunnel. Those cases corresponded to tunnels located far from the seismic source.

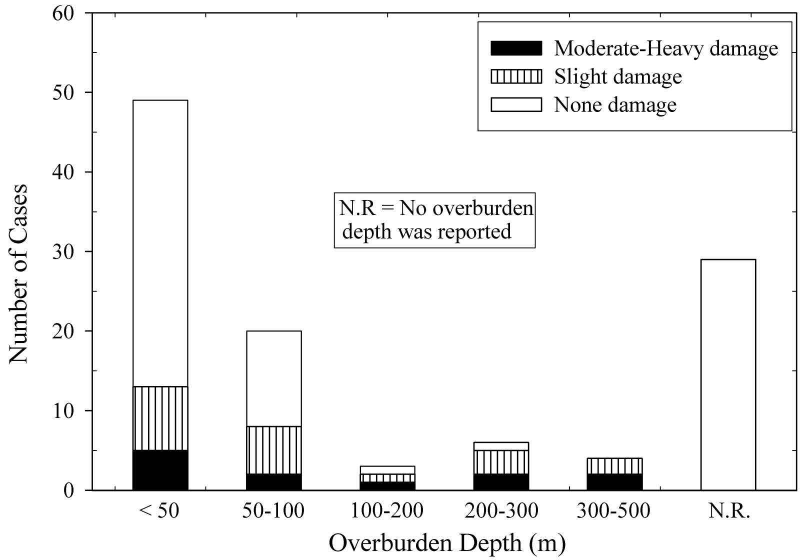
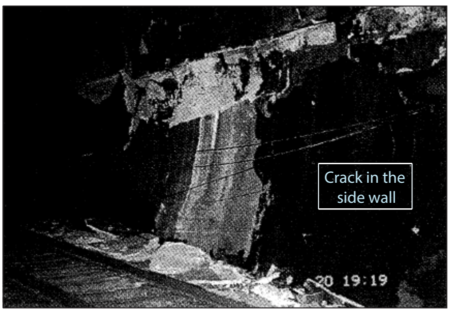
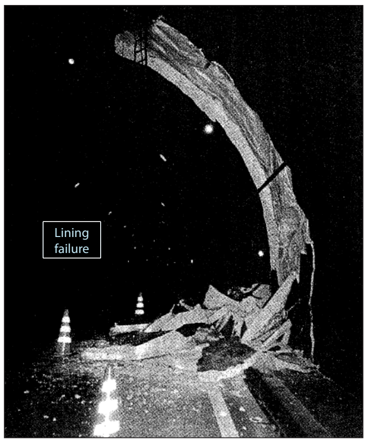


Fig. 2.3. Effect of overburden depth on damage of mountain tunnels during the Hyogoken-Nambu earthquake (adapted from Asakura & Sato, 1996).



(a) Cracks in the side wall of Rokko tunnel.



(b) Liner failure of Bantaki tunnel.

Fig. 2.4. Damage to mountain tunnels during the Hyogoken-Nambu earthquake (adapted from Asakura & Sato, 1996).

W. Wang et al. (2001) investigated 57 mountain tunnels in central Taiwan, the area affected by the Chi-Chi earthquake. 49 tunnels (86% of the total) suffered damage. In the database, 12 tunnels were located in the near-field, while the other 45 tunnels were in the far-field. Only one of the tunnels crossed a fault; for the other tunnels, the authors reported that the earthquake produced significant damage such as cracking, spalling of concrete liner and deformation of steel reinforcement. Figure 2.5 shows different types of damage for the 56 tunnels no crossing the fault. As seen in the figure, 25 tunnels (45% of the total) suffered moderate to heavy damage; 23 tunnels (41% of the total) experienced slightly damage; and only 8 tunnels (14% of the total) were not affected by the earthquake. The figure also includes the number of tunnels that suffered a particular type of damage (liner cracks, spalling of liner, etc.) As one can see in the figure, a large number of tunnels experienced damage during the earthquake.

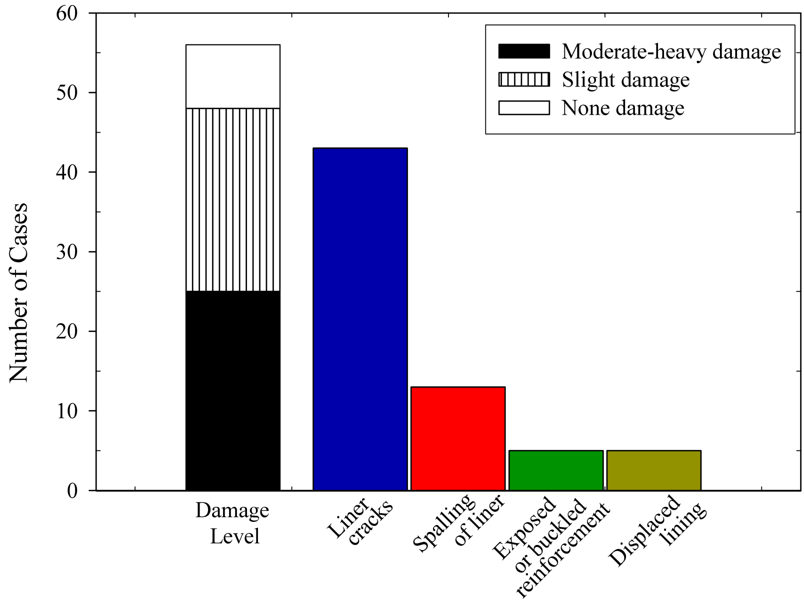


Fig. 2.5. Damage level and some cases of damage of mountain tunnels during the Chi-Chi earthquake (adapted from W. Wang et al., 2001).

There is more recent evidence of tunnels being affected by earthquakes. For example, Yu, Chen, Yuan, and Zhao (2016) reported the behavior of 55 tunnels during the Wenchuan earthquake in China, in 2008; 44 of the 55 tunnels were located in the far-field (epicentral distances larger than 10 km), of which, 25 suffered cracking and 2 experienced spalling. Yu, Chen, Bobet, and Yuan (2016) investigated in detail the damage of the Longxi tunnel,