Tunnels under seismic loading: a review of damage case histories and protection methods

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ABSTRACT: Underground structures are essential in urban areas and their number is continuously increasing. Even if buried structures commonly show a better performance under seismic actions than above-ground structures, during recent strong earthquakes some urban underground structures suffered severe damages and collapses. In order to understand the behaviour of tunnels during earthquake, a wide collection of case histories has been reviewed from the available literature and some of them have been described in detail. Criteria are also shown in the paper which are used to classify the damage database. Such a classification involves entity and type of damage and is aimed to highlight the possible causes of damage, in order to improve performance-based seismic design of tunnels.

1 INTRODUCTION

For a long time it has been generally believed that earthquake effects on underground structures are not very important. This is because these structures have generally experienced a low level of damage in comparison to the surface engineering works. Nevertheless, some underground facilities were significantly damaged during recent strong earthquakes (Hashash et al. 2001).

In modern urban areas, underground space has been used to store a wide range of underground structures. Most underground structures are essential to human life and include many utilizations: pipelines for water, sewage, gas, electricity and telecommunication; subways; underground roads. For these reason it is very important to study how tunnels are damaged during earthquakes to protect human life and the service efficiency.

2 CASE HISTORIES COLLECTION

Very few data are available concerning damage to underground structures and tunnels after earthquakes before 70’s. In fact damages and failures were accurately documented only after strong earthquakes: after San Fernando earthquake (1971), ASCE (1974) published some data about the damage to underground structures in the Los Angeles area. Moreover in many cases an accurate monitoring of lining cracks existing before the earthquake was missing. Therefore the real damage suffered by structures during the earthquake was unknown. After 1974 a systematic data collection of tunnel damages concerning different earthquakes was carried out, for the purpose of recognizing common features and similar causes.

Dowding & Rozen (1978) collected 71 cases of damage concerning both American (7) and Japanese (6) earthquakes. Such a database includes both railway and roadway tunnel and water pipelines. Most of the cases are in compact rock (12), other in fractured rock (11) and only 3 cases concern tunnel in soil.

Owen & Scholl (1981) updated the work by Dowding & Rozen, collecting 127 cases of damage to underground structures. An important adding came from the cut-and-cover tunnels damaged during the San Francisco (1906) and San Fernando (1971) earthquakes. These structures were shallow and generally constructed in poor soil.

Sharma & Judd (1991) enlarged the collection of the previous Authors reaching a total number of 192 cases for 85 different earthquakes. To correlate seismic vulnerability of a tunnel to some relevant factors, six parameters were examined: tunnel cover, subsoil type, peak ground acceleration, magnitude of the earthquake, distance from the epicentre and type of lining support. Most of the damages (60%) affect shallow tunnels (depth lower than 100m); Many cases (42%) concern unlined tunnels in rock.
Power et al. (1996) added to the data collected by Sharma & Judd (1991), the cases of damages to underground structures after Kobe (1995) and Northridge (1995) earthquakes. They collected 217 cases of bored tunnels only. Most of the data are from the tunnel damaged during the extremely severe earthquake of Kobe (1995).

3 EXAMPLES OF DAMAGE TO UNDERGROUND STRUCTURES

California and Japan have suffered many seismic events in the last century, which have been generally very well documented.

From 1900 to 2004, six severe earthquakes occurred in California. At the beginning of the 20th century was the catastrophic earthquake of San Francisco (1906) with moment magnitude $M_w=7.8$. This event destroyed completely the city of San Francisco, causing over 3000 deaths. More recently three severe earthquakes occurred in five years only: Loma Prieta in 1989 ($M_w=7.1$), Petrolia in 1992 ($M_w=6.9$) e Northridge in 1994 ($M_w=6.7$). Power et al. (1998) give a consistent account of damages occurred during these earthquakes (64 cases).

In order to minimize the damage suffered by tunnels during the earthquakes, many studies had been carried out in California for both static and seismic design of these structures. Therefore for the construction of the Bay Area Rapid Transit (BART) and the Los Angeles Metro special seismic joints had been designed to permit differential displacements limiting the increase of stresses in the lining.

During the Loma Prieta (1989) event such joints had a good performance, because the subway structures had no damages (Hashash et al. 2001). On the contrary many tubes of the water supply system suffered severe damages. Schmidt & Hashash (1999) account for the structural damages of the Alameda Tubes, two submarine tunnels of 12m diameter: they were extremely cracked due to liquefaction phenomena occurred in the marine sand.
Bardet & Davis (1999) relate many cases (61) of steel tubes, which were strongly damaged during the Northridge (1994) earthquake. In Fig.1 some drawings illustrate the deformation of the tubes after the seismic event. They show mechanisms of deformation which are peculiar of thin steel tubes: in most cases they underwent a kind of shrivelling due to lateral buckling for lack of confinement.

The extremely strong earthquakes occurred in Japan caused millions of dead people and hundreds of crashed buildings. The high seismic vulnerability, the living density and sustained industry of Japan are the crucial patterns that make this geographic area one of the country with the highest seismic risk in the world. During severe earthquakes, many above-ground and underground structures have suffered enormous damage, even if the buried structures are generally considered safer. In 1995, the catastrophic event of Hyogoken-Nambu caused many damages to the city of Kobe, located near the earthquake epicentre. The main shock, with magnitude moment $M_w=6.9$ and duration of 20s caused the death of 5100 people and the collapse of bridges, buildings and other civil structures. The whole Kobe metro system was damaged, forcing the service to stop.

Power et al. (1996) produced a database of observed cases after the Kobe earthquake (around 110), considering only bored tunnels. This is an important information to understand the impact of this event on metro and roadway tunnels.

Iida et al. (1996) and Yoshida (1999) have shown (Fig. 2) the damage suffered by the metro station of Daikai: just above the station platforms the ceiling collapsed as some supporting columns buckled. Yoshida (1999) reports also the damage occurred in the metro lining (Fig.3): they consisted mainly in longitudinal cracks, up to 250 mm wide, located at $\theta = \pi/4+n\pi/2$ (n=0,1,2,3) along the section.

In 1999 a very strong earthquake occurred in the island of Taiwan, causing destructive consequences in the near Popular Republic of China too. The Chi-Chi earthquake, from the name of the city placed near the epicentre, occurred on September 21st at 01:47 AM, with a magnitude moment $M_w=7.6$. Miyajima & Hashimoto (1999) studied the data relative to the damages suffered by the water supply system during this earthquake: cracking affected around 0.14Km of transmission pipelines and around 4.56Km of service pipelines. The Water Works Association of the Chinese Republic estimated that around 50% of cracking was caused by soil shaking, and the other 50% was due to slopes failure and liquefaction occurred near the tubes.

4 DAMAGE CLASSIFICATION CRITERIA

The collection work until Power et al. (1998) provides a relatively wide database of damages observed in tunnels which underwent seismic loads. The database is very heterogeneous, as very different cases can be distinguished for type of cracks, damage level, soil and lining characteristics.

In order to classify the behaviour of tunnels during earthquake, some criteria were chosen from the literature.

Power et al. (1996) recognized three types of buried structures that behave differently during the earthquakes:

- **Bored tunnels**
- **Cut-and-cover structures**
- **Steel and plastic pipelines**

The database should be then subdivided according to such categories.

Also the damages need to be classified as Dowding & Rozen (1978) did for the first time. They noticed three different patterns of cracking or failure in a tunnel, which can be also found combined, due to:
• Ground failure, such as liquefaction or landslides at tunnel portals;
• Fault displacement;
• Ground shaking or ground vibrations;

Particular geological conditions cause the onset of damage of first and second type: in the first case it is necessary that the tunnel entrance is near a slope; in the second case the lining needs to pass through an active fault. A prudent siting can avoid these conditions. Damage due to ground shaking occurs when the tunnel crosses very poor ground. In this case a wide cracking appears on the lining for long stretches.

Dowding & Rozen (1978) divided their database using the damage level as a criterion. They considered three damage classes (no damage, minor damage, damage). Huang et al. 1999 and Wang et al. 2001 added a damage level to such classification, subdividing the second group in two classes (slight and moderate).

Following the approach of Dowding & Rozen (1978), the three damage levels can be defined by using the crack width (W) and length (L), the tunnel functionality and the need of restoration after earthquakes:

- **Class A**: Slight damage. L<5m W<3mm. Perfect functionality. No restoration needed. No service stop;
- **Class B**: Moderate damage. L>5m W>3mm. Differential displacements cause deep cracks, spalling and exposed reinforcement. Compromised functionality. Service interruption until the complete restoration with a-seismic expedients;
- **Class C**: Severe damage. Landslide and liquefaction. Structural collapse of the lining. Service stop without any possible restoration;

Corigliano (2007) more recently subdivided 230 worldwide cases from 35 different earthquakes in these three classes: severe damage occurred only for 6 seismic events.

5 SEISMIC PARAMETERS AFFECTING THE DAMAGE

Once the database is classified, it is possible to highlight the dependency of the tunnel damages on some significant variables (earthquake parameters or soil/structure characteristics).

Dowding & Rozen (1978) tried to correlate the damage level with the peak ground acceleration and the peak ground velocity of the seismic signal at surface above the tunnel. The values of acceleration and velocity, as computed by using attenuation laws, were plotted in a graph (Fig.4) along the ordinal number of the case observed.

Figure 4: Peak Ground Acceleration against damage level (Dowding & Rozen, 1978)

For each case they used different indicators to distinguish the damage levels.

Two PGA thresholds can be recognized in the graph of Fig.4: the first at 0.2g, which separates the cases of slight damage (Class A) from the cases of moderate damage (Class B); the second at 0.5g, used to distinguish the cases of moderate damage (Class B) from the cases of severe damage (Class C).

This important information was confirmed by following Authors, showing that severe damage occurred only for particularly strong earthquakes. In fact the 0.5g limit is very high compared to the values that cause damage to above-ground structures. This notice confirms the intuitive point which the underground structures are generally safer than the above-ground structures: obviously, the tunnel confinement limits considerably the structure displacements due to seismic shaking.

Sharma & Judd (1991) extended the work of Dowding & Rozen (1978) to other parameters which they considered crucial for the tunnel behaviour. Beyond the PGA, they took into account the epicentral distance, the magnitude, the tunnel depth, the ground type and the lining support. In Fig. 5 the six histograms concerning these six variables are shown, where the distribution of the 4 levels of damage (no damage, slight damage, moderate damage and severe damage) can be quantified.
It is important noticing that shallow tunnels suffer higher damage compared to deep structures (Fig. 5a). This different behaviour is likely due both to the degree of confinement and to the improvement of the ground characteristics with depth. During the earthquake the shallow tunnels suffer larger deformations and subsequently higher stresses.

The graphs relative to rock type (Fig. 5b) and lining support (Fig. 5c) suggest that higher damage occurs in compact rock and for concrete linings without reinforcements. Nevertheless, such graphs do not clarify the influence of the relative stiffness between soil and lining.

The graphs of PGA (Fig. 5f), epicentral distance (Fig. 5d) and magnitude (Fig. 5e) confirm that the damaging effects increase with the earthquake magnitude and reduces as the epicentral distance increases. It is also confirmed that only severe earthquakes can cause high damages to the underground structures.

6 CRACK DISTRIBUTION ALONG THE TUNNEL LINING

Wang et al. (2001) suggest several patterns of cracking induced into the tunnel lining during an earthquake. The six patterns are (Fig.6):

a) Sheared off lining: it occurs for tunnel passing through active faults;
b) Slopes failure induced tunnel collapse: it occurs when the tunnel runs parallel to slopes generating landslides passing through the lining;
c) Longitudinal cracks: it occurs when the tunnel is subjected to higher deformations due to surrounding ground;
d) Traverse cracks: it occurs when the tunnel has weak joints;
e) Inclined cracks: it occurs for a combination of longitudinal and transversal cracks;
f) Extended cracks: it occurs when there is the partial collapse of linings for seismic intense deformation;
g) Wall deformation: it occurs when there is a transverse reduction due to the invert collapse;
h) Spalling of lining: it occurs when the transversal section completely collapses.

In Tab.2 the possible links between causes (geological, geotechnical and structural factors) and effects (type of damage according to Fig.6) are reported, showing when the influence is weak or decisive.

Figure 6: Types of damage: sheared off lining (a); slopes failure (b); longitudinal cracks (c); transverse cracks (d); inclined cracks (e); extended cracks (f); wall deformation (g); spalling of lining (h)

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* decisive link * weak link (Wang et al. 2001)

Table 1: Links cause/effects to tunnel damage

7 DESIGN ISSUES

In order to summarize some considerations about the seismic damage to tunnels, Yoshida (1999) gives a schematic drawing of typical conditions inducing cracking and collapse on the lining during an earthquake (Fig. 7), only referred to seismic ground shaking.
A structural or lithological modification determines unfavourable conditions and causes lining cracking and collapse. When there is no external or internal variations along the tunnel longitudinal axis, the damage can occur for tunnel buried in soft soils. In such cases the most frequent cracking pattern consists in longitudinal cracks developed longitudinally at $\theta = \pi/4 + n\pi/2$ ($n=0,1,2,3$) positions along the transverse section, sometimes symmetric, sometimes anti-symmetric, as shown by Wang et al. (2001), reporting some observations of damaged tunnels during the Chi-Chi earthquake (Fig.8).

After considering several cases of damage to underground structures, it is possible to establish that:

- During an earthquake underground structures suffer minor damage compared to above-ground structures. All the cracks and collapses take place only for severe earthquakes, with high magnitude and without special a-seismic expedients. Generally for moderate earthquakes, the static design is enough to protect structures from seismic motion;
- Deep tunnels are safer compared to shallow tunnels;
- All the structures buried in soft soils suffers higher damage compared to structures in rock;
- Some seismic parameters have crucial influence on the stresses arising in the structure: peak ground acceleration, frequency content and duration;
- Damage degree increases with magnitude and decreases with epicentral distance;
- Tunnels running across active faults suffer severe damage due to differential displacements which are incompatible with structure strength. Wherever it is possible, the tunnel should not pass through active faults;
- Some damage occurs at portals due to landslide near the entrance. As for the active fault, the tunnel should not pass near provisory slopes;
- Ground motion may be amplified upon incidence with a tunnel if wavelengths are between one and four times the tunnel diameter. This observation shows that high frequencies can be more dangerous than lower ones, but such frequencies are generally outside the range of a typical earthquake energy content;
• Water and gas supply systems are more vulnerable compared to metro and road tunnels, as steel tubes have a thickness/diameter ratio lower than concrete tunnels. Most of the damage of such lines occurs in saturated sand due to liquefaction;
• Most of the metro lines and roadway tunnels are only damaged by extremely severe earthquakes. Some authors (Iida et al., 1996; Yoshida, 1999), describing the damage of the metro line of the city of Kobe during the earthquake of 1995, show that many sections suffered cracks and collapses for the absence of a-seismic expedients. On the other hand some American metro lines had good performance during the Loma Prieta earthquake (1989), thanks to special seismic joints used in the tunnel design.

8 SEISMIC PROTECTION OF TUNNELS

Protective measures against seismic actions are particularly important for underground structures having abrupt changes in structural stiffness or ground conditions (Fig. 7) as occurs for:
• connections between tunnels and buildings or transit stations;
• junctions of tunnels of different structural material;
• passing through distinct geologic media of varying stiffness;
• local restraint on tunnels from movements of any type.

At these locations, stiffness difference may subject the structure to differential movements and generate stress concentration.

In order to avoid this stress increase the most common solution is to follow differential displacements by means of seismic flexible joints, that usually consist of bended steel plates and rubber. The design of this joints has three important goals: allowing differential movements in longitudinal and transverse directions and relative rotation; resisting to static and dynamic earth and water loads; water tightness.

Joints are particularly useful at tunnel portals. In fact tunnel portal has a different behaviour compared to tunnel lining. Yeh (1974) and Hetenyi (1976) develop methods to calculate additional stresses due to the tunnel-portal stiffness change. But the seismic design of this structure has usually to account also for the inertial effects due to the above-ground structure. For the design of the Alamedas Tubes (Schmidt et al. 1998) two dynamic analyses were carried out both for the running tunnel and the portal structure. Therefore the tunnel is assumed to move independently from portal structure. The joint was designed to allow a displacement equal to the difference between the two time histories (tunnel and portal). Generally the longitudinal differential displacement is higher than the transverse displacement.

When the structure passes through two different soil (in terms of stiffness) Kawashima (2000) proposes, beyond the seismic joint solution, an extended isolation of tunnel from the surrounding ground (Fig. 9). If a soft layer between the underground structure and the surrounding medium is placed, the transmission of the seismic deformation may be mitigated, reducing the forces in the tunnel.

Figure 9: Isolation for a shield tunnel (Kawashima, 2000)

As an example, a 10m diameter tunnel is considered that intersects a discontinuity between soft and stiff soil (Fig. 10). A 200mm thick elastic material was provided around the tunnel. The elastic modulus of the isolation material was lower than that of the stiffer soil by a factor of 1.5·10^{-3}.

Figure 10: Effect of seismic isolation: case of study (a); bending moment decreasing (b) (Kawashima, 2000).
Fig. 10b shows how the computed bending moment decreases in accordance with tunnel isolation, and has negligible increments beyond 40m from the discontinuity. The material used for seismic isolation need to be stable to settlements and long-term use.

In order to protect existing structures from ground shaking, an accurate investigation of soil/lining contact is required, through sampling and geophysical techniques. If the tunnel is in poor conditions some restoration interventions are needed. Full restoration would require replacing the tunnel and adding steel reinforcements. Lining thickness increase is not an acceptable solution, as it increases the structural stiffness and hence the internal forces in the lining. Instead, ductility increase is proved to be more effective (Power et al. 1996).

Structure protection against ground failure, i.e. large permanent ground deformations, is not easy to be designed. For the construction of a new tunnel the lining can be simply relocated. Otherwise, design strategies include ground stabilization, drainage, soil reinforcement, grouting or earth retaining systems. For example, protection from structure flotation is required in liquefiable soils: the structure buried in liquefiable soil during an earthquake tends to move up, causing high deformations. Schmidt and Hashash (1999) proposed the use of cut-off walls made by sheet pile walls, stone or jet-grouted columns (Fig. 11).

Barrier walls reduce the rise of excess pore water pressure in the ground under the tunnel: adding the wall makes the underground structure wider and the uplift more difficult. This expedient should be used combined with flexible joints to allow differential displacements.

In order to protect underground structures against landslide the potential of slope instability need to be reduced: in fact, tunnels cannot accommodate irreversible displacements due to slope failure (Power et al. 1996).

Design strategies for tunnels crossing active faults depend on the magnitude and displacement of expected earthquake. If the deformations are concentrated in a narrow zone, a common retrofit design is to enlarge the tunnel across and beyond the displacements zone. The reason of this solution is to give a wide gap to permit roads or rails restoration when the tunnel has high differential translations in the active fault lining section. San Francisco BART and Los Angeles Metro rapid-transit tunnel systems were designed according to this philosophy (Hashash et al., 2001). Moreover for BART tunnels concrete-encased steel ribs were adopted to provide sufficient ductility. Under axial fault displacements, the tunnel compressions are more damaging than tensions, causing water inflow. One more time, flexible joints are the adequate solution (Wang, 1993).

In the past most of the underground structures were designed without seismic considerations, because generally the tunnels had a good performance during the earthquakes compared to above-ground structures behaviour. In other cases, the design of buried structures was carried out with the same seismic considerations of above-ground structures. In order to optimize the tunnel seismic design, a correct evaluation of stresses under seismic waves is needed.

Performance-based seismic design should be aimed both to maintain in operation the tunnels during the more frequent events (of lower intensity) and to avoid human life losses for exceptional
earthquakes (of higher intensity), according to the local seismic hazard predictions. In some cases, and almost always in presence of ground discontinuity, structural discontinuity or high potential of ground failure, protecting measures need to be carefully designed.

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