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Seismic behaviour of tunnels: From experiments to analysis

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ABSTRACT

The paper presents a state-of-the-art review of the current understanding of the seismic behaviour of tunnels. Emphasis is placed on recorded responses of actual tunnels during past earthquakes, as well as relevant experimental studies. In particular, the observed seismic performance of tunnels is initially discussed, by providing cases of reported damage during past earthquakes. This is followed by a review of the current monitoring systems for this infrastructure, which can be used to create future case studies based on actual recordings of the seismic response. Subsequently, the paper provides a summary of relevant experimental studies that took place in the centrifuge or on shaking tables, followed by a short discussion of current analytical models, simplified methods and numerical schemes for the seismic analysis and vulnerability assessment of tunnels. Throughout the presentation, the current overall gaps in understanding the seismic response of tunnels are identified in an attempt to stimulate further work in these areas by the research community.

1. Introduction

Tunnels constitute vital components of the transportation and utility systems in both urban and national systems. They are being constructed at an increasing rate to facilitate the expanding needs for space in already densely-populated urban areas and mega-cities. The Tunnel Market Survey 2016 estimates the market size as €86BN, with China catering for almost 50%, and an annual growth of 7% for the next 5 to 10 years. This equates to 5200 km of tunnels being built every year globally.

Considering the size of the market, the significant construction cost per unit, as well as the vital role of this infrastructure in modern societies, even slight seismic effects and associated downtimes may lead to significant direct and indirect losses. Hence, a careful consideration of the effects of earthquake loadings on the analysis, design, construction, operation and risk assessment of tunnels is of great importance.

While there have been reports of damage on underground structures due to seismic events since the mid-seventies (e.g. Dowding and Rozen, 1978; Yoshikawa and Fukuchi, 1984; Wang, 1985), no systematic investigation of the interplay that exists between the ground and tunnels was carried out until much later. Indeed, it was in 1993, when Wang highlighted the concept of relative flexibility as a key parameter to understand the seismically-induced deformation of underground structures interacting with the surrounding ground. The failure of the Daikai station in Kobe, Japan, during the 1995 Hyogoken-Nambu earthquake clearly highlighted that not properly-designed underground

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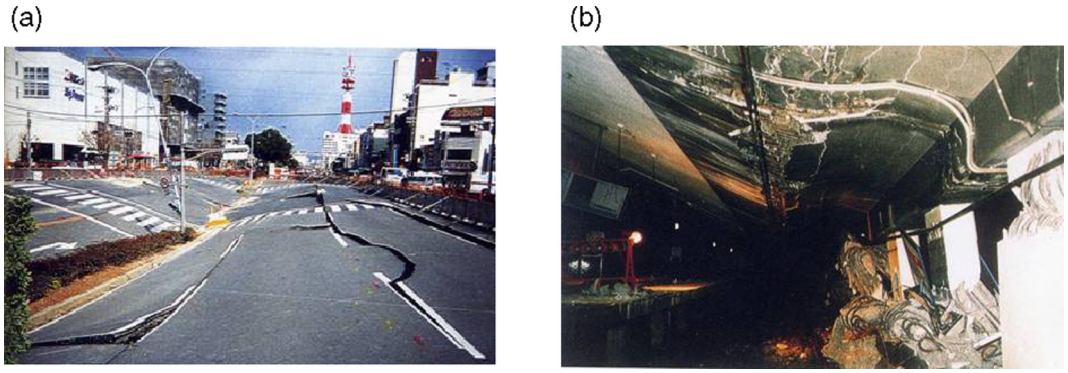

Fig. 1. Collapse of the Daikai Subway Station during the 1995 Hyogoken-Nambu earthquake: (a) settlement of the overlaying roadway caused by the subway collapse, (b) collapse of the central columns of the station (Special Issue of Soils and Foundations, 1996).

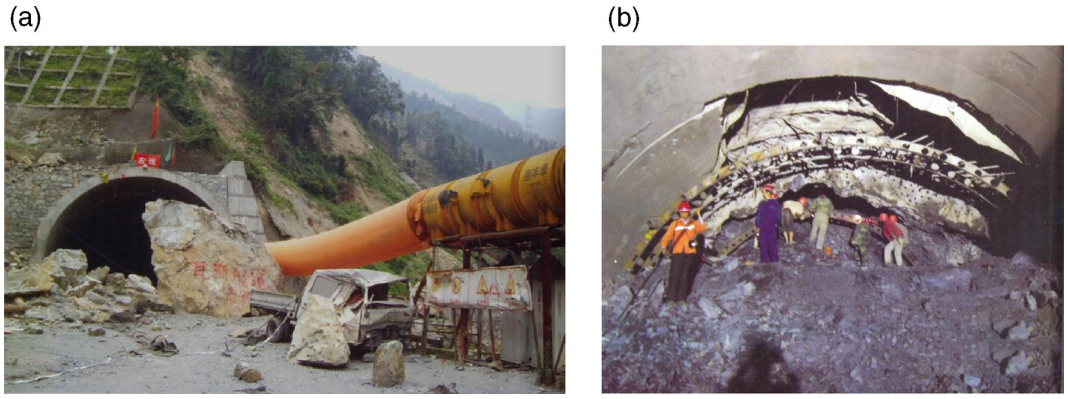

Fig. 2. Collapse of the Longxi tunnel during the 2008 Wenchuan earthquake: (a) collapse at the eastern portal of the tunnel, (b) collapse of the lining section at its crossing with a fault (after Yu et al., 2016).

structures were vulnerable to wave propagation effects (Iida et al., 1996; An et al., 1997; Huo et al., 2005; Montesinos et al., 2006; see Fig. 1). Since then, the failure of the Daikai station, the collapse of the Bolu tunnel in Turkey during the 1999 Düzce earthquake (Kontoe, et al., 2008), as well as the damage and failure of the Longxi tunnel in China during the 2008 Wenchuan earthquake (Yu et al., 2016; see Fig. 2) have been used as large-scale 'benchmark cases'. The relatively well-documented information of these cases, has been used to understand the interplay between structure and ground, with the ultimate goals being: the verification of the capabilities of existing methods of analysis and the validation of relevant material models (Huo et al., 2005; Kontoe et al., 2011; Kampas et al., 2019) or interface conditions (Huo et al., 2006; Sedarat et al., 2009; Kouretzis et al., 2013) needed to capture the observed response.

The observations from the above cases are extremely useful, as they provide invaluable insights of the actual behaviour of tunnels considering the 'scale effects', which are difficult to account for in the laboratory, at least to a full extent. Indeed, *centrifuge tests* on reduced scale physical models can impose the stress level to the ground that exist in the field but have limitations in modelling some of the details of the section and special components of tunnels (e.g. joints between lining segments), as well as in simulating accurately construction processes. One further limitation is the material adopted to model the tunnel linings (often aluminium) and the potential effect of this selection on the recorded response. Nevertheless, very useful data have been obtained from this type of tests and they have been widely used to develop and calibrate numerical models for the seismic analysis of tunnels (e.g. Kutter et al., 2008; Chou et al., 2010; Lanzano et al., 2010, 2012; Amorosi et al., 2014; Conti et al., 2014; Tsinidis et al., 2014, 2015a, b, c, 2016a, b; Esmaeilzadeh et al., 2018; Hashash et al., 2018, among others). *Shaking table tests* may provide an alternative or complement centrifuge tests since they allow for much larger models and for the use of more realistic materials for the tunnel lining. However, these 1g tests are performed at a confining stress much lower than in the field, thus introducing a difference in the recorded response, compared to actual one. This limitation poses a challenge when the objective of the test is to represent accurately the actual conditions in field, but it may be of less importance, if the experimental results are used to calibrate or to verify numerical and analytical models, when the latter duplicate the geometry and boundary conditions used in the tests. Indeed, this was the case in recent studies, where efforts were made to reproduce the recorded response either from a single table test (Abate et al., 2010; Chen et al., 2012) or multiple, connected, shaking tables (Yan et al., 2016; Yu et al., 2018). The increased space offered by shaking table tests may also allow for the investigation of the interaction of complex structural systems under seismic loading, e.g. dynamic interaction between underground structures and aboveground high-rise buildings.

To facilitate the seismic design of tunnels and account for critical aspects of their seismic response, analytical solutions, simplified methods, as well as numerical models have been developed extensively, mostly since the early 90′s. However, knowledge gaps regarding complex characteristics of the tunnel-soil configuration still remain and need to be bridged.

This paper, which builds upon the legacy of two previous seminal review papers on the same subject (St John and Zahrah, 1987; Hashash et al. 2001), presents a state-of-the-art review of the current understanding of the seismic behaviour of tunnels under seismic loading. It starts with a discussion of the observed damage during past earthquakes, presented as phenomenological seismic tunnel performance. This is followed by a review of the current monitoring systems for tunnels, which can be used to create future case studies based on actual

recording of the seismic response. This is clearly identified as a significant current gap in the field. Subsequently, the paper provides a critical review of current analytical solutions, simplified analysis methods and numerical schemes, as well as physical models. Finally, the current overall gaps in the field are identified in an attempt to stimulate further research.

2. Seismic performance and behaviour of tunnels

2.1. Observed seismic performance of tunnels

As compared to buildings and aboveground civil infrastructure, tunnels have been traditionally considered less susceptible to earthquake-induced damage. Nevertheless, several cases of extensive damage, or even collapse, have been reported in the literature. Dowding and Rozen (1978) correlated seismically-induced tunnel damage with surface peak ground acceleration using data from 70 case histories and employing relevant attenuation relationships. Extending the above database to 127 cases, Owen and Scholl (1981) concluded that slight damage occurred in rock tunnels for Peak Ground Accelerations (PGA) below 0.4 g. Sharma and Judd (1991) attempted to develop correlations between observed damage and salient parameters affecting seismic behaviour, namely lining geometrical properties, geotechnical conditions and earthquake characteristics. They concluded that deeper tunnels or rock tunnels were generally safer, while damage was more extensive with increasing earthquake magnitude and decreasing epicentral distance. Using the most recent, at that time, ground motion prediction relationships and expanding the previous database with damage reports of tunnels during the 1995 Hyogoken-Nambu earthquake in Kobe, Japan, Power et al. (1998) observed minor damage on tunnels for PGA values lower than 0.2 g and slight to heavy damage for PGA greater than 0.2 g (Fig. 3). It is worth noticing that the 1995 Hyogoken-Nambu earthquake was a rather destructive event for tunnels, as more than 12% of the tunnels in the epicentral area were heavily damaged (Asakura and Sato, 1996; Asakura and Sato, 1998; Yashiro and Kojima, 2007). The damage mechanisms were extensively studied by several researchers (i.e. EQE, 1995; Iida et al., 1996; An et al., 1997; Uenishi and Sakurai 2000; Huo et al., 2005; Montesinos et al., 2006; Kheradi et al., 2017; Ma et al., 2019; Lu and Hwang, 2019), highlighting that most of the damaged tunnels were designed and built neglecting an appropriate seismic assessment (Iida et al., 1996; Matsuda et al., 1996; Samata et al., 1997; Kawasima, 2000, 2006; Hashash et al., 2001.) The collapse of the Daikai Station was used as a case study for the investigation of seismic isolation elements for tunnels (e.g. Chao et al., 2018).

Another representative example of extensive damage caused by the

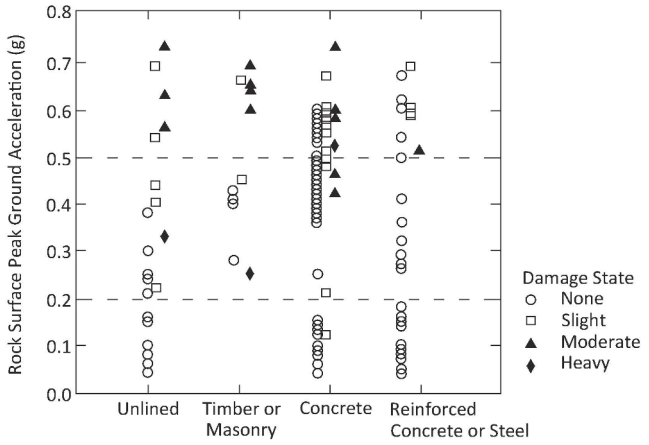

Fig. 3. Summary of observed bored/mined tunnel damage due to ground shaking (adapted after Power et al., 1998).

combined effects of ground shaking and ground permanent deformation is the collapse of the twin Bolu tunnel during the 1999 Kocaeli earthquake (Hashash et al., 2001; Kontoe et al., 2008). The collapse took place during construction in the unfinished section of the tunnel, which was deformed in an oval shape, causing crushing of the shotcrete and buckling of the steel ribs at the shoulder and at the knees.

During the 1999 Chi-Chi earthquake in Taiwan, a large number of mountain tunnels suffered significant damage (Wang et al., 2001; Lu and Hwang, 2019). In particular, 26% of the 50 tunnels located within 25 km of the earthquake fault were severely damaged, while over 20% of the tunnels were moderately damaged. Various types of damage were observed, including: lining cracks, portal failures, spalling of the concrete lining, groundwater inrush, exposed and buckled reinforcement, displaced lining, rockfalls in unlined sections, lining collapses caused by slope failures, pavement cracks and lining shear-off (Fig. 4). Severe damage was observed close to surface slopes or portal openings, while deeper buried sections behaved generally better.

Similar damage patterns to those reported in Chi-Chi earthquake, were identified in mountain tunnels during the 2004 Mid Niigata Prefecture earthquake in Japan (Yashiro et al., 2007; Konagai et al., 2009; Jiang et al., 2010), the 2007 Niigata Prefecture Chuetsu Offshore Earthquake (Saito et al., 2007), and the 2008 Wenchuan earthquake in China (e.g. Wang et al., 2009; Tao et al., 2011; Chen et al. 2012; Li, 2012; Wang and Zhang 2013; Yu et al., 2013; Yu et al., 2016a,b; Shen et al., 2014).

Chen et al. (2012) reported the following parameters as the most critical affecting the response of mountain tunnels: earthquake magnitude, depth and epicentral distance of the seismic source, geometrical properties of the lining, burial depth and sudden changes of tunnel dimensions.

Wang and Zhang (2013) proposed a damage classification based on 254 damage reports from the Chi-Chi earthquake, the 2004 Mid Niigata Prefecture earthquake and the 2008 Wenchuan earthquake, providing a short damage description for each proposed damage level. Zhang et al. (2016) examined the damage of the Tawarayama tunnel caused by the 2016 Kumamoto Earthquake, reporting that ring cracks were found on the tunnel with a spacing of 10 m in around 20% of the spans of the tunnel. This observation was attributed to the interaction between the seismic wave propagation and the geological conditions at site. Recently, Callisto and Ricci (2019) carried out a back analysis of the damage suffered by the San Benedetto tunnel during the 2016 Norcia earthquake in Italy, aiming at evaluating the ability of available methods of analysis to predict its seismic performance. Simplified methods, where the seismic loading is introduced in an equivalent static manner, were found to provide reasonable predictions, while more accurate responses were provided by dynamic analyses of the case study.

A special category of tunnels is that of *submerged tunnels*. These tunnels are made by large prefabricated reinforced concrete or steel elements-segments, which are constructed in a dry dock and then transported and placed in shallow trenches, excavated in the seabed under the water. The connection of the segments is established via specially-designed joints, comprised of rubber gaskets and prestressed tendons (e.g. Kiyomiya, 1995). During the 1989 Loma Prieta earthquake (M_s 7.1) the submerged tunnel of the Bay Area Rapid Transit (BART) tunnel system, crossing San Francisco Bay in California, behaved satisfactorily for accelerations in the order of 0.20–0.30 g. BART was one of the first underground structures that was studied and constructed including seismic design considerations (Kuesel, 1969). A second example is that of the Osaka South Port immersed tunnel. During the 1995 Hyogoken-Nambu earthquake (M_{JMA} 7.2), the under construction 1 km immersed tunnel behaved very well for accelerations around 0.27 g (Ingerslev and Kiyomiya, 1997; Anastasopoulos et al., 2007), and the construction continued without any repairs.

Other detailed reviews of the seismic performance of tunnels and underground structures can be found in relevant publications (e.g.

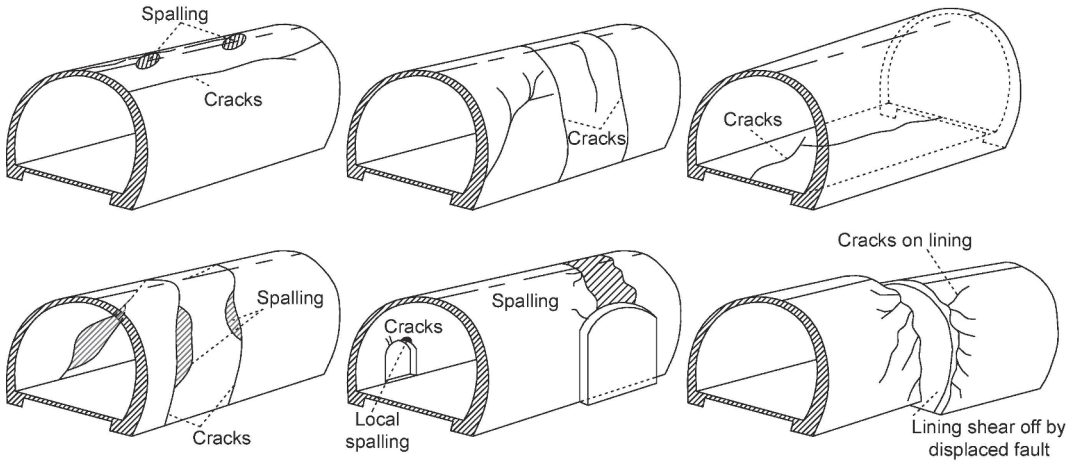

Fig. 4. Typical failure modes of mountain tunnels reported during the 1999 Chi-Chi earthquake in Taiwan (redrawn after Wang et al., 2001).

Gazetas et al., 2005; Hashash et al., 2001; Lanzano et al., 2008; Jaramillo, 2017; Roy and Sarkar, 2016).

2.2. Seismic response mechanisms

The seismic response of tunnels is quite distinct compared to that of above ground structures since the kinematic loading induced by the surrounding ground prevails over inertial loads stemming from the oscillation of the tunnel itself (Wang, 1993; Hashash et al., 2001).

The observation of damage induced by past-earthquakes highlighted that tunnels in seismic-prone areas should be generally designed to cope with *ground shaking* due to wave propagation or permanent ground deformations due to seismically-induced *ground failures*, such as liquefaction, lateral spreading, landslides and fault rupture.

Ground shaking along the longitudinal axis of a tunnel is expected to cause axial deformations and longitudinal bending (Owen and Scholl, 1981), whereas for shaking in the transverse direction, the tunnel undergoes ovalling (for circular sections) or a combined racking-rocking distortion (for box-shaped sections), with racking prevailing (Fig. 5). The seismic response of a tunnel is highly affected by the soil-structure interaction (SSI) effects that take place during ground shaking. Hence, the properties of the surrounding ground and its response during ground shaking, the geometrical features and burial depth of the tunnel, the soil to tunnel relative stiffness, the soil-tunnel interface characteristics, as well as the ground motion characteristics are especially important parameters that affect the response (Wang, 1993; Hashash et al., 2001; Kawashima, 2006; Pitilakis and Tsinidis, 2014). For instance, for an 'elastic soil-tunnel system', i.e. elastic response of the soil and the tunnel lining, with a perfect bonding assumed for the soil-tunnel interface, the rocking rotation of the tunnel section is expected to take place around the geometric centroid of the section, while material or interface nonlinearities are expected to move the rotation pole from the centroid (Tsinidis, 2017).

Seismically-induced ground failures, on the other hand, e.g. failures due to liquefaction, fault movements or slope failure (Fig. 6), may induce large permanent ground deformations to tunnels. Actually, a large number of failures of mountain tunnels have been attributed to seismically-induced ground deformations (e.g. Power et al., 1996).

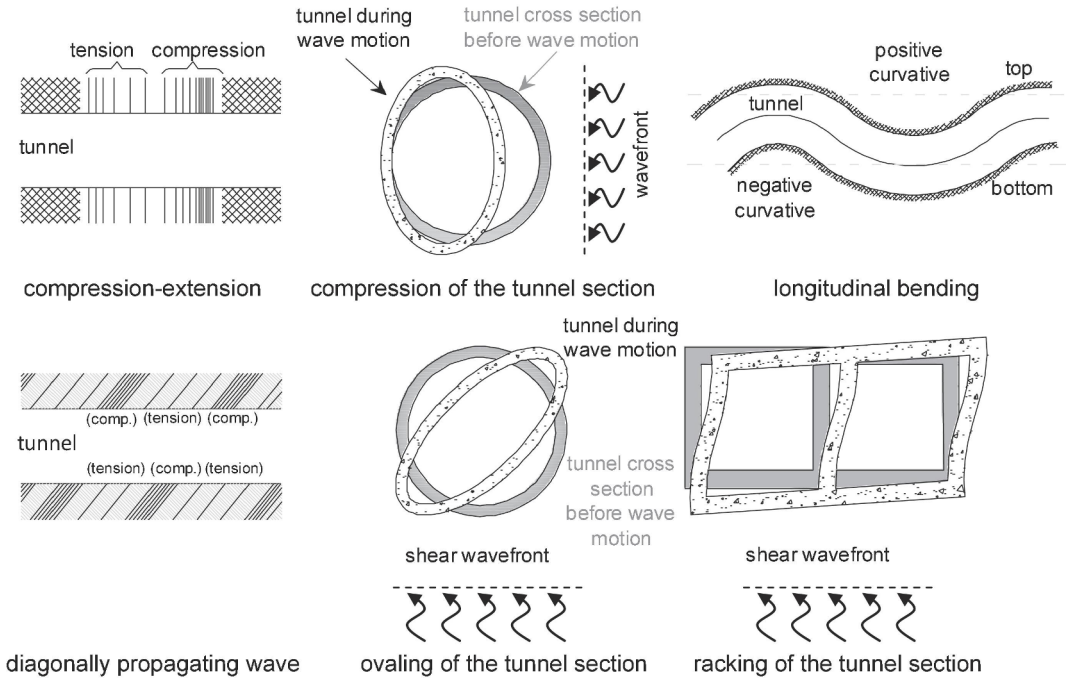

Fig. 5. Deformation modes of underground structures subjected to seismic waves (redrawn and modified after Owen and Scholl, 1981).

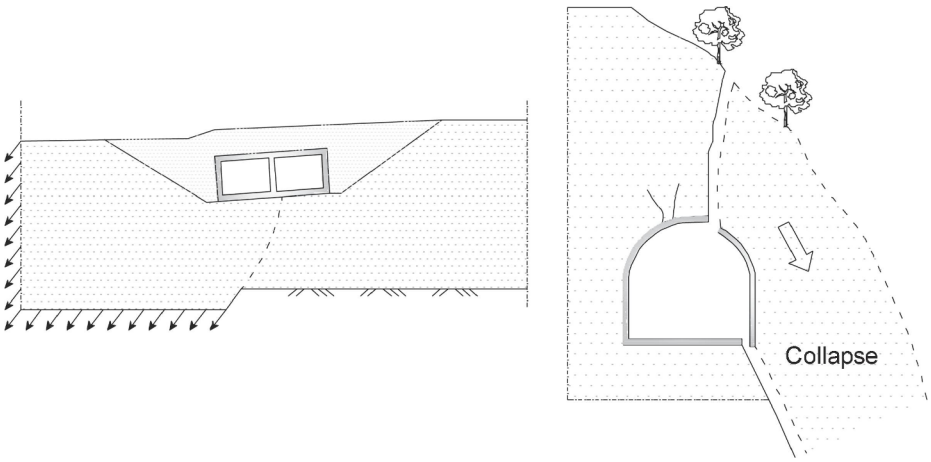

Fig. 6. Examples of the effects of seismically-induced ground failures on tunnels.

Due to the distinct deformation modes of tunnels and associated potential level of damage induced by ground shaking in the longitudinal and transverse directions, as well as by seismically-induced ground failures, the analysis of these structures against the above seismic effects is commonly disaggregated (e.g. Ingerslev and Kiyomiya, 1997; St. John and Zahrah, 1987; Hashash et al., 2001; Paolucci and Pitilakis, 2007; Pitilakis and Tsinidis, 2014). In this context, different methods are commonly employed for the analysis of tunnels against ground shaking in the transverse and longitudinal directions, as well as for the seismically-induced ground failures. Some of these methods are actually introduced in relevant design guidelines (e.g. ISO 23469, 2005; FHWA, 2009). Similarly, relevant experimental and numerical studies have commonly focused on one of the above seismic effects in isolation, with some exceptions, e.g. Anastasopoulos et al. (2008) who studied the combined effect of ground shaking and faulting on the seismic response of immersed tunnels.

3. Field observations and monitoring of actual seismic response of tunnels

The monitoring of the seismic response of full-scale structures has been mainly focused on above ground structures, such as bridges and tall buildings (e.g. Brownjohn, 2007). Conversely, the monitoring of tunnels has routinely focused on assessing deformations, stability, integrity and alignment during construction and operation (Bhalla et al., 2005). The limited efforts towards monitoring of the seismic response of tunnels may be attributed to the seemingly reduced seismic vulnerability of these structures. Other intrinsic limitations to monitoring the seismic response of tunnels, such as the significant length and therefore the difficulty to gather synchronous information on ground and structural motion and deformation, have also contributed towards the lack of case studies. This need to better monitor earthquake tunnel responses is not new and dates back to the 70′s, when Brekke and Korbin (FHWA, 1981) proposed three candidate tunnels in California for permanent structural instrumentation of their dynamic response. Nowadays, there is a growing list of tunnels equipped with Structural Health Monitoring (SHM) systems, for instance the 1800 m Chungliao Tunnel in Taiwan that was retrofitted after damage during the 1999 Chi-Chi earthquake (Hou et al., 2007), the 660 m George Massey Tunnel in Canada that was also seismically upgraded years after its initial construction (Kaya and Ventura, 2019), and the 6042 m Nanjing Yangtze River Tunnel in China (Li et al., 2016).

Early studies, dating back to the 60′s and 70′s, focused on the seismic response of the ground at the tunnel's depth, providing a series of field acceleration records at the tunnel's position (Pratt et al., 1978; FHWA, 1981). Likewise, a number of Japanese researchers instrumented boreholes in various soils with accelerometers at different depths, in an effort to understand and quantify the seismic motion amplification towards ground surface during ground shaking and provide the acceleration at various depths were tunnels were located. By monitoring a vertical shaft in the Kinugawa Power Station, for depths between 17.2 m and 67.2 m, Okamoto (1971) reported a noticeable amplification of the horizontal acceleration towards ground surface but rather similar displacements at the top and bottom of the shaft, showing the potential influence of tunnels on wave propagation and its implication on ground-based structures.

Okamoto et al. (1973) employed strain gauges to record the axial strains of a submerged railway tunnel crossing the Tama River in the Tokyo area. Data from more than 10 small to medium magnitude earthquakes highlighted the significance of axial (i.e. along the tunnel axis) straining in addition to the straining caused by the transversal deformation of the tunnel. Iwasaki et al. (1977) enriched the above studies, referring to ground response, by examing deep soil sites in the Tokyo bay area (i.e. sand, clay, siltstone soil deposits with depth up to 150 m), for a wide range of earthquake magnitudes.

The most complete and interesting of the early studies was presented by Hamada and co-workers (see review in Hamada, 2013). The study focused on the seismic response of two tunnels, a 1035 m long and a 744 m long, both submerged in the Tokyo Port. The researchers acquired distributed triaxial acceleration and strain information along various sections of the tunnels and provided novel evidence on the axial straining mechanisms that the tunnels experienced in the course of an earthquake. The study was extended by 4-year long monitoring of the seismic response of a 4600 m mountain tunnel, which experienced 11 earthquakes of different magnitude during the course of this monitoring period.

In more recent research efforts, Ikuma (2005) reported on the earthquake data collected, over a 14-year period, from the 240 m undersea, 54 km long Senkai Tunnel in Japan. The tunnel experienced four large earthquakes. During the Hokkaido Southwestern Offshore earthquake, a maximum PGA of 0.056 g was reported on the tunnel, whereas the reported PGA near the tunnel reached 0.214 g. Based on the above observation, Ikuma supported the broad view that the ground motion acceleration and hence, its impact on a tunnel, are much smaller than that for structures on the ground surface. Additionally, the study highlighted the temporal development of deformation on different tunnel sections (see Fig. 7), possibly cumulative, observing the downwards trend of the readings, although it was still quoted as having minimal impact on the lining integrity.

Dikmen (2016) reported findings from the comprehensive Marmaray submerged tunnel (Gokce et al., 2009) monitoring system, consisting of 26 triaxial force-feedback accelerometers, during the 2014 North Aegean earthquake. The maximum recorded tunnel acceleration was lower than 0.02 g, but nonetheless it was larger than that recorded

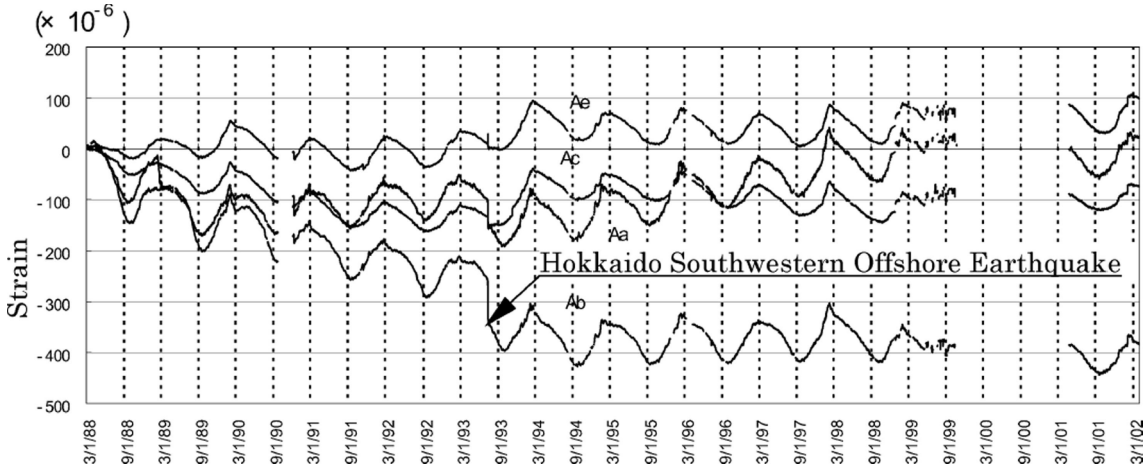

Fig. 7. Axial strain recordings at various positions along a single section of the Senkai Tunnel. Note the cyclic temporal pattern and the "jump" associated with the earthquake event. (see Fig. 11 within Ikuma, 2005).

at the outcrops located near the tunnel by a factor ranging between 1.9 and 3.5. Such responses is comparable, amplitude-wise, to ordinary cyclic traffic-induced accelerations of the tunnel.

Reviewing the monitoring system of the Dujiashan Tunnel that belongs to the Guang-Gan Expressway tunnel network in China, Wang et al. (2017) focused on the importance of measuring lining stresses and highlighted the need for creating relevant networks of SHM systems that may help towards this direction.

Based on this short review, it is evident that the two parameters that have been mainly recorded by monitoring systems, dedicated to the seismic response of tunnels under ground shaking, are the acceleration in the ground or on the tunnel lining and the lining strain. Both parameters may be used for damage detection purposes, or broader, for uncovering the condition of the tunnel's lining (e.g. degradation due to ageing phenomena). To this purpose, accelerometers and ordinary point strain gauges can be complemented by modern techniques and instrumentation, for instance, Fibre Optic sensors. A latest review on tunnel-specific, full-scale applications of distributed Fibre Optic Sensors (providing information beyond strain) is provided by Soga et al. (2018), while an account of complementary modern, non-permanent and non-contact tunnel inspection techniques is given in White et al. (2014). Namely, air-coupled ground penetrating radar, and a vehicle-mounted scanning system that combines laser, visual, and infrared thermography scanning methods, when combined, are shown to be very efficient for monitoring tunnel lining integrity, such as delamination or reinforcement de-bonding. Zhang et al. (2014) addressed the issue of optimisation of tunnel sensor (i.e. tiltmeters) placement; although practiced increasingly for other types of structures, this is entirely novel for tunnels.

Yamamoto and Matsukawa (2007) presented a non-destructive methodology based on Laser Doppler Vibrometry to assess fatigue potential for a section of the 75-year old Ginza Subway Line that began service as the first subway in Japan. Fatigue assessments, even independent of earthquake studies, are very rare in tunnels even though they are topical, considering the extreme ageing signs presented by long-standing tunnel infrastructure (see, e.g., the Prague Metro case in Vaníček and Vaníček, 2007). Cases, such as the earthquake-damaged Norcia Tunnel, where post-damage, intrusive control of the lining thickness uncovered construction faults with insufficient lining depth for one of the side walls (Callisto and Ricci, 2019), are clearly motivating the need for surveying and assessing the current state of a tunnel.

It is worth noting that future monitoring campaigns in tunnels may benefit from the lessons learnt from instrumenting tunnels in laboratory conditions (see Section 4.4).

4. Investigation of the seismic response of tunnels by physical testing

The majority of existing experimental studies have investigated the response of tunnels under ground shaking, while seismically-induced ground failures on the response of tunnels have received considerably less attention, mainly due to limitations of existing experimental facilities. This section focusses on the three main tests that have been develop to date: small-scale centrifuge dynamic tests, focusing mainly on the transversal seismic response of tunnels; reduced scale 1g shaking table tests, considering both longitudinal and transversal shaking directions, and static tests, focusing on the investigation of the response of the joints or shear keys of tunnels.

4.1. Dynamic centrifuge tests

Centrifuge modelling of the seismic behaviour of tunnels has been involved in examining both the effects of ground failures, such as seismically-induced slope failures near the tunnel portal, shearing of the lining due to fault rupture and liquefaction-induced flotation (e.g. Kutter et al., 2008; Chou et al., 2010; Chian and Madabhushi, 2012), as well as ground shaking. The latter studies focused mainly on the response of tunnels under vertically propagating transverse shear waves (e.g. Ounoe et al., 1994, 1998; Yamada et al., 2002; Ito et al., 2006; Izawa et al., 2006; Shibayama et al., 2007, 2010; Tohda et al., 2010; Gillis et al., 2014; Abuhajar et al., 2015a,b). However, only few of these centrifuge tests included measurements of internal forces of the lining (e.g. Yang et al. 2004). More recently, Chen et al. (2010) and Cao and Huang (2010) provided recorded strain time histories of a model tunnel under ground shaking, while Chen and Shen (2014) provided recorded bending moments (not time histories) of a rectangular model tunnel tested under ground shaking, to investigate the effect of an isolation layer surrounding it.

Cilingir and Madabhushi modelled in a centrifuge the behaviour of circular and rectangular tunnels in sand under ground shaking in the transversal direction (Cilingir, 2009, Cilingir and Madabhushi, 2011a, 2011b, 2001c). They observed three stages in the experimentally-measured time histories of earth pressures, namely: a transient stage, a steady-state cycling stage, and a residual (post-earthquake) stage. The first stage includes the first few cycles, after which the tunnel structure reaches a dynamic equilibrium. During the following steady-state stage, the earth pressures around the tunnel oscillate around a mean residual value that is locked in the tunnel lining in stage 3, after the shaking stops. By conducting similar tests on circular tunnels, Lanzano (2009), Lanzano et al. (2010) and Lanzano et al. (2012) confirmed that such

residual forces arise, possibly due to the densification of sand around the tunnel (Bilotta et al., 2014). According to Cilingir and Madabhushi (2011a), the magnitude of these residual forces seems to depend more on the peak ground acceleration (PGA) of the seismic motion rather than the number of cycles the tunnel is subjected to (hence the duration or frequency content of the seismic motion).

By applying Particle Image Velocimetry (PIV) techniques and using high resolution images obtained from a high-speed camera, the researchers also examined the deformation patterns of flexible box-type model tunnels, tested in the centrifuge under ground shaking in the transversal direction (Cilingir and Madabhushi, 2011b). They showed that these tunnels exhibit a rocking deformation pattern during shaking, in addition to the prevalent racking distortion. They attributed such a response to the plastic soil strains developing around the tunnel in the initial stages of strong shaking. This coupled racking-rocking deformation pattern of box-type tunnels was also verified by a series of dynamic centrifuge tests, which were performed on flexible aluminium square model tunnels embedded in dry sand (Tsinidis et al., 2014; Tsinidis, 2015; Tsinidis et al., 2015a,b; Tsinidis et al., 2016a,b). The interpretation of the results of the later experimental campaigns revealed: (a) a rocking response of the model tunnels in addition to their racking distortion; (b) residual earth pressures on the tunnel side walls; and (c) residual internal forces in the tunnels' linings after shaking ceased. The residual response (earth pressures and internal forces) was amplified with increasing tunnel lining flexibility. Actually, the effect of lining stiffness was found to be an important parameter for the seismic response of these tunnels. A companion series of dynamic centrifuge tests were carried out on box-type culverts in the geotechnical centrifuge at IFSTTAR, Nantes (Tsinidis et al., 2015c; 2016c), to investigate further the response of these structures in dry and saturated sand, when subjected to sinusoidal and seismic excitations, as affected by soil-tunnel relative flexibility and soil-structure interface roughness. The results confirmed that a rocking deformation mode was coupled with the well-known racking distortion of box-type tunnels under transversal seismic shaking. Confirming Lanzano et al. (2012) results on circular tunnel models, soil densification and yielding were found to lead to residual dynamic earth pressures, shear stresses and lining forces in the post shaking stage, especially in the case of flexible linings (e.g. for tunnels with flexibility ratio $F > 2.0$). Interface characteristics were also found to affect the distributions of response parameters around the perimeter of the tunnel section. For instance, a rougher soil-tunnel interface generally led to much higher shear stresses around the perimeter of the tunnel during ground shaking, subsequently causing higher axial loadings on the tunnel lining, compared to those developed in the case of a smoother interface (Tsinidis et al., 2015c; 2016c). The effect of interface roughness on the seismic bending moment of the lining found to be less important. Ulgen et al. (2015) conducted similar tests on rectangular model tunnels in dry sand, showing that the measured racking deformations in the dynamic centrifuge tests had a good fit with the analytical estimates derived by Penzien's (2000) and Bobet et al.'s (2003) solutions. The efficiency of comparisons was found to depend on the value of the soil to tunnel relative stiffness (Wang, 1993), with better matches obtained for the stiffer tunnels compared to surrounding ground (i.e. for tunnels with flexibility ratio $F < 1.0$).

The above studies focused on the response of tunnels under green-field conditions, which are not representative of real urban environments. Using centrifuge tests, Hashash et al. (2018) have recently shown that, in urban areas, these green-field conditions do not apply in the vicinity of tall buildings and, actually, the interaction phenomena between the building and the tunnel can change significantly the performance of cut-and-cover tunnels. In particular, they examined the effect of a 13-story midrise and a 42-story high-rise structures on the response of an adjacent cut-and-cover tunnel, indicating a transmission of large lateral loads to the underground structures by the adjacent buildings during ground shaking, with these loads being proportional to building base shear and dependent on the geometric details of both the underground structure and the building foundation.

It is worth mentioning also that a number of centrifuge studies were devoted to the analysis of retrofitting and isolation techniques (e.g. Adalier et al., 2003; Chen et al., 2014; Chen et al., 2018). For instance, Adalier et al. (2003) assessed the effectiveness of countermeasure retrofit techniques against potential liquefaction for the existing immersed George Massey tunnel, examining the water pore pressures around the model tunnel, as well as the potential induced deformation patterns in each case. Chen et al. (2014) examined the effect of an isolation rubber layer, introduced around the perimeter of box-type tunnel, on the transverse seismic response of the tunnel. Comparing the recorded bending moment at critical locations of the 'isolated' tunnel's lining with those of the equivalent non-isolated tunnel, they concluded that the isolation layer affected the bending moment on the lining, with the effect being positive or negative depending on the frequency characteristics of the shaking motion.

In summary, the main lessons from centrifuge tests are:

- Residual internal forces have been reported on the tunnel lining after ground shaking has ended, especially in case of tunnel linings that are flexible compared to the surrounding ground (e.g. for $F > 10$).
- Box-shaped tunnels exhibit a combined racking-rocking behaviour under ground shaking in the transversal direction, with racking prevailing.
- Most tests to date were carried out representing green-field conditions. However, the presence of other structures affects significantly wave propagation and therefore, the behaviour of tunnels.

4.2. Shaking table tests

Shaking table tests at 1 g have been used to study the dynamic response of tunnels under seismic vibrations. The model tunnels have been modelled using either slurries of gypsum and water (e.g. Xu et al., 2016), reinforced concrete (e.g. Luzhen et al., 2010, Chen et al., 2010), micro-concrete (i.e. sieved cement-aggregate-water mixtures), reinforced with steel mesh or polypropylene fibers (e.g. Xin et al., 2019) or organic glass (e.g. Guobo et al., 2018).

Ohtomo et al. (2001) carried out one of the first experimental studies on box-type underground ducts within the framework of the earthquake safety evaluation of civil engineering structures, after the 1995 Hyogoken-Nambu earthquake in Kobe, Japan. The Japanese electric power industry funded such research projects to investigate the safety of nuclear power plants. The study highlighted the significant effect of the shear stress, developed along the roof slab of the duct during shaking, on the seismic response of the duct (i.e., on the structural racking deformation).

Many other investigations of the seismic behaviour of tunnels using 1 g shaking table tests have been carried out in the last decade. Shi et al. (2008) examined the seismic response of a model utility tunnel in sand. Luzhen et al. (2010) recorded the bending strains on a reinforced concrete scaled model, indicating higher strains towards corners. Chen et al. (2010) and Chen et al. (2012) conducted a series of shaking table tests on reduced-scale utility tunnel models, accounting for the spatial variability of the input motion induced along the longitudinal axis of the tunnel, by means of two independent shaking tables. They showed that the tunnel behaviour was largely affected by the non-uniform earthquake excitation; in particular, the non-uniform excitation of the model tunnel led to much higher structural response (e.g. higher axial straining of the model tunnel) compared to the one recorded under uniform excitation. Hence, the effect of spatial distribution of the ground motion should be considered in the seismic design of tunnels.

Non-uniform excitations by a multi-point shaking system, i.e., four independent shaking tables that worked in coordination as a large linear shaking table array, were applied in a series of tests to a reduced-scale model of the Hong Kong-Zhuhai-Macau immersed tunnel (Yan

et al., 2016; Yu et al., 2018; Yuan et al., 2018; Yu et al., 2018) and of the Shanghai riverine-passage shield tunnel (Yuan et al., 2017; Bao et al, 2017). The test results on these segmental and immersed shield model tunnels indicated that non-uniform excitation along the longitudinal axis led to a considerably higher acceleration response of the tunnel segments, as well as in a much higher deformation response of joints, compared to the recorded response under uniform excitation. This observation constitutes an additional experimental evidence of increasing the risk of failure of the tunnel lining during non-uniform excitation.

Some work has been dedicated to special seismic design issues, such as portals (Sun et al., 2011) or other critical components, such as connections to shafts (Zhang et al, 2019) and cross-passages (Zhang et al, 2019a), joints and passages through different soil strata (Kawamata et al., 2016; Zhao et al., 2018; Jinghua et al., 2019), shallow tunnels in slopes (Wang et al., 2017), fault crossing (Kiani et al., 2016), ground fissures (Liu et al., 2017) and liquefiable soil conditions (Chen et al., 2013, 2015). Xin et al. (2018) examined the effect of voids between primary and secondary linings of tunnels on their seismic response. Recently, Wang et al. (2019) have investigated the effect of water on immersed tunnels, showing that their response in the transverse direction (e.g. in terms of lining strains) is influenced by the presence of water more than that in the longitudinal direction. Despite the above research efforts, the above issues have not been thoroughly studied, at least not covering a wide range of actual tunnels and associated parameters affecting their seismic response.

As in the case of centrifuge tests, 1g shaking table studies were also devoted to the analysis of retrofitting and isolation techniques (e.g. Hua et al., 2016). Some studies have also used experimental results from shaking table tests to examine the efficiency of proposed pseudo-static analysis methods (e.g. Zou et al., 2017).

However, many of the above-examined physical tests did not examine into detail the inelastic response of the tunnel lining, whilst the field observations in terms of damage indicate that cracking is a prominent mode of lining damage. A few experimental campaigns examined the elasto-plastic response of tunnel linings due to seismic loading. Sun et al. (2011) conducted shaking table tests to study the post-cracking behaviour of the portals of two parallel tunnels in rock, while Wang et al. (2015) carried out tests to identify progressive damage in unreinforced concrete linings following multiple earthquake loadings. Recently, Xin et al. (2019) examined model tunnels with linings made of either plain concrete, steel reinforced concrete or polypropylene fiber reinforced concrete, under increasing seismic excitations, in an effort to understand the response of diverse linings under ground shaking. A remaining limitation of these tests is the similitude laws, and therefore the scaling of the tunnel lining material in order to guarantee similitude in the post-cracking phase.

Finally, the dynamic interaction between buildings and tunnels in urban areas was examined by Guobo et al. (2018) via shaking table tests. The study indicated a reduction of the horizontal acceleration of 'urban tunnels' compared to that predicted on 'equivalent tunnels' under green-field conditions.

Based on the above observation, the results of 1 g shaking table tests conclude that:

- Asynchronous excitations can affect the performance of the tunnel significantly.
- Lining plastic behaviour is not appropriately accounted for in these tests, even when damage is the objective of the investigation.
- As in centrifuge tests, green-field conditions are usually tested. However, the increased scale allows for potentially investigating realistic urban conditions more easily.

4.3. Static tests

Only few studies were developed to analyse the response of joints, flexible rubber gaskets (e.g. Gina type, Horn type, Stirn type. Kiyomiya, 1995) and shear keys of tunnels, which might be considered as the weakest components of these structures under seismic effects (Kiyomiya, 1995). In this context, Xiao et al. (2015) tested the response of rubber gaskets and shear keys of immersed tunnel joints under axial compression and bending loadings. For this purpose, they constructed a scaled model of a two segments-joint system, replicating (with some simplifications) the connection joints of the Hong Kong–Zhuhai–Macao immersed tunnel in China. Among other findings, the dependency of the stiffness of joints on the axial loading acting upon it was verified. The authors stated the limitation of potential scale effects on the recorded response and therefore on their conclusions, highlighting the need to examine the response of such elements in real scale. This could be done by properly instrumenting actual tunnels in seismic-prone areas. Jin et al. (2017) examined the rotational response of segmental joints of shield tunnel linings through a series of full-scale static tests, highlighting the effects of joint section details, loading condition and contact condition between the two adjacent segments of the joint (e.g. effect of initial small gaps between segments on the response of the joints) on joint' response. Yu et al. (2017) tested statically a buckling restrained brace (BRB) that was proposed as a seismic mitigation measure for enhancing the performance of joints of immersed tunnels. Hu et al. (2018) investigated the mechanical properties of the segmental joints of the Hongkong-Zhuhai-Macao immersed tunnel in China, via large-scale static tests carried out on segmental model joints. Li et al. (2019) performed a series of static tests on models of shear keys made of hybrid fibre-reinforced concrete. The shear keys were actually developed and tested in the framework of the Hong Kong–Zhuhai–-Macau immersed tunnel project. Generally, the existing studies lead to case-specific observations and conclusions.

4.4. Instrumentation

In most of the tests presented above, accelerometers were used to record the acceleration amplification within the soil, as well as the acceleration on the model tunnels during ground shaking (e.g. Lanzano et al., 2012; Luzhen et al. 2010; Zhang et al, 2019). Sets of accelerometers were also employed in conjunction with air hammers, to perform air hammer tests and have an estimation of the stiffness of the soil poured in laminar or equivalent shear boxes, used in centrifuge tests (e.g. Ghosh and Madabhushi, 2002; Tsinidis et al., 2015a). Displacements of the model tunnels were extensively recorded by employing linear variable differential transformers, position sensors or even specially design extensometers (e.g. Ulgen et al. 2015; Tsinidis et al., 2016b). Displacement sensors were also used to record displacements of joints of tunnels (e.g. Yu et al. 2018). The lining strain and forces of tunnels have been recorded by means of strain gauges setups (e.g. Lanzano et al., 2012; Tsinidis et al., 2014).

Pressure cells have been utilized to record the earth pressures around the tunnels (e.g. Cilingir, 2009; Cilingir et al., 2011a). It is worth noting that the measurement of the earth pressures by means of miniature pressure cells might be biased (at least to some extent) in case of dry sand (commonly used in relevant tests) by the relative stiffness of the sensing plate, as well as problems related to the grain size effect (e.g. Cilingir, 2009). The recent advances in the tactile pressure sheets, made it possible to measure more accurately the dynamic earth pressures around the tunnel in dynamic centrifuge tests. Tekscan sheets have been used to measure dynamic earth pressures behind retaining walls, e.g., Madabhushi and Haigh (2019). Like any used instrument, tactile pressure sheets must be carefully calibrated, as highlighted by the special procedures prescribed by Madabhushi and Haigh (2019) and Gillis et al (2015).

Particle Image Velocimetry (PIV) techniques and high-quality images have been employed during dynamic tests to investigate soil movements around tunnels, e.g., uplift of tunnels due to soil liquefaction (Chen and Madabhushi, 2012; Hughes and Madabhushi, 2019).

As discussed, it is vital to understand in more detail the effect of the soil-tunnel interface on the seismic response of tunnels. Traditionally, this effect is examined through numerical analyses, by considering a full-slip or no-slip condition of the soil-tunnel interface (see for example, Tsinidis et al. 2015b, 2016a,c); however, the reality will be somewhere in between these two extreme cases (see for example, Lanzano et al., 2015; Fabozzi and Bilotta, 2016). Unfortunately, the measurement of shear stresses along the soil-tunnel interface, either in the field or in tests is not a straightforward task. Hence, additional research is required in establishing measurement instrumentation capable of revealing the role of interface shear response.

5. Analytical and numerical investigation of the seismic response of tunnels

As shown above, understanding of the seismic behaviour of tunnels has continuously improved, thanks to the introduction of rational methods of analysis, based on the interpretation of observations from the response of actual tunnels during seismic events, as well as laboratory testing. These methods, in the form of analytical solutions, simplified pseudo-static analyses, and numerical tools, are becoming standard practice for new tunnels in seismic areas, as well as for the retrofit of existing tunnels that are vulnerable to seismic effects. This section intends to provide a summary discussion on the use of analytical methods to estimate the seismic response of tunnels, as well as highlight those aspects that, in the authors' opinion, still need attention from the engineering community.

5.1. Analytical solutions

Analytical solutions were proposed by many researchers to estimate the seismic internal forces of tunnels' linings, under certain assumptions and conditions, e.g. elastic response of the soil and the tunnel lining, and simulation of seismic loading in quasi-static fashion, among others. Even though analytical solutions are formed using relatively strict assumptions and simplifications, they are useful, relatively fast and easy to use for preliminary seismic design of tunnels. Hence, they are widely utilized in preliminary design stages. The seismic design basis for underground structures was first laid out by St. John and Zahrah (1987), who proposed simplified closed-form solutions based on Newmark's pioneering work (Newmark, 1968). At the time, these solutions provided a very useful tool for practicing engineers to estimate the seismic behaviour of tunnels under ground shaking in both longitudinal and transversal directions. The authors used the free-field deformation approach to estimate the strains and curvature of the tunnel for ground motions propagating at an angle to the tunnel axis and, subsequently, proposed some modifications to their analytical solutions to account for soil-tunnel interaction effects. Wang (1993) examined further the soil-tunnel interaction effects in the framework of a comprehensive review study, which also contained new elements. Two solutions were provided for full-slip and no-slip contact interface conditions, following Hoeg (1968). Similarly, Penzien (2000) proposed closed-form solutions for the seismic analysis of deep rectangular and circular tunnels, with the seismic loading being simulated in a simplified way as an uniform shear-strain distribution, τ_{ff} , imposed on the soil boundaries of the soil-tunnel system, away from the tunnel (Fig. 8). However, Penzien's solutions neglect the effect of the normal stresses developed during loading along the soil-tunnel interface. They assumed that the deformation of the tunnel may be approximated by the deformations of a circular cavity (e.g. through relevant consideration of parameter β in Fig. 8). Huo et al. (2006) provided improved solutions by considering the actual deformation pattern of rectangular-shaped cavities and accounting for both the normal and shear stresses at the soil-tunnel interface.

Analytical solutions typically assume linear elastic behaviour of the soil and, therefore, they do not account implicitly for the strain-dependent soil shear modulus. Bobet et al. (2008) incorporated this shear modulus reduction by using an iterative procedure to adjust the shear modulus of the ground depending on the level of shear strain until the convergence of shear strain was reached. The compatible shear strain-shear modulus was then used in the analytical solution to estimate the racking deformation (Huo et al., 2006).

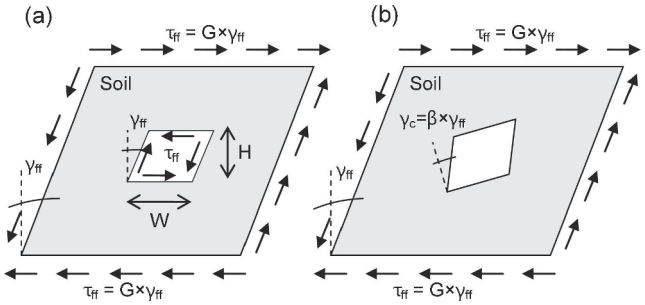

Fig. 8. Deformation of W × H rectangular cavity subjected to a uniform shear-strain distribution γ_{ff}: (a) with free-field shear stress distribution applied to cavity surface; (b) with free-field shear stress distribution removed from cavity surface (after Penzien, 2000) (G: soil shear modulus, γ_c: shear distortion of cavity without the application of shear stress distribution around the cavity, $\beta = \gamma_c / \gamma_{ff}$).

All the above closed-form solutions were developed disregarding the effect of soil saturation. Bobet (2003) proposed solutions for circular tunnels in saturated soil under the assumption of a no-slip interface. In a later study Bobet (2010) expanded the previous solutions to analyse the response of rectangular tunnels under both no-slip and full-slip interface conditions, as well as under both drained and undrained soil conditions. Park et al. (2009) revisited the above solutions and introduced a new method to account for potential slippage along the soil-tunnel interface.

Most of the proposed analytical relations summarized above refer to shear S-waves propagating upwards in the transversal direction of the tunnel. Kouretzis et al. (2006, 2011 and 2014) presented a series of relations for tunnels subjected to compression P-waves as well.

Following the rapid development in the computational power capabilities witnessed in the last two decades, researchers started cross-validating the analytical solutions results against the predictions of sophisticated numerical models, so that to identify the shortcomings of these analytical solutions. For instance, Kontoe et al. (2014) compared four different analytical models (i.e. Bobet, 2010; Park et al., 2009; Penzien, 2000; Wang, 1993) and validated them against finite element (FE) simulations. Tsinidis et al. (2016c) compared the outcome of analytical solutions (i.e. Park et al., 2009; Penzien, 2000; Wang, 1993) with numerical predictions for extreme lining flexibilities, i.e. very flexible or very rigid tunnels compared to the surrounding ground. Consistent with previous findings (Hashash et al., 2005), both Kontoe et al. (2014) and Tsinidis et al. (2016c) studies revealed that the analytical solution by Penzien (2000) underestimated the thrust exerted on the tunnel structure for no-slip interface; the use of this solution is therefore not recommended for a rough soil-lining interface.

The applicability of the analytical solutions is limited by the assumptions on which they are based (Table 1). Since the soil response is always considered to be linear elastic, with the only exception of Bobet et al. (2008), the solutions are generally more accurate only when the ground experiences small deformations, e.g. for very stiff clays and rocks for a low level of shaking. The solutions for the transversal seismic response are derived in plane strain condition and, hence, they cannot be used for complex layouts. The contact interface is in the majority of cases limited to two extreme conditions, namely full- or no-slip, while the lining is assumed to be continuous; hence appropriate representation of segmental lining by an equivalent continuous lining are mandatory. Based on the above discussion, the analytical solutions

Table 1
Summary of assumptions and applicability of analytical solutions for the analysis of tunnels under ground shaking (✗ - the method does not cover it / ✓- the method covers it.)

Solution	Tunnel lining		Soil type		Saturation conditions		Soil layering		Soil-tunnel interface			Cross-section		Section	
	Elastic	Plastic	Elastic	Plastic	Dry	Saturated	Homogeneous	Layered	No-slip	Frictional Slip	Full Slip	Circular	Rectangular	Transversal	Longitudinal
St. John and Zahrah (1984)	✓	✗	✓	✗	✓	✗	✓	✗	✓	✗	✓	✓	✗	✓	✓
Wang (1993)	✓	✗	✓	✗	✓	✗	✓	✗	✓	✗	✓	✓	✗	✓	✗
Penzien and Wu (1998)	✓	✗	✓	✗	✓	✗	✓	✗	✓	✗	✓	✓	✗	✓	✗
Penzien (2000)	✓	✗	✓	✗	✓	✗	✓	✗	✓	✗	✓	✓	✗	✓	✗
Bobet (2003)	✓	✗	✓	✗	✓	✓	✓	✗	✓	✗	✓	✓	✗	✓	✗
Huo et al (2006)	✓	✗	✓	✗	✓	✗	✓	✗	✓	✗	✓	✗	✓	✓	✗
Park et al (2009)	✓	✗	✓	✗	✓	✗	✓	✗	✓	✓	✓	✓	✗	✓	✗
Bobet (2010)	✓	✗	✓	✗	✓	✗	✓	✗	✓	✗	✓	✓	✗	✓	✗
Kouretzis et al (2006)	✓	✗	✓	✗	✓	✗	✓	✗	✓	✗	✓	✓	✗	✗	✓
Kouretzis et al (2011)	✓	✗	✓	✗	✓	✗	✓	✗	✗	✗	✓	✓	✗	✓	✗
Kouretzis et al (2014)	✓	✗	✓	✗	✓	✗	✓	✗	✗	✗	✓	✓	✗	✓	✗

should be used for preliminary design only, after having identified those that are applicable to the case at hand, considering the soil-tunnel relative stiffness (Penzien, 2000; Wang, 1993), the nature of the tunnel-soil interface (Park et al., 2009; Penzien, 2000; Penzien and Wu, 1998), the site conditions (Bobet, 2003; Bobet et al., 2008), and the type of seismic wave that is most likely to be experienced by the tunnel (Kouretzis et al, 2006, 2011 and 2016). The results of analytical solutions should, in most cases, be validated by numerical simulations, which represent better the seismic tunnel-ground interaction phenomena.

5.2. Simplified static and dynamic analysis methods

Due to the distinct deformation modes of tunnels and the associated potential levels of damage induced by ground shaking in the longitudinal and transverse directions, the seismic analysis of tunnels is commonly decoupled in the two directions, employing methods of analysis of different complexity (e.g. St. John and Zahrah, 1984; St. John and Zahrah, 1987; Wang, 1993; Penzien, 2000; Kawashima, 2000; Hashash et al., 2001; Pitilakis and Tsinidis, 2014), some of which have also been introduced in relevant design guidelines (e.g. FHWA, 2009; AFPS/AFTES, 2001; ISO 23469, 2005).

In the transverse direction, it is quite common to simplify the analysis using an equivalent static procedure (FHWA, 2009; Kawashima, 2006; ISO 23469, 2005; JRA, 1992). For instance, for rectangular tunnels one may use the method proposed by Wang (1993), which implies a simplified static analysis of the tunnel's lining frame (Fig. 9). The seismic distortion of the tunnel (δ_{str}) is obtained from the 'free-field' ground distortion at the tunnel depth (δ_{ff}), multiplied by the racking ratio, R, to account for the soil-tunnel interaction effects. In turn, the racking ratio is related to the flexibility ratio, F, (e.g. Wang, 1993; Penzien, 2000; Anderson et al., 2008; Debiasi et al., 2013), the latter expressing the relative stiffness of the tunnel with respect to the surrounding ground. Upon determination of the structural racking distortion, δ_{str}, this is imposed on the lining frame either as an equivalent static load (P) atop corner of the frame or as a pressure distribution (p) on the side walls of the frame (Fig. 9). Tsinidis and Pitilakis (2018) recently developed a new set of R-F relations based on the results of dynamic analyses of a wide range of soil-tunnel configurations. These analyses were explicitly accounting for the coupled racking-rocking deformation patterns of rectangular tunnels during transversal ground shaking, as identified and quantified by recent experimental and numerical studies (e.g. Tsinidis et al., 2015a; Tsinidis et al., 2016a, 2016b; Tsinidis, 2017).

According to ISO 23469 (2005), a tunnel may also be analysed in the transversal direction using a frame-spring model (Fig. 10). In this case, the structure is modelled with beam elements, while the soil is simulated via 'appropriate' springs. The equivalent seismic loading is statically introduced in terms of: (i) equivalent inertial static loads (caused by the structure and the overburden soils mass), (ii) seismic shear stresses along the perimeter of the structure and (iii) seismic earth pressures or ground deformations, imposed on the side-walls of the structure. Although the method can easily be applied, it has some very important shortcomings. The definition and simulation of the actual seismic earth pressures and shear stresses distributions around the tunnel is not an easy task for tunnels, particularly if the soil stress redistributions that might take place around the tunnel during shaking are considered. Additionally, the simulation of the soil by means of soil springs is quite an intricate problem, as there are not many suggestions in the technical literature for this type of structures (e.g. AFPS/AFTES. 2001). Actually, the introduction of the soil springs makes very difficult, if not impossible, to account for the soil stress redistributions effect on the earth pressures and shear stresses around the tunnel.

To avoid the problems associated with the simulation of the ground by means of springs, numerical methods that treat the surrounding ground as a continuum have been developed. In the framework of the

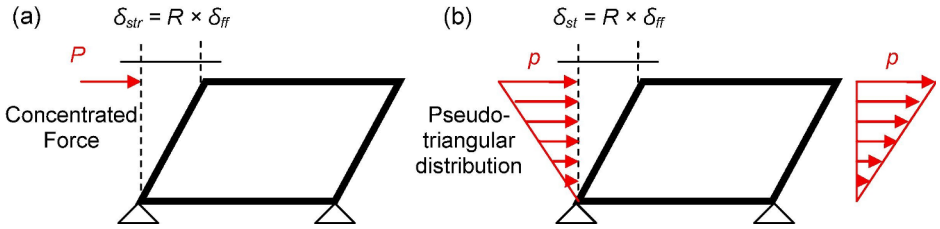

Fig. 9. Simplified frame analysis models, (a) concentrated force, (b) triangular distribution (modified after Wang, 1993).

"detailed or advanced equivalent static analysis" (ISO 23469, 2005) or "pseudo-static seismic coefficient deformation method" (FHWA, 2009) for instance, the soil-tunnel configuration is simulated via a 2D numerical model. The seismic load is introduced statically, as an equivalent inertial body force throughout the entire numerical model, corresponding to the ground free-field acceleration amplification profile (Fig. 11**a**). The acceleration profile may be derived through a separate one-dimensional site response analysis of the soil deposit (linear, equivalent linear or non-linear). Evidently, the method is applicable to both circular and rectangular tunnels. As an alternative to this method, the equivalent seismic load is introduced as a ground deformation pattern on the numerical model boundaries (Fig. 11b), corresponding to the free-field ground response (Gil et al., 2001; Tateishi, 2005; Hashash et al., 2010). FHWA (2009) recommends a procedure of analysis in which the equivalent seismic load is introduced statically in terms of displacement time histories, within a pseudo-static time history analysis. The displacement time histories are computed for each depth through a 1D seismic soil response analysis and applied in the 2D numerical model statically through a stepping procedure.

Generally, the non-linear response of the soil during shaking is accounted for by employing soil equivalent properties (e.g. strain compatible shear modulus and damping) in the framework of the equivalent linear approximation (FHWA, 2009; Hashash et al., 2010). Being essentially a static analysis, this approach is cost-effective compared to the more elaborate full dynamic time-history analysis. There are, however, some issues that may affect the effectiveness of this approach, such as: (i) the modelling of soil non-linear response and (ii) the selection of the appropriate grid size of the soil deposit (e.g. distance of the side-boundaries to the cross-section of the structure). With reference to the first point; simplified static analysis approaches cannot reproduce the soil loading history during shaking as efficiently as the dynamic analysis. This loading history affects significantly the yielding response of the ground surrounding the tunnel and therefore the tunnel response. Regarding the second point, the grid size should be properly selected, in order to eliminate any potential boundary effects (FHWA, 2009; Pitilakis and Tsinidis, 2014). Hashash et al. (2010) provided suggestions regarding the numerical model height, for the cases where the seismic load is introduced in terms of ground deformations.

Subgrade reaction methods, modelling the tunnel as a beam on elastic springs have been proposed for the seismic analysis of tunnels in the longitudinal direction (ISO 23469, 2005). In this type of analyses, referred to as to 'simplified equivalent static analyses' or 'simplified dynamic analyses' (ISO 23469, 2005), the 'seismic load' is applied to the springs as an equivalent static ground deformation that may account for the spatial variation of the ground motion (Fig. 12). A parameter that may affect significantly the computed response is the distance between the springs, which depends on the predominant wavelength and, therefore, on the frequency range of interest. Similar to the simplified equivalent static analysis is the simplified dynamic analysis (ISO 23469, 2005). In this case, the seismic loading is introduced in terms of displacement–time histories that may account for the spatial variation of the seismic ground motion. This method permits to model efficiently complex mechanical properties (e.g. soil-tunnel interface behaviour, joints behaviour, etc.). A crucial issue for the implementation of the above methods is the adequate estimation of the soil impedance functions (springs and dashpots). As for the transversal direction, only limited solutions exist in the literature for the longitudinal analysis of tunnels (e.g. St John and Zahrah, 1984).

Recent studies have examined the accuracy of the simplified methods of analysis described above by comparing their predictions against the results of full dynamic analyses, as well as experimental data from centrifuge tests (e.g. Bilotta et al., 2007; Kontoe et al., 2008; Hashash et al., 2010; Vrettos et al., 2012; Pakbaz and Akbar, 2005; Pitilakis et al., 2014; Tsinidis et al., 2015a, 2016a, 2016b, 2016c). The comparisons indicate that the simplified methods may underestimate or overestimate the tunnel response compared to experimental data and

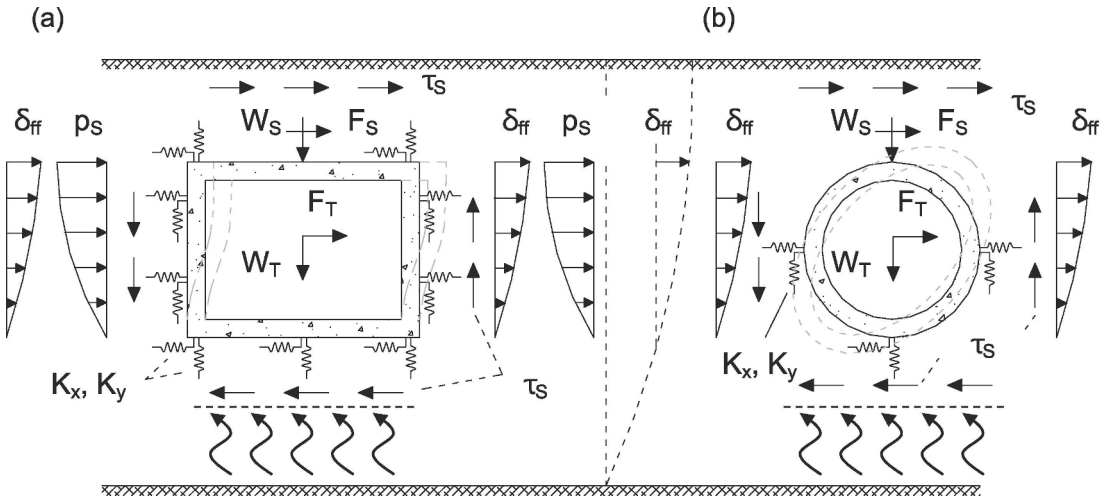

Fig. 10. Simplified equivalent static method for the transversal seismic analysis of (a) rectangular and (b) circular tunnels; δ_{ff}: free-field seismic ground deformation, p_s: seismic earth pressures on the side-walls of the rectangular structure, τ_s: seismic shear stresses around the perimeter of the tunnel, W_S: weight of overburden soil, F_S: inertial forces of overburden soil, W_T: weight of tunnel, F_S: inertial forces of tunnel, K_x, K_y normal and shear soil springs along the perimeter of the tunnel lining (redrawn after Pitilakis and Tsinidis, 2014).

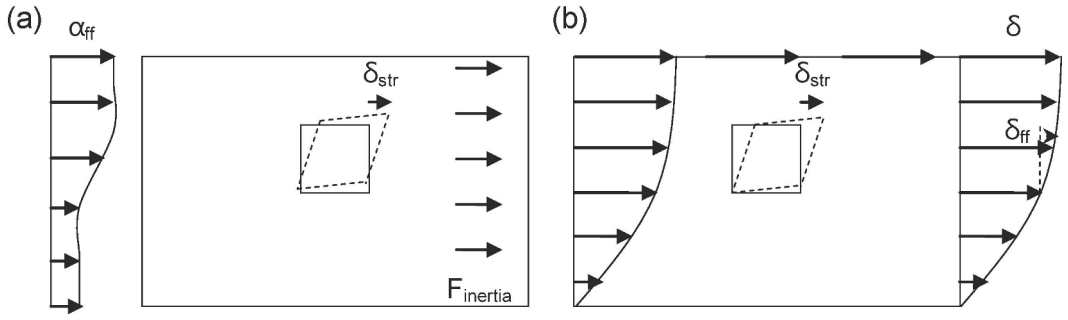

Fig. 11. Detailed equivalent static analysis: (a) distributed inertial loads (b) imposed ground distortions at the boundaries (a_{ff}: ground acceleration at free-field, $F_{inertia}$: equivalent to ground acceleration inertial body force).

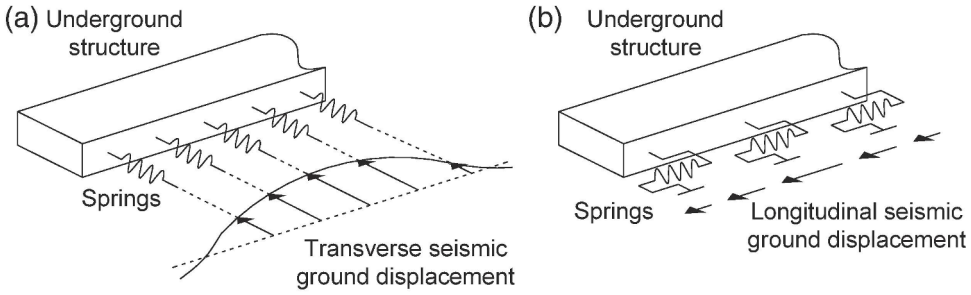

Fig. 12. Simplified equivalent static analysis method for tunnels (ISO23469, 2005), (a) transversal analysis, (b) longitudinal analysis.

full dynamic analysis, particularly when high levels of soil yielding are anticipated around the tunnel. For instance, Tsinidis et al. (2015a) compared the outcome of equivalent static analyses with recorded internal forces from dynamic centrifuge tests on box-type tunnels, as well as with predictions of full-dynamic time history analyses, the later calibrated based on relevant experimental results. The comparisons referred to rather extreme soil-tunnel relative flexibilities (i.e. flexibility ratio of examined cases $F = 62.5$ and 0.29) and examined both simulation approaches regarding the earthquake loading (i.e. distributed inertial loads or imposed ground distortions at the model's boundaries, as per Fig. 11). Moreover, the comparisons were conducted considering the non-linear soil response through either a properly-calibrated visco-elasto-plastic model or via soil equivalent properties in the framework of the equivalent linear approximation. When the soil was modeled via equivalent linear properties (e.g. visco-elastic analyses), the equivalent static analyses underestimated the seismic bending moment by around 30% compared to the dynamic analyses. The discrepancies between the predictions of the dynamic analyses and the equivalent static analyses were even higher, when soil nonlinear response was accounted for via an elasto-plastic model (differences up to 50%), with higher deviations being reported for the flexible tunnel case (i.e. $F = 62.5$). It is worth noticing that the seismic lining forces computed via full dynamic analyses, compared reasonably well to the relevant values recorded during centrifuge testing. Similar comparison studies were conducted for rectangular culverts (e.g. Tsinidis et al. 2016b), as well as circular tunnels (e.g. Bilotta et al., 2014, Tsinidis et al., 2016c). Depending on the soil-tunnel relative stiffness, the soil-tunnel interface condition adopted in the dynamic and equivalent static analyses, as well as the simulation of the soil non-linear response during ground shaking (e.g. equivalent static approximation, nonlinear model etc), equivalent static analyses tend to either underestimate or overestimate the computed seismic lining forces of the examined tunnels or culverts, compared to full dynamic analyses, with the differences reaching 20–40%. Not clear tendencies of the discrepancies between the outcome of simplified static and dynamic analyses, as affected by the above parameters (e.g. soil-tunnel relative stiffness, soil-tunnel interface conditions etc) have been identified so far; hence, further studies towards this direction will be very useful.

Gomes (2013) presented a numerical study on the effects of stress disturbance caused by the construction of bored tunnels on their seismic performance. Sun and Dias (2019) examined the effect of the stress relief during tunnel excavation on the predictions of pseudo-static analyses of the transversal seismic response of circular tunnels in soft soil. However, additional studies towards this direction seem necessary, since a limited number of cases have been examined.

5.3. Numerical full dynamic analysis

Analytical solutions and simplified methods of analysis are extremely useful for preliminary design purposes. However, for more thorough predictions, full dynamic analyses, employing numerical models, may be needed. A full dynamic time history analysis of the coupled soil-tunnel configuration is potentially the most accurate method for the seismic analysis of tunnels (FHWA, 2009; ISO 23469, 2005). Different numerical approaches have been reported in the technical literature, for the investigation of tunnel response, for design, or for back-calculation of the observed dynamic behaviour of tunnels in field or in the laboratory (e.g. Kampas et al., 2018; Huo et. al., 2005; Hwang and Lu, 2007; Kontoe et al., 2008; Kontoe et al., 2011; Bilotta et al. 2014a, 2014b; Tsinidis et al., 2014, 2016; Wang, 2011; Conti et al., 2014; Esmaeilzadeh et al., 2018; Hleibieh et al., 2014; Gomes, 2014; Lanzano et al., 2015; Abate et al., 2015; Kheradi et al., 2017; Patil et al., 2018; Fabozzi et al., 2018; Lu and Hwang, 2019). Numerical analyses can inherently describe the kinematic and inertial aspects of soil-structure interaction, while they can adequately simulate complex geometries and heterogeneities of the soil deposit, as well as the effects of other existing structures, the latter located in the near area. Using appropriate constitutive laws, it is possible to model the non-linear behaviour of the soil, the structure and the soil-structure interface.

Arguably, 2D or 3D numerical codes, based on the Finite Element (FE) or the Finite Difference (FD) method, are the most used for calculations involving buried structures in a continuous medium, i.e. soil and rock, while the Discrete Element Method (DEM) has been employed for analyses of discontinuous media, i.e. fractured rock (Bobet et al.,

2009). New methods of analysis, such as multi-scale FE models (e.g. Ding et al., 2006; Yu et al., 2013), coupling finite – boundary element schemes (Liang and Zhu, 2019) or 2.5-D FE-BE approaches (Zhou et al., 2019) have been examined recently, to improve computations in a cost-effective manner. Evidently, the use of different soil constitute models may lead to distinct numerically predicted responses for the examined tunnels (e.g. Bilotta et al., 2014; Tsinidis et al., 2016c). Additionally, Kontoe et al. (2011), as well as Sun and Dias (2018), highlighted the importance of rational tuning of soil damping in the numerical analysis of tunnels under ground shaking, while Andreotti and Lai (2017) and Kampas et al. (2019) highlighted the effect of modelling approach (i.e. linear or nonlinear) of the tunnel lining on the predicted response.

Finally, some recent numerical studies have focused on specific phenomena such as the non-synchronous ground shaking affecting long tunnel lining (Fabozzi et al., 2018b; Fabozzi et al., 2019), response of tunnels subjected to seismically-induced ground failures, such as faulting (e.g. Anastasopoulos and Gazetas, 2010), ground liquefaction (e.g. Kutter et al.,2008; Bao et al. 2017), or uplifting phenomena due to ground liquefaction (e.g. Azadi and Mir Mohammad Hosseini, 2010; Liu and Song, 2005).

5.4. Fragility functions for the vulnerability assessment of tunnels

In addition to the seismic analysis of new tunnels, the vulnerability assessment of existing tunnels is of utmost importance, especially when considering the large number of old tunnels all over the world. In this context, fragility functions or fragility curves are essential tools since they allow for the pre-seismic assessment of existing tunnels, as well as for real-time analyses, to achieve prompt and functional decisions in post-earthquake management (see, e.g., Fabozzi et al., 2018a).

Fragility functions describe the conditional probability of a structure reaching or exceeding a specific damage state for a given seismic intensity. In the past, the vulnerability assessment of tunnels was based mainly on fragility curves derived from expert elicitations (ATC-13, 1985) or damage data from previous earthquakes (ALA, 2001; HAZUS, 2004; Corigliano et al., 2007). More recently, fragility curves have been developed using numerical procedures for both circular (Salmon et al., 2003; Argyroudis and Pitilakis, 2012; Osmi et al., 2015; Osmi and Hamad, 2016; Fabozzi et al., 2017; Argyroudis et al., 2017; Avanaki et al., 2018; Qui et al., 2018; de Silva et al., 2019; Huang et al., 2019) and rectangular tunnels (Salomon et al., 2003; Argyroudis and Pitilakis, 2012; Huh et al., 2017a, 2017b; Nguyen et al., 2019) embedded in soft or stiff soils. Andreotti and Lai (2019) proposed a numerical methodology for developing fragility curves for mountain tunnels subjected to transversal seismic loading. In most analytical studies, the seismic performance of a tunnel is generally quantified in a simplified way, by employing the ratio between the loading and the resisting bending moments (Argyroudis and Pitilakis; 2012), while other approaches have recently proposed. Fabozzi et al. (2017) defined the performance of the lining by comparing the permanent relative rotation between two segments of the lining with predefined threshold values. Andreotti and Lai (2019) considered the nonlinear response of the tunnel lining, by employing a numerical approach they developed earlier. In their study they define the damage states based on the relative displacement between the crown of arch of and the inverted arch normalized by the equivalent diameter of the tunnel lining cross-section. Most fragility curves are expressed in terms of an intensity measure, referring to 'free-field' conditions, i.e. peak ground acceleration or peak ground velocity (e.g. Nguyen et al., 2019) or, more rarely, Arias Intensity (Huang et al., 2017). Others express fragility curves as a function of the intensity measure at the bedrock depth (Mayoral et al., 2016; de Silva et al., 2020), which makes them more useful for real-time analyses, since signals provided by the seismic stations are recorded on stiff rock outcrop and consequently do not include site effects. Fig. 13 compares empirical (i.e. ALA, 2001) and numerical fragility curves (i.e. Argyroudis and Pitilakis, 2012; Argyroudis et al., 2017; de Silva et al., 2020), obtained under different assumptions. The comparisons of the curves indicate a significant scatter highlighting the need for further investigation of the seismic fragility of tunnels under seismic shaking.

From the above short review, it is evident that most research efforts were devoted to the response of tunnels to seismic actions, while their vulnerability to seismically induced ground failures has received considerably less attention; hence, additional research towards this topic seems to be necessary. The implementation of adequately validated nonlinear models, in simulating the lining response in the framework of fragility studies, will contribute in a more rigorous evaluation of response of linings under increasing earthquake loadings, as well as in a more robust definition of damage states.

6. Summary and discussion

Despite the significant efforts and progress made to date in understanding and predicting the seismic behaviour of tunnels, more work is still required. In particular, the response of tunnels to earthquake-induced ground failures has not been thoroughly investigated. Most of the work done has focused on the transversal seismic response of tunnels under the assumption of plane strain conditions, examining the cross section of the tunnel, with seismic input in the form of S-waves. This approach seems to be able to predict the seismic lining forces under transversal seismic loading reasonably well (Bilotta et al. 2014b), but as shown in shaking table tests (Yan et al., 2016; Yu et al., 2018; Yuan et al., 2017; 2018; Bao et al, 2017 Yu et al., 2018), asynchronous excitation can change the tunnel response significantly. It is worth noticing that only a few studies focused on the effects of surface waves on the seismic response of tunnels (e.g. St John and Zahrah, 1987; Kouretzis et al., 2011). Since Love waves induce a horizontal motion perpendicularly to the direction of their propagation, the longitudinal bending strains associated with this type of seismic waves are expected to be rather reduced. On the contrary the effect of Rayleigh waves on the response of tunnels might be more important.

3D approaches, using computationally-efficient beam-and-spring type models (e.g. Anastasopoulos et al., 2007; Anastasopoulos et al., 2008), can potentially be used for the investigation of spatially-variable ground motion along long tunnels (e.g. Park et al., 2009), variations in layer boundaries between different geomaterials, variations in structural properties along the tunnel length (e.g. Kontoe et al., 2008), including the presence of station boxes (e.g. Huo et al., 2005) and near-fault effects (e.g. fault rupture; Anastasopoulos and Gazetas, 2010). However, such methods are currently based on linear elastic behaviour of the ground, and improvements are required to make properties of impedance functions consistent with the non-linear behaviour that can now be simulated in FEM analyses (e.g. Anastasopoulos and Gazetas, 2010; Kontoe et al., 2011; Bilotta et al., 2014b, among others). Hatzigeorgiou and Beskos (2010), and Yu and co-workers (i.e. Yu et al. 2013, 2017), performed full three-dimensional non-linear analyses, whereas Hashash and co-workers (see, e.g., Hashash et al., 2018 and Basarah et al., 2019), employed advanced nonlinear hysteretic soil models to capture volumetric changes in the ground, in addition to the shear response of underground structures and adjacent superstructures. However, due to the computational cost of 3D numerical simulations, it seems that the ability to run the simulations reside almost exclusively within the academic and research communities.

Tunnel response in undrained conditions (particularly associated with liquefaction) has only received limited attention to date via analytical poro-elastic (Bobet 2003; Bobet 2010) and numerical (e.g. Liu and Song 2005; Bilotta 2018) approaches. It is perhaps time to develop further these studies adopting recently developed constitutive models (e.g. Boulanger and Ziotopoulou, 2013) capable to account for deviatoric volumetric coupling even at relatively small strains. Any numerical study of the behaviour of tunnels under undrained conditions will require extensive validation against physical model tests or field observations, similar to what has been conducted for drained conditions.

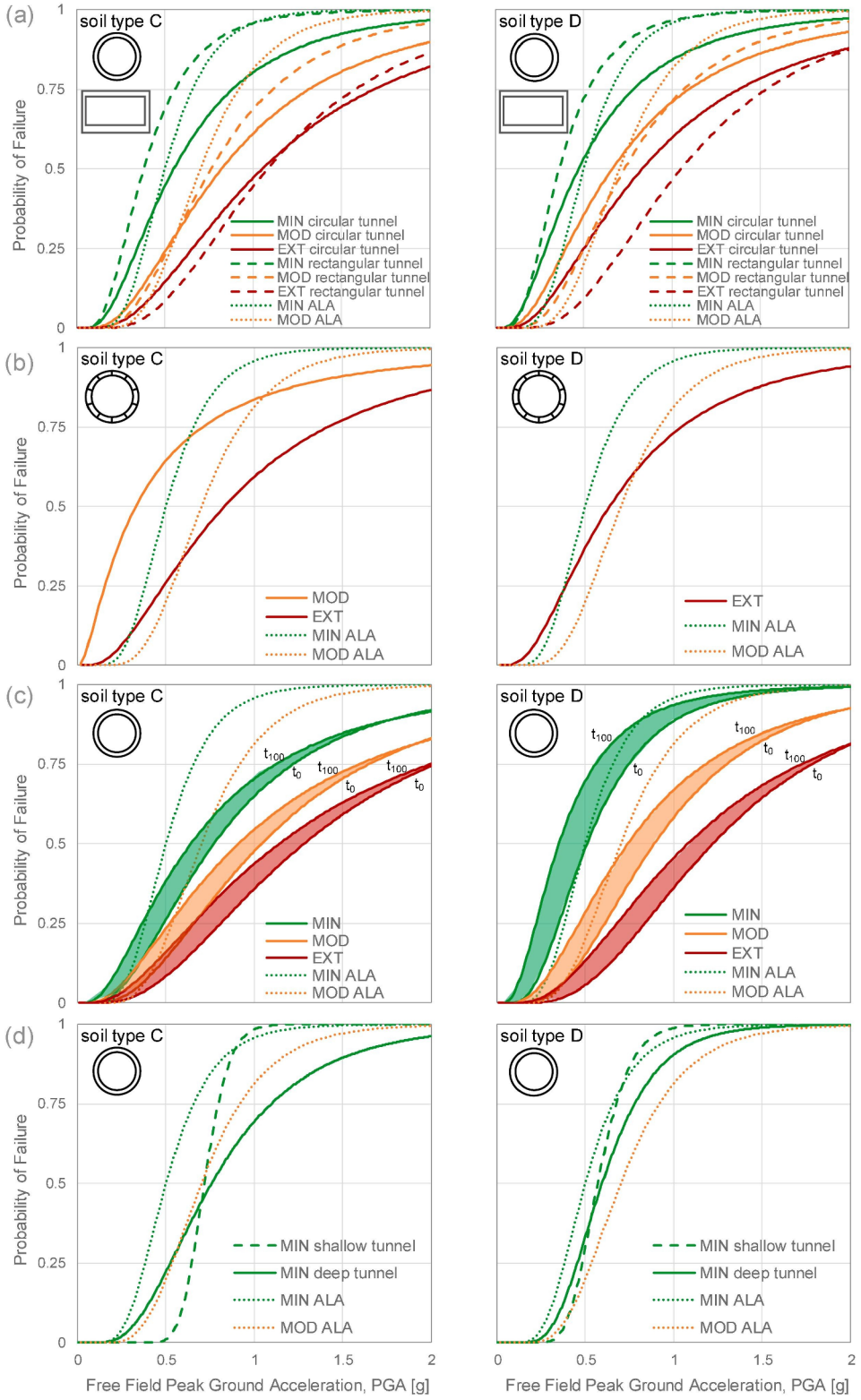

Fig. 13. Comparison between empirical fragility curves by ALA (2001) and numerical fragility curves from (a) Argyroudis and Pitilakis (2012); (b) Fabozzi et al. (2017); (c) Argyroudis et al. (2017); and (d) de Silva et al. (2020), referring to ground shaking. t_0 and t_{100} are associated to the material properties at the tunnel construction and after 100 years; MIN, MOD and EXT stand for minor, moderate and extensive damage, respectively.

As summarized in Bilotta et al. (2014b), there is still work to be done for the validation of non-linear numerical models against the results of reduced scale physical tests or through the installation of Wireless Sensor Networks (WSN) for monitoring field structures, to benchmark predictions against measured performance, rather than against other models.

Continuous improvement in the modelling of tunnel structural response is also required. Most methodologies rely on equivalent linear elastic approaches and even in this case, correct identification of relative soil-structure stiffness is important (Nam et al. 2006; Tsinidis

et al., 2016; Bobet et al. 2008), especially for reinforced concrete (RC) linings (Kampas et al. 2019). While careful modelling can help with seismic detailing and resilient design of new tunnels, an increasingly important problem is the behaviour of older tunnels beyond their original design life, where exposure to seismic hazards is increased and their support may have aged or degraded substantially. For such problems, relative strength is also important for understanding tunnel structural damage (Hatzigeorgiou and Beskos 2010; Kampas et al. 2019) and for generating appropriate fragility curves (e.g. Argyroudis et al. 2017). Both stiffness and capacity of reinforced concrete elements are heavily affected by hoop stresses, and accurate prediction of these is heavily dependent on the soil-tunnel interface model used (Hashash et al., 2005; Sedarat et al., 2009; Kouretzis et al., 2013). Wireless Sensor Networks may be used for pro-active structural health monitoring, but this requires the development of suitable interpretative models to identify and differentiate between soil and structural damage (e.g. Alonso-Rodriguez et al., 2018). Some of the physical testing has shown that residual forces develop in tunnels following a single earthquake (Cilingir and Madabhushi, 2011a, 2011b, 2001c; Lanzano, 2009; Lanzano et al., 2010; Lanzano et al., 2012; Bilotta et al., 2014; Tsinidis et al 2015a,2015b, 2015c), which points towards the possibility that multiple subsequent earthquakes may exacerbate the problem throughout the life of a tunnel.

Recent investigations have started focusing on the interaction between tunnels and surface structure based on 2D simulations, using equivalent elastic soil models (Wang et al., 2013; Abate and Massimino, 2017a, 2017b) or elasto-plastic models (Pitilakis et al., 2014a; Tsinidis, 2018). These studies focus on the effects of surface structures on tunnel response. Since it is very rare to have structures built in 'isolation' the dynamic interaction effects between tunnels and adjacent buildings is an important research subject that calls for further investigation.

While elastic models may be suitable for tunnel design (Amorosi and Boldini, 2009; Kontoe et al., 2014), none of the constitutive models used to date in these studies appear to be able to accurately capture post-earthquake ground surface settlements (Bilotta et al., 2014b), a fact that Kampas et al. (2020) have also confirmed when showing the impact of tunnel construction effects on subsequent ground movement profiles. Improved models able to address this issue could be useful to estimate pre-earthquake change of stresses due to tunnel construction (e.g. Bilotta, 2017, 2018) and to understand the impact that building new tunnels could have on the seismic hazard of existing infrastructure (Hashash et al., 2018; Knappett et al., 2019).

The current literature in mitigation and remediation techniques for improving the seismic response of tunnels is rather limited and is mainly based on old-dated guidilines (e.g. Power et al., 1996). A few studies have tried to examine experimentally isolation techniques for tunnels subjected to ground shaking (e.g. Chen et al. 2014). However, the outcomes of these studies are rather limited to the investigated tunnels. Some experimental tests have also carried out in the framework of rehabilitation studies, referring to specific tunnels. For instance, Adalier et al. (2003) performed centrifuge tests to assess the effectiveness of countermeasure retrofit techniques against potential liquefaction for the existing immersed George Massey tunnel, while Chou et al. (2010) examined the effect of potential liquefaction on the seismic response of the BART transbay tube, again by means of dynamic centrifuge tests. Based on the above observations, it is evident that further studies are still needed to establish rigorous mitigation and remediation techniques for tunnels, considering also the critical effect of ageing of existing tunnels.

7. Future developments

This paper presents a review of the current state-of-the-art knowledge of the seismic behaviour of tunnels. Based on this, the following areas may be identified for further developments:

- More well-documented case studies of actual tunnels under seismic loadings are necessary, beyond the limited available qualitative post-earthquake observations, to improve the understanding of the complex behaviour of tunnels during earthquakes and validate analysis tools. These case studies should not refer necessarily to significant damage or tunnel collapses, which are obviously not desirable, but should rather cover a wide range of tunnel responses, including relatively low or moderate seismic events. The implementation of adequate monitoring schemes of tunnels in seismic prone areas is of great importance in this respect.
- Numerical models studying the role of soil poro-plasticity, up to soil liquefaction, heterogeneity and anisotropy, and its interplay with the lining plasticity are needed. These should be validated against data from field case studies and the results of tests on reduced scale physical models.
- The effects of the characteristics of seismic input motion, such as frequency content (most work has been done for tunnels far from the epicentre), earthquake duration, and surface waves, are still not entirely understood and should be further explored.
- The cumulative effect of earthquakes on tunnels is not well-understood since little work has been carried out to date to understand this and therefore more work is necessary.
- The lining ageing effects on the seismic response and vulnerability of existing old tunnels is another topic which calls for further investigation. This might be of great importance for developing further cost-efficient retrofitting techniques.
- Physical models that may be capable of replicating the actual response of soil-tunnel systems, particularly when soil and lining plasticity are reached during seismic loading, are necessary.

CRediT authorship contribution statement

Grigorios Tsinidis: Conceptualization, Writing - original draft, Writing - review & editing, Visualization. **Filomena de Silva:** Conceptualization, Writing - original draft, Writing - review & editing, Visualization. **Ioannis Anastasopoulos:** Conceptualization, Writing - review & editing. **Emilio Bilotta:** Conceptualization, Writing - original draft, Writing - review & editing. **Antonio Bobet:** Conceptualization, Writing - original draft, Writing - review & editing. **Youssef M.A. Hashash:** Conceptualization, Writing - review & editing. **Chuan He:** Conceptualization, Writing - review & editing. **Georgios Kampas:** Conceptualization, Writing - review & editing. **Jonathan Knappett:** Conceptualization, Writing - review & editing. **Gopal Madabhushi:** Conceptualization, Writing - review & editing. **Nikolaos Nikitas:** Conceptualization, Writing - original draft, Writing - review & editing, Funding acquisition, Resources. **Kyriazis Pitilakis:** Conceptualization, Writing - review & editing. **Francesco Silvestri:** Conceptualization, Writing - review & editing. **Giulia Viggiani:** Conceptualization, Writing - review & editing. **Raul Fuentes:** Conceptualization, Writing - original draft, Writing - review & editing, Funding acquisition, Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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