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REVIEW PAPER

A REVIEW OF DAMAGE CASE HISTORIES AND METHODS FOR THE PROTECTION OF UNDERGROUND STRUCTURES IN CASE OF EARTHQUAKE AND BLAST LOADS

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Abstract: Underground facilities are an integral part of the infrastructure of modern society and are used for a wide range of applications, including subways and railways, highways, material storage, and sewage and water transport. Underground facilities built in areas subject to earthquake activity must withstand both seismic and static loading. Historically, underground facilities have experienced a lower rate of damage than surface structures. Nevertheless, some underground structures have experienced significant damage in recent large earthquakes, including the 1995 Kobe, Japan earthquake, the 1999 Chi-Chi, Taiwan earthquake and the 1999 Kocaeli, Turkey earthquake. In order to understand the behavior of underground structure during earthquake and blast loads, 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 papers 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. This article presents a summary of the current state of seismic analysis and design for underground structures.

Keywords: *Underground structure, earthquake, case histories, blast loads*

1.0 Introduction

A common believe in the past times was that earthquakes had a negligible impact on underground structures in comparison with the surface engineering works. However, as can be seen, recent strong earthquakes damaged many underground facilities (Hashash *et al.,* 2001). In the current urban zones, too much of underground spaces have been employed for storing various underground structures. The underground structures play a very important role in human life and they have a wide range of uses such as bunkers, tunnels, subways, nuclear power plants, sewage, water pipelines, gas, telecommunication and electricity (Myers *et al.,* 2003; Myers and Elkins, 2006).

In recent decades the world observes severe accident In Nuclear Power Plants (refer to Tables 1 & 2). The natural and human errors are the main reason of them. Tornado, tsunami and also terrorist attack, explosions are some of the treatment in NPPs that constructed on the ground. Because of these problems, some of the codes and guidelines recommended to construct the NPPs underground to protect them against natural and human events (Bach, 1977; AFPS/AFTES, 2001). It is necessary to conduct adequate studies to explore the way underground structure are damaged by earthquakes in order to protect human life.

2.0 Case Histories of Earthquake Damages

Prior to 70's, there had been an inadequate amount of information about the damages that earthquakes caused to underground structures. Indeed, damages were perfectly documented and reported only after some strong earthquakes. For example, following the San Fernando earthquake occurred in 1971, ASCE documented some data in 1974 concerning the damages to the underground structures in Los Angeles. Furthermore, in several cases, there was no monitoring of the lining cracks that had existed prior to earthquake (ASCE, 1974). Consequently, it was not possible to know the actual damages that occurred for structures due to earthquakes. In 1974, a systematic data collection was designed for collecting data about damages to tunnels, which have been occurred due to various earthquakes. It was helpful for recognizing the similar causes and common characteristics.

Dowding and Rozen (1978) reported 71 damage cases regarding both Japanese and American earthquakes. This included roadway and railway tunnels as well as water pipelines. 12 reported cases were in compact rock, 11 cases were in fractured rock, and 3 cases included tunnels in soil. The Dowding and Rozen's study was updated by Owen & Scholl (1981) through collecting 127 damage cases to underground structures. Its important parts were in regard to the cut-and-cover tunnels that were damaged by the San Fernando and San Francisco earthquakes in 1971 and 1906 respectively. The structures were mostly constructed in poor soil, hence very shallow. Sharma & Judd (1991) extended the two previously-conducted studies and collected 192 damage cases occurred due to 85 earthquakes. Six parameters (i.e., subsoil type, tunnel cover, peak ground acceleration, epicenter distance, earthquake magnitude, and lining support type) were evaluated for obtaining the correlation of seismic vulnerability of tunnel to related factors. 60% of damages affected the shallow tunnels (those with depth lower than 100m), and 42% of cases were related to the unlined tunnels in the rock. Power *et al.* (1996) updated the data gathered by Sharma and Judd (1991) by adding the data collected from 217 cases of bored tunnels after the earthquakes of Northridge and Kobe in 1995.

Ultimate viability of UNP concept is of an acceptable confidence since underground reactor operation and siting have been seriously taken into account for deploying commercial, full-size nuclear power plants. The origination of the idea of technical feasibility of underground siting and operation of the nuclear reactors is an area close to Zheleznogorsk, in central Siberia, Russia, wherein three reactors have been sited underground inside a granitic rock mass (Sovacool, 2008). Yenisey River provides the required cooling water. Two reactors that have been constructed in 1958 and 1961 were utilized to produce plutonium, and the other one, constructed in 1964 generated both district heat and electricity. For decades, the three reactors have been worked in a successful way. It is also noticeable that a radio-chemical plant has been sited underground. This can be considered as a support to the argument for potential feasibility of underground collocation of the reprocessing facilities, thus this case is of a great importance for the UNP concept. Additionally, in Western Europe and Scandinavia, from the 1950s, a total of four small experimental reactors and one demonstration reactor have been sited underground and have operated for a number of years (Sovacool, 2008).

During the 1970s, nuclear power had a rapid growth, which caused the underground siting of commercial nuclear power plants to be considered as a substitute to surface siting. The underground siting was extensively investigated by researchers from U.S., Japan, Canada, and other countries and their results were summarized and presented in proceedings from the Hannover conference in 1981 (Bender, 1982). The presented studies covered issues such as safety, cost and security, and carried out an evaluation on the advantages and disadvantages of the underground siting. They concluded that, from an engineering viewpoint, the underground siting was feasible and it was shown capable of providing a higher protection against security threats; sever accident consequences, seismic activity, and harsh weather conditions. Nevertheless, underground siting was also shown to increase the costs accompanied with tunneling, shaft sinking, and other underground constructions. However, their studies did not take into consideration the virtues of siting several reactors underground, as does the UNP approach. The UNP approach avoids the problem of increased cost through raising the number of reactors to an extent that causes to decrease to an acceptable level the per-reactor cost of underground infrastructure.

Table 1: Some of severe accident in NPP caused by natural disaster and human error

Year	Site	Descriptions
2011	Fukushima, Japan	An earthquake and tsunami caused to damage the 5 active reactor plants. Explosion.
2004	Fukui Prefecture, Japan	Steam explosion at Mihama Nuclear Power Plant kills 5 workers and injured 6 more
1986	Chernobyl, Ukrainian SSR	Overheating, steam explosion, fire, and meltdown cause the evacuation of 300,000 people from Chernobyl.
1961	Idaho Falls, Idaho, United States	Explosion at SL-1 prototype at the National Reactor Testing Station.
1957	Mayak nuclear waste , Chelyabinsk	The explosion causes a severe damage in NPP.

Table 2: List of incidents associated with military attack

	Description of event	Year
1	Destroyed Iraq’s Osirak nuclear was completely destroyed by an Israeli air strike.	1981
2	Koeberg nuclear power plant in South Africa was attacked by Umkhontowe Sizwe	1982
3	Iran’s Bushehr nuclear power plant was bombed by Iraq six times.	1984-87
4	The U.S. bombed three nuclear reactors in Iraq	1991
5	Israel’s Dimona nuclear power plant was attacked by Iraq’s missiles	1991
6	Syrian reactor was bombed by Israel	2003

3.0 Examples of Damage to Underground Structures

In the last century, California and Japan have witnessed many strong earthquakes, which are generally well documented. Specifically, in California, from 1900 to 2004, six strong earthquakes have happened. In 1906, a catastrophic earthquake occurred in San

Francisco with magnitude of Mw=7.8, which completely destroyed San Francisco and killed more than 3000 people. Three strong earthquakes happened in duration of only five years, including Loma Prieta (Mw=7.1) in 1989, Petrolia (Mw=6.9) in 1992, and Northridge (Mw=6.7) in 1994. Power *et al.* (1998) reported 64 damages cases that occurred due to these earthquakes.

For minimization of the damages that may occur to tunnels due to earthquakes, a great deal of research was conducted in California on both seismic and static design of tunnels' structures. Thus, to construct the Los Angeles Metro and Bay Area Rapid Transit (BART), special seismic joints were designed in a way to permit differential displacements, leading to a limitation on increase of stresses in lining. Once Loma Prieta was occurred in1989, these joints showed a good performance, since the structures of the subway were not damaged (Hashash *et al*., 2001); while several water supply tubes were damaged severely.

Bardet & Davis (1999) reported 61 cases of strongly damaged steel tubes during the Northridge earthquake occurred in 1994. They demonstrated the deformation mechanisms that were unusual for thin steel tubes. Often, they underwent shriveling because of lateral buckling for the lack of confinement.

The Japan's strong earthquakes have killed millions of people and remained hundreds of damaged buildings. Factors such as high seismic susceptibility, density of citizens, and its nonstop industry are most importantly have made Japan one of the highly risky countries in terms of seismic events (Haque *et al*., 2013). Earthquakes have brought about enormous damages to both underground and above-ground structures. For instance, the Hyogoken-Nambu earthquake occurred in 1995 caused catastrophic damages to Kobe that was situated nearby the earthquake epicenter. The earthquake was with magnitude moment Mw=6.9 that was shaking the ground for 20 seconds. This event killed 5100 people and caused many buildings, bridges, and other civil structures to be collapsed completely. The Kobe metro system was also entirely damaged and this was forced to stop its services (refer Figures 1 & 2).

In another event, a very severe earthquake that is known as The Chi-Chi earthquake was took place in Taiwan in 1999 with a magnitude moment Mw=7.6. This earthquake caused also many destructive consequences even to some parts of Popular Republic of China. Miyajima & Hashimoto (2001) made an investigation on damages this earthquake had brought about for water supply system. Approximately 0.14Km of transmission pipelines and near 4.56Km of service pipelines were cracked during this event. The China's Water Works Association declared that about 50% of cracking had been occurred due to soil shaking and other cases were due to liquefaction and slopes failure that had been took place near the tubes.

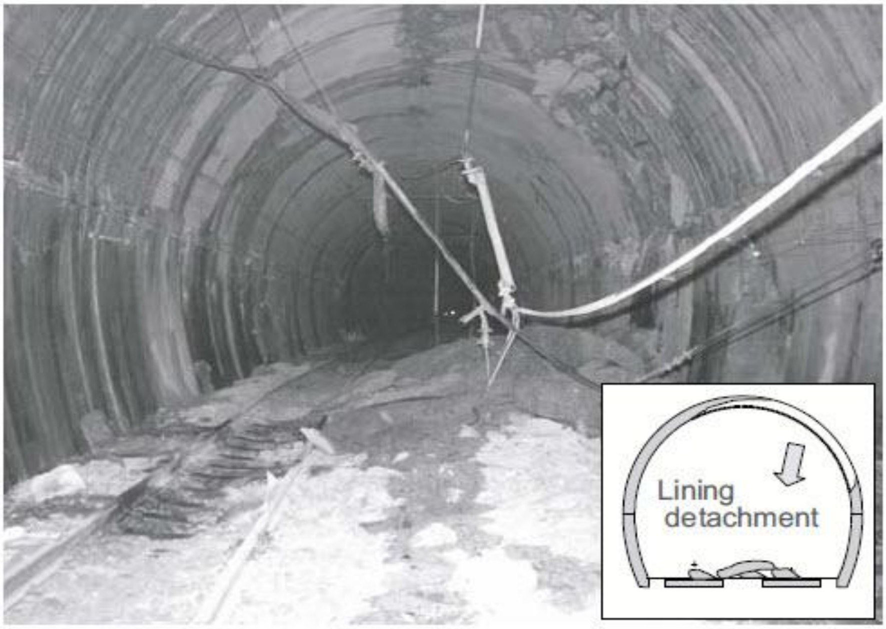

Figure 1: Damage to the Wanatsu tunnel

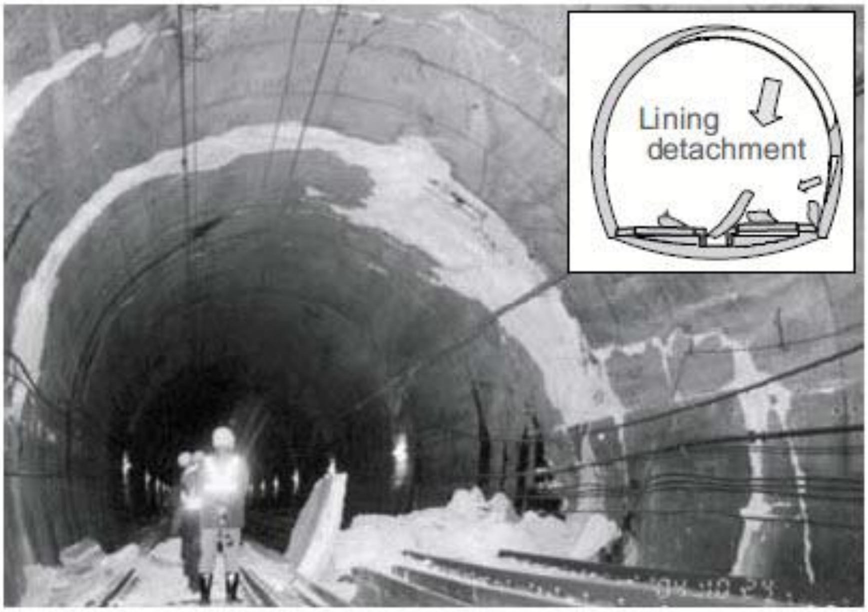

Figure 2: Damage to Uonuma Tunnel

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 epicenter, occurred on September 21st at 01:47 AM, with a magnitude moment Mw=7.6. Miyajima and Hashimoto (2001) 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 were caused by soil, shaking, and the other 50% was due to slope failure and liquefaction occurred near the tubes.

One of the most important events during recent years was Fukushima Daiichi disaster. It was one of the 15 largest nuclear power plants in the world (refer Figure 3). It is located on a 3.5-square-kilometer site in the towns of Okuma and Futaba. The earthquake occurred in the Futaba District On March 11, 2011. It's categorized as 9.0 M on the magnitude scale at the northeast coast of Japan with the epicentre approximately 70 kilometres east of the Oshika Peninsula of Tohoku and the hypocentre at an underwater depth of approximately 30 km.

Figure 3: Fukushima Daiichi disaster during the earthquake occurred in the Futaba District On March 11, 2011(Hot *et al*., 2012)

4.0 Damage Classification Criteria

The studies conducted by Power *et al.* (1998) and prior to that make available a relatively extensive database of data concerning the damages occurred to tunnels that undergo seismic loads. This provided database is diverse, consequently various cases can be differentiated based on the cracks types, soil, level of damage, and lining characteristics. For classification of the tunnels behavior while earthquake occurs, some criteria are selected from the related literature.

Power *et al*. (1996) identified three different types of buried structures with different behavior during earthquakes: bored tunnels, cut-and-cover structures, and steel and plastic pipelines.

The database should be divided based on such categories and the damages are required to be classified like the classification performed by Dowding & Rozen (1978). They identified three tunnel cracking patterns that can also be combined with each other and can be because of ground failure like landslides or liquefaction that may occur at tunnel portals, fault displacement, and/or ground shaking or ground vibrations.

Some certain lithological conditions can lead to damage of the first and second type. For the first case, the tunnel entrance should be near to a slope. For the second case, the lining should pass through an active fault. These conditions must be avoided cautiously. Tunnels may be damaged due to the ground shakings when it crosses through a very poor ground. In this condition, a wide cracking can be appeared on lining for long stretches.

Using the damage level criterion, Dowding and Rozen (1978) divided their database with considering three different damage classes, i.e., damage, minor damage, and no damage. A damage level was added by Huang *et al*. (1999) and Wang *et al*. (2001) to Dowding and Rozen’s Classification, which subdivided the minor damage class into two classes: slight and moderate.

Based on the approach proposed by Dowding & Rozen (1978), three levels of damage can be defined by means of crack length (L) and width (W), the functionality of tunnel and the restoration requirement 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 lead to deep cracks, exposed and reinforcement. Compromised functionality; service interruption until complete restoration with aseismic expedients.
- *Class C*: Severe damage. Liquefaction and Landslide; structural collapse of lining; service stop without any possible restoration.

There are five factors that impede collectively or individually the expansion of nuclear power, including nuclear waste, high capital cost, physical security, safety, and production of nuclear expertise and material. Nowadays, these factors continue to limit the expansion of nuclear power despite new and more favorable status of the nuclear power.

The studies that have been carried out on Underground Nuclear Power plants (UNPs) concept are limited, qualitative, and conceptual. Prior to determining economic and technical feasibility of the UNP concept, there is a need for detailed system, engineering, and economic studies on this concept. Even if we can assume its feasibility, previous to siting, constructing, licensing, and operating of the first UNP, a regulatory framework should be developed to enable the UNP deployments; additionally, political, industry, and market conditions should be promising. As a result, a full-scale UNP deployment in the U.S.A cannot be probably started until 2025 – 2030 time-frame. Therefore, the UNP concept cannot be considered as a substitute to the usual approach for 30+ new reactors that are presently planned, and this cannot be taken into account as an alternative to the requirement for the Yucca Mountain repository. A growth scenario must be developed involving an accelerating expansion of nuclear power in the U.S.A with growing recognition of energy security, reliability and environmental aspects in order to take the deployment of UNPs into consideration.

5.0 Parameters Affecting Structure Damage

In classification of the database, the dependency level of the tunnel damages on some important variables (earthquake parameters or soil/structure characteristics) can be highlighted. Dowding & Rozen (1978) attempted to make a correlation between damage level with the peak ground acceleration and the seismic signal's peak ground velocity at the surface above the tunnel.

Literature confirms this important information, which shows that severe damages occur only to strong earthquakes. Indeed, the 0.5g limit is high in comparison with values that bring about damage to the above-ground structures. This confirms that underground structures are commonly safer compared to above-ground structures. Perceptibly, the confinement of tunnel places a considerable limitation on the structure displacements that occur because of seismic shaking.

Sharma & Judd (1991) conducted a study to extend the study carried out by Dowding & Rozen (1978) to the other parameters that were considered very significant for the behavior of tunnel. In addition to the PGA, they considered some other parameters such as epicentral distance, the tunnel depth, the lining support, the magnitude, and the type of ground.

Note that shallow tunnels can be exposed to more damage in comparison with deep structures. This can be because of both the confinement degree and improvement of characteristics of ground with depth. In an earthquake, shallow tunnels are exposed to larger deformations, hence higher stresses.

Different parameters have effect on NPPs' damages under different events, distance, intensity and other parameters which were mentioned in above section.

6.0 Crack Distribution on Underground Structure

Wang *et al.* (2001) suggested a number of cracking patterns that can be induced into the tunnel lining while an earthquake occurred. Among them, six patterns are as follow:

a) *Sheared off lining*: it takes place for tunnels that pass through active faults;

b) *Slopes failure induced tunnel collapse*: it takes place in cases where the tunnel runs parallel to slopes and generates landslides that pass through the lining;

c) *Longitudinal cracks*: it takes place when the tunnel is subjected to higher deformations because of surrounding ground;

d) *Traverse cracks*: it takes place in cases where the tunnel is with weak joints;

e) *Inclined cracks*: it takes place for an integration of transversal and longitudinal cracks;

f) *Extended cracks*: it takes place in cases where there is the partial collapse of linings for seismic intense deformation;

g) *Wall deformation*: it takes place in cases where there is a transverse reduction because of invert collapse;

h) *Spalling of lining*: it takes place in cases where the transversal section collapses completely.

7.0 Design Issues

For the summary of some considerations regarding the seismic damages to tunnels, Yoshida (1999) proposed a schematic drawing of general conditions that induced cracking and collapse on the lining when an earthquake occurs, which referred to only seismic ground shaking.

A lithological or structural modification identifies unfavorable conditions that lead to lining cracking and collapse. In cases where internal or external variations do not exist along the tunnel longitudinal axis, damage may take place for those tunnels that are buried in soft soils (refer Figure 4). In these cases, the most recurrent cracking pattern is composed of longitudinal cracks that are developed longitudinally positions along transverse section, sometimes anti-symmetric, sometimes symmetric as illustrated by Wang *et al.* (2001), in which some damaged tunnels are reported at the time of the Chi-Chi earthquake. With consideration of various cases of damage occurred to underground structures, it can be established that:

- Once an earthquake occurs, underground structures are less exposed to damage in comparison with above-ground ones. Collapses and cracks occur only in strong earthquakes that have a high magnitude and do not have a-seismic expedients. In general, in case of moderate earthquakes, static design is enough for the protection of structures from the seismic motions.

- The deep tunnels are safer than the shallow ones.

- Structures that are established in soft soils are exposed to higher level of damage in comparison with structures established in rock (Kramer, 1996).

- Some of the seismic parameters are crucially effective on stresses that arise in the structure, such as frequency content, peak ground acceleration, and duration.

- The degree of damage is increased with magnitude; while it is decreased with epicentral distance.

- The tunnels that run across the active faults are exposed to severe damages because of differential displacements that are not compatible with the strength of the structure. Thus, as far as possible, tunnels should not run across the active faults.

- Some of the damages take place at the portals because of a landslide near entrance point. Therefore, tunnels should not run near to the provisional slopes.

- The ground motions can be augmented for a tunnel in cases where wavelengths are between 1-4 times bigger than the diameter of the tunnel. This indicates that that high frequencies may be more hazardous compared to the lower ones; although, such frequencies are commonly outside the range of energy content of a usual earthquake. Another issue is that the gas and water supply systems are more susceptible than road and metro tunnels. This is because the thickness/diameter ratio of steel tubes is lower than the concrete tunnels. The majority of damages to such lines take place in saturated sand because of liquefaction.

- The majority of roadway tunnels and metro lines are damaged only by an extremely strong earthquake. Iida *et al*. (1996) and Yoshida (1999) stated that, in the earthquake of Kobe occurred in1995, many parts of the Kobe's metro line were exposed to cracks and collapses due to the absence a-seismic expedients. However, in the Loma Prieta earthquake occurred in 1989, some American metro lines remained undamaged, which was due to using special seismic joints in the tunnels design.

During a terrorist attack, tornado and tsunami, the underground N.P.Ps is protected by ground and lead to safer situation. Moreover, during an internal explosion in underground NPPs, the ground protects environment against revealing of radioactivity. According to Forni (2010), the most important difference between a civil structure and NPP is that the latter must maintain its integrity even after sever events

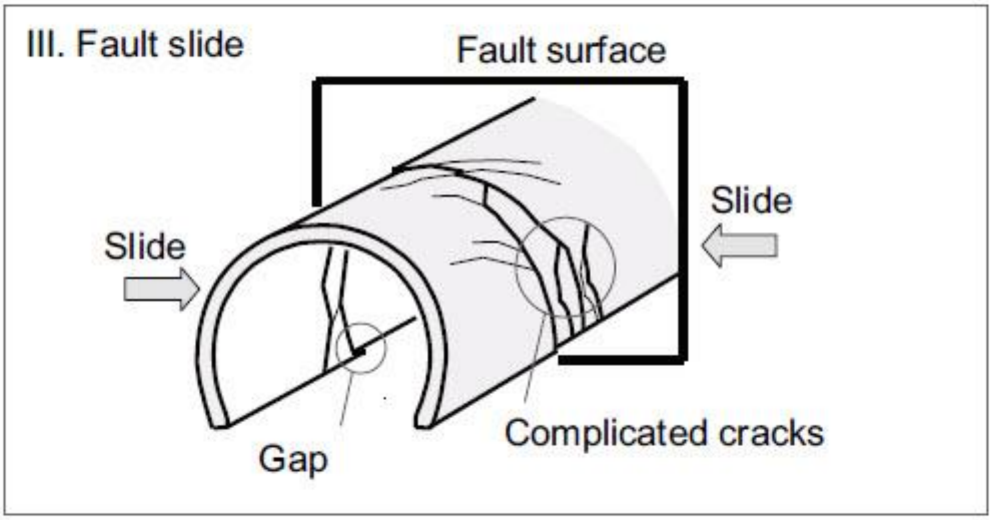

Figure 4: damage to tunnels caused by fault slide

8.0 Protective Measures of Underground Structures

It is very important to do protective measures for the underground structures against the seismic actions that may occur. These measures bring about abrupt changes to the structural stiffness or the ground conditions as take place for:

- Connections that exist between tunnels and buildings
- Junctions of the tunnels of various structural materials
- Local restraint that are established on the tunnels from any type of movements.

To avoid the increase of this stress, the most commonly-used solution is following the differential displacements using seismic flexible joints that typically are composed of rubber and bended steel plates. These joints are designed for three significant purposes: water tightness, to allow differential movements in transverse and longitudinal directions and relative rotation, and to resist against dynamic and static water and earth loads.

The joints are of a high usability in tunnel portals. Indeed, the tunnel portal behaves differently in comparison with tunnel lining. Yeh (1974) and Hetenyi (1976) developed methods for computation of additional stresses that occurred because of the changes to tunnel-portal stiffness. However, this structure's seismic design typically should consider also the inertial effects of above-ground structure. In designing the Alameda Tubes, Schmidt *et al.* (1998) conducted two dynamic analyses for portal structure and running tunnel. Thus, tunnel is supposed to be moving independently from the portal structure.

The joint was designed in order to allow a displacement that was equal to the difference existing between two time histories (i.e., portal and tunnel). Longitudinal differential displacement is normally higher than transverse displacement. In cases where structure passes through two types of soil that are different in their stiffness) level, an extended isolation of tunnel from the surrounding ground was suggested by Kawashima (2000). If a soft layer is placed between underground structures and surrounding medium, the seismic deformation transmission may be decreased, which leads to a reduction in the forces in the tunnel.

The materials that are utilized for seismic isolation should be stable for long term use. For the protection of existing structures from the ground shaking, sampling and geophysical techniques, a perfect study on soil/lining contact should be carried out. In cases a tunnel is established in poor conditions, a number of restoration interventions are required to be performed. A full restoration needs to replace the tunnel and add the steel reinforcements. The increase of lining thickness cannot be a suitable solution since this raises the structural stiffness, hence increasing internal forces in lining; however, the increase of ductility has been shown more efficient (Power *et al.*, 1996).

This is difficult to design an instrument to protect the structures against the ground failures, especially ground deformations that are large and permanent. To construct a new tunnel, lining can be relocated simply. Otherwise, protection from the structure flotation is needed in the liquefiable soils. Once an earthquake occurs, structures that are buried in liquefiable soil tend to move upward, which leads to high deformations. Schmidt and Hashash (1999) suggested the utilization of cut-off walls that are normally made up of sheet pile walls, stone or jet-grouted columns.

The barrier walls cause a reduction in the rise of excess water pressure in ground under tunnel; the wall makes underground structure wider and it makes the uplift more difficult. This method must be utilized together with flexible joints in order to allow the differential displacements. For the protection of underground buildings against the risk of landslide, there is a need to reduce potential of slope instability. Indeed, tunnels are not able to accommodate irreversible displacements because of slope failure (Power *et al.*, 1996).

The proper strategies in designing the tunnels that cross active faults are dependent on the displacement and magnitude of probable earthquake. In cases where deformations have been occurred in a narrow zone, a general retrofit design is enlarging tunnel beyond and across the displacements zone. This is performed in order to give a wide gap in such a way that roads or rails restoration can be done once the tunnel is under high differential translations within the active fault lining section. This philosophy is the basis of designing the Los Angeles's Metro rapid-transit tunnels and San Francisco BART (Hashash *et al.,* 2001).

Furthermore, for the BART tunnels, for providing enough ductility, the concrete-encased steel ribs have been utilized. When there are axial fault displacements, tunnel compressions are more destructive compared to tensions, which causes water inflow. One more time, the adequate solution is the flexible joints (Wang, 1993).

9.0 Conclusions

In past years, the majority of underground structures were designed and constructed without taking into consideration any seismic issues; it was because designers generally believed that the tunnels had a good behavior under the effect of earthquakes in comparison with the behavior of aboveground structures. In some cases, the buried structures were designed with taking into account the same seismic issues that are generally considered in the design of above-ground structures. For optimization of the tunnel seismic design, there is a need for an accurate assessment of stresses under the seismic waves.

Based on local seismic hazard predictions, the performance-based seismic designs must aim at both maintaining the tunnels in operation during the occurred events and avoiding human life losses that may be occurred during exceptional earthquakes. In cases where there is ground discontinuity, high possibility of ground failure, or structural discontinuity; the protecting measures must be designed in a very careful way.

Specialists believe that underground nuclear power plants are more secure against environmental effects, harm, and terrorist strikes compared to those located on the surface; additionally, set up decommissioning of reactors has ecological, security, and waste transfer preferences.

Based on recent studies about underground NPPs, there are lots of advantages in comparison the NPPs which construct on the ground, as follow: In generally, the underground NPPs have higher resistance subject to exterior and interior explosion and air craft impact. Furthermore, they have higher level of protection against severe weather and also higher level protection against revealing radioactivity.

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