The Effect of Overburden Depth on the Damage of Underground Structure during Earthquake

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Abstract. Nowadays underground structures are essential components in urban areas and their number are increasing continuously. Generally, underground structures show a better performance during seismic actions than structures above ground. During recent strong earthquakes, some urban underground structures suffered severe damages and collapses. Many researchers have worked in this field. Most of them have a common view of shallow underground structures are more vulnerable. Damages in deep underground structures are negligible compared to the surface structures and shallow underground structure. But there are some case histories, where there is severe damage in deep underground structure too. So we cannot neglect the seismic damage of deep underground structure. Nowadays there are many deep underground structures being constructed and in operation. We need to take into account the safety of the deep underground structure. The influencing factors for causing damages in deep underground structures should be studied carefully. In this paper, various case studies are taken into consideration and their results are observed. And the damages in different underground structures at different locations due to corresponding earthquakes are studied and compared, and the pattern of damage occurrence is reviewed.

Keywords: Underground structure, Earthquake, Overburden depth.

1. Introduction

For a long time, it has been believed that the effects of the earthquake on underground structures are not very important. And, most of the underground structures were designed without giving any significance to seismic considerations. This was due to the fact that those structures did not experience considerable damage due to the earthquake in comparison to those in surface structures. Nevertheless, it was found that some underground structures were damaged significantly during recent earthquakes[1].

We know that the specifications for earthquake resistant design, for highway engineering, in China was introduced in 1978. There was no consideration in code, for earthquake resistant design, before 1978. Tunnels that were constructed before this would have been weak in terms of anti-seismic ability. Tunnels constructed after this have better anti seismic ability. Earlier most of the underground structures were built without considering any seismic effects. But, in the last few decades, the need for the design of aseismic tunnels has been identified, especially in earthquake-prone regions.

While taking the seismic factor into consideration for underground structures, various factors play a role in the extent of seismic damage. These factors are a type of rock, fault zones, geological location,
site geography, overburden depth, etc. In this paper, the effect of overburden depth on seismically induced damage is discussed. The findings of different scholars on this are observed and looked into in detail. These findings are then compared and thorough discussion and thought are given to contrasting results and difference for similar conditions. This paper mainly targets to put forward the effect of overburden depth on seismic damages in underground structures, at different places at different times. For this different previous and current studies are referred and compared to the findings of each other.

2. Role of Overburden Depth on Seismic Damage of Underground Structure

2.1. Review of Case Studies Where Only Shallow Underground Were Damaged

Most of the researchers agree to the view that shallow underground structures are more vulnerable than deep underground structures. Many studies have documented damages to underground structures due to earthquake. ACSE (1974)[2] described about the damages in Los Angeles area due to the 1971 San Fernando Earthquake. JSCE (1988)[3] elaborated the performance of some underground structures, also included an immersed tube tunnel, at the time of shaking in Japan. Duke and Deeds (1959)[4], Stevens (1977)[5], Dowding and Rozen (1978)[6], H.R. Pratt et al (1978)[7] Owen and Scholl (1981)[8], Sharma and Judd(1991)[9], Power et al. (1998)[10], Kaneshiro et al (1999)[11], Hashash et al. (2001), Wang et al. (2001)[12] etc., all presented summaries of case histories of damages to various underground structures due to different earthquakes.

Dowding and Rozen 1978, studied 71 cases of rock tunnel damages in America and Japan, in which 42 cases were damaged. In his study, he concluded that the underground structures are much safer than surface structures. Also, deep tunnels are safer when compared to shallow tunnels. Robert Rowe (1992) [13] analyzed the effect of earthquake wave, fault, hard rock and liquefaction on tunnels. He concluded that the tunnel safety index increases with the increase in depth, when the depth is less than 500 meter. H.R. Pratt et al, 1978, in his investigation results, shows that surface displacement range from at least 1-10m, depending on geology, magnitude etc., when measured at 100m depth in in-situ rock masses. Displacement in the region of depth more than 500m is almost negligible. Sharma and Judd 1991 enlarged the collection of the previous authors further to reach a total number of 192 cases for 85 different earthquakes throughout the world. Most of the damages, 60% affected shallow tunnels; depth lower than 100 m. And his study showed that the degree of damage in underground structures decreased at depths > 50 m while for depths > 300 m no serious damages were seen (figure 1). G. Lanzano et al, observed a wide collection of case histories and highlighted the possible causes of damages. It is important to notice that, in shallow tunnels higher damages occurred when compared to deep tunnels [14]

![Figure 1. Number of cases of tunnel damage plotted with overburden depth.](image-url)
Fang Xiaoqing [15] investigated 27 tunnels that were damaged due to Kobe earthquake and 7 tunnels due to chi chi earthquake and it shows, there were no damages in the region of above 500 m overburden depth. Only below 500m overburden depth, there were damages. Zhiyichen [16] 2012 investigated about 81 mountain tunnels that were damaged in 10 strong earthquakes. Yusheng Shen [17] 2014, investigated 52 mountain tunnels. Among 52 mountain tunnels, approximately 42 were damaged, including 20 or so that required major repairs. In their study, they summarised seismic damage mechanism and characteristics for mountain tunnels. Seismic damages at the portals are mainly caused due to the action of seismic inertia force or secondary disasters. After Kumamoto Earthquake (2018) [18], Tawarayama tunnel was observed and they found significant damages in shallow depth and only slight damages where overburden depth was high. Yu et al. [19] investigated 55 tunnels near the epicenter. Damages ranging from small cracks to heavy cracks were observed at the portal as well as inside the tunnels. Whereas, some sections near to the faults collapsed completely.

Little attention has been paid to the stability of caverns, excavated from the rock, during an earthquake, such as underground power house and mountain tunnels. This is so because the inherent seismic stability of rock caverns was considered, empirically, to be in safe condition as long as the excavation work is done safely, and if seismic motion within the rock is, generally, smaller than that of quaternary ground strata like alluvial layers. Certainly, for underground caverns built within the hard rock, no major damages have been reported similar to which occurred in above-ground structures. Even though damages to tunnels due to earthquakes have occurred, most of such damages have been reported at portals in deposits of talus and at the region of intersections with faults or weak strata. No damage has occurred in hard rock [20]. F. Krizher and G. Rosehouse [21] performed the numerical analysis of tunnel and their studies showed that earthquake induced stresses are usually much smaller than the strength of rock surrounding the tunnel.

![Figure 2. Mode of earthquake damages to mountain tunnels.](image2)

![Figure 3. Number of railway tunnel judge to have serious damage.](image3)
The following observations can be made, in general, about the performance of underground structures with respect seismic characteristics:

1. Underground structures suffer significantly less damage than those in above ground structures.
2. Reported damages goes decreasing with the increase in overburden depth. So, deep tunnels are deemed as safer and less susceptible to earthquake shaking as compared to shallow tunnels.
3. Underground structures constructed in soils can be expected to have more damages than in structures made in competent rock.
4. Lined and grouted tunnels are considered safer than unlined tunnels, in rock. Damage due to shaking can be reduced by stabilizing the ground surrounding the tunnel, and the contact between the lining and the surrounding ground is improved through grouting.
5. Damages at tunnel portals and near it may be considerable due to instability of slope.
6. Damages in tunnels may be related to peak ground acceleration and velocity on the basis of the magnitude and distance from epicenter of the considered earthquake.
7. During earthquakes, duration of strong motion shaking is vastly important because it may cause fatigue failure and hence leading to large deformation.

2.2. Review of Case Studies Where Deep Underground Structures Were AlsoDamaged

Most of the researcher presented and explained that shallow tunnels suffer higher damage as compared to deep structures. But there are some cases where deep tunnel was also damaged in recent earthquakes.

Chen et al. (2008) investigated seismic damages to the youyi tunnel after the Wenchuan earthquake, taking into account the vertical earthquake action. The finding of his study was different to those in previous studies. The greater tunnel damages were found in the region where the overlying rock mass was thicker. It is then concluded that the main reason may be the vertical earthquake action for the occurrence of more severe damages to the tunnel body than those at its entrance. Cheng-hsun chen et al, (2008) investigated the influence of depth of tunnel on its seismically induced damages. The analysis discloses that seismically induced stress is strongly correlated to the depth and wavelength of the incidental wave; when the depth is a quarter of the wavelength, the amplitude of the seismically induced stress is notably pronounced. Potential of damage to a tunnel is higher when the tunnel is at a depth that close to 0.25 times the wavelength. So it is concluded that shallow tunnels in weak rocks and deep tunnels in competent rocks are particularly vulnerable.

Yusheng 2014, observed that the deeply buried tunnel structures in poor geological conditions, as faults, were likely to have seismic damages, particularly at fracture zone, active fault, the interface of soft and hard rocks, and so on, as illustrated in figure 2 and 3. The rupture or dislocation of the structure generally results from the large scale surrounding rock excavation (or blasting) or higher shear force action. G. Androtti et al 2015, performed a numerical analysis to clarify the effect of overburden depth on the seismic vulnerability of deep tunnels constructed in weak rock.

Tunnel entrance and portals are more likely to be affected by earthquake because often lose ground exist in these areas. Here earthquake motion is amplified and the deformation in the ground is of large extent. If the tunnel is constructed in such a ground where earth covering is large, earthquake resistance is good, generally, due to the presence of stiff rock mass. However, a number of tunnels, with large earth covering, have also suffered damages due to earthquake. A typical example is damages to the Rokko Tunnel after the 1995 Hyogoken-Nanbu Earthquake. Figure 4 shows the longitudinal profile of the earthquake damage in Rokko Tunnel. Here, in hard rock where overburden depth is 460 m major damage occurred.
A preliminary analysis on the relationship of seismic damages with overburden depth of DU Wen highway tunnels showed that the extent of seismic damages was moderate or slight in hard rock tunnels at depths of more than 50m and there was no/ slight damage at depths more than 100m; similar to the results of Sharma and Judd (1991). The relationship was not very clear for weak rocks with faults and/or high in situ stresses. There were serious earthquake damages in the Zipingpu weak rock at depths of more than 50m, but only slight damages at depths of more than 300 m. In the weak rock section of the Longxi Tunnel, the earthquake damages were significant even at depth of 500m and hence resulted to the collapse of some secondary concrete lining [26]. Large amounts of strain energy were accumulated on the rock masses in the longmenshan fault zone and were under high geostress conditions. The high geostress in the rock masses were released by earthquake due to the movements along the faults and strong vibrations. Evidence of fractures characteristic of geostress release was seen in the tunnels. This type of seismic damage occurring due to the high geostress release, which has barely been discussed in previous cases, was most obvious in the Longxi tunnel. Lai Jin Xian et al. (2017) [27], longxi tunnel was the unique case in the Wenchuan earthquake, where deep mountain tunnel exhibited heavy damage which was the first time for such tunnels, the collapse of secondary lining occurred in large scale, and some cavities crumbled away. This strongly contradicts the view: “the tunnels with a depth of over 300 m do not suffer significant damages”. Liao and guo 2012 [28].

The statistic of tunnel damages after Wenchuan earthquake categorized by tunnel depth less than 500 m are shown in table 1. Results show that the shallow tunnels had significant seismic damages in tunnels with depth of 25 m, the seismic damages decreased with the increase in tunnel depth; meanwhile, tunnels showed a few seismic damages in tunnels with depth above 500 m. It contradicts the view that, in the tunnels with depth of 300 m to 500 m there are slight damages and for depth of more than 500 m there will be no damage [29].

**Table 1. Tunnel damages after Wenchuan earthquake.**

| Tunnel Depth (m) | Damage Number | Damage percentage (%) |
|------------------|---------------|-----------------------|
|                  | Light | Intermediate | Serious | No |
| <25              | 14    | 9            | 10      | 24  | 58 |
| 50-100           | 2     | 1            | 2       | 12  | 29 |
| 100-200          | 3     | 0            | 1       | 6   | 40 |
| 200-300          | 3     | 2            | 1       | 13  | 32 |
| 300-500          | 4     | 3            | 0       | 4   | 14 |
Here are the general information of earthquake with damages in underground structures. (table 2)

### Table 2. General information of the earthquakes.

| Earthquakes    | Date       | Location | Magnitude | General description of the damages                                                                 |
|----------------|------------|----------|-----------|---------------------------------------------------------------------------------------------------|
| San Francisco  | 1906 April | USA      | 8.3       | Two Tunnels crossing San Andrea Faults suffered significant damages; three aqueducts also suffered damages |
| Kanto          | 1923 September | Japan   | 7.9       | Nearly 150 tunnels were affected in Tokaido, Yokohms, Yokosuka and other lines, among which many collapsed. 82 tunnels out of the 116 tunnels of the railways were destructed or deformed, lining cracked, and sidewall collapsed. |
| Kern Country   | 1952 July | USA      | 7.7       | Four tunnels on the south Pacific Railways suffered seriously damages.                             |
| San Fernando   | 1971, February | USA    | 6.4       | In San Fernando Tunnel, Crossing Thelma Faults, destruction and dislocation appeared; other two tunnels showed cracks but not destroyed, and one was slightly damaged. |
| Izu            | 1978, January | Japan    | 7.0       | Nine railways and road tunnels were damaged with various degree of damages.                        |
| Kobe           | 1995, January | Japan    | 7.2       | Five stations and about 3 km long section of subway line were damaged. Cracks appeared on the cement wall in two tunnels of Kobe subway station and on running tunnel at more than 100 points; three cracks appeared within the length of 10m in Luijia Tunnel, and cracks appeared in high density within 100m length of the inspection tunnel |
| Chi-Chi        | 1999       | Taiwan   | 7.3       | Damages occurred in 49 tunnels, out of the 57 mountain tunnels inspected.                          |
| Chuetsu        | 2004 January | Japan    | 6.8       | Severe destructions were observed in 24 railway tunnels.                                           |
| Wenchuan       | 2008, May | China    | 8.0       | Underground transportation and other infrastructures were severely damaged. Extensive area in underground chambers and many tunnel structures collapsed completely; more than 2000 damaged spots were recorded along 380 m of aqueduct pipes in Dujiang Dam |
| Gorkha         | 2015, April | Nepal    | 7.8       | Few underground structures were damaged due to earthquake. Melamchi tunnel was damaged. More than 150 damages were found along the tunnel. |

[9]

### 3. Case study on Nepal Earthquake 2015

There was a devastating earthquake in Nepal in 2015 April with number of aftershocks. The underground structures are supposed to be much safer than the surface structures. After Nepal Earthquake, the damages in underground structures were less and there were only slight damages [30]. After the Nepal earthquake 2015 [31], some of underground structures in the nearby region were visited. Figure 5 is the location map of main shocks, aftershocks and visited project sites. Among them, Melamchi Tunnel had damages caused by the earthquake. Underground structures of other projects investigated showed no damages. Tunnel in Upper Tamakoshi hydropower project was intact after earthquake even though it is just 6 km from the Major after shock in April Tunnel of Kulekani III hydropower project was also intact even though this tunnel passes through Mahabharat fault zone (figure 6). Trishuli 3A hydropower project site was also visited but underground structures of this project were aslo intact even though it is near by the epicenter of Earthquake. Middle Bhole Koshi Hydropower project is near to the epicenter of earthquake but the underground structures were not damaged.
Figure 5. Location map of earthquake, aftershock and some projects.

Figure 6. Kulekani III tunnel crossing Mahabharat fault zone.

The Melamchi Water conveyance tunnel was damaged due to the Earthquake. Figure 7 shows the longitudinal profile with damages in Melamchi Tunnel. And figures 8 shows the damages in the Melamchi Tunnel during 2015 earthquake. The seismic damage assessment was done after the earthquake. There are more than 150 damages in the tunnel and they are divided into slight damages,
moderate damages and severe damages as per the severity of damages. In Melamchi tunnel, investigation result shows that, slight damages are more than severe damages figure 9 and table 3.

The damages were categorized into different types for different overburden depths. The results are different from the common pattern seen before. Damages at high overburden depth are more than those at lower overburden depth. It may be due to many influencing factors such as rock type, fault zones, distance from epicenter, etc. [32].

There have been such exceptional cases before like in longxi tunnel during Wenchuan Earthquake and Rokko tunnel during Kobe Earthquake. This calls for more research on it with new perspective.

Figure 7. Longitudinal profile of Melamchi Tunnel showing damages.

Figure 8. Damages in Melamchi Tunnel during 2015 earthquake.

3.1. Damages in Tunnel During 2015 Earthquake

Table 3. Damages of tunnel based on degree of damages.

| Damage Degree | Counts of Damages | Percentage of Damages |
|---------------|-------------------|-----------------------|
| Slight (Sl)   | 112               | 51.85                 |
| Moderate (M)  | 62                | 28.70                 |
3.2. **Damages in Tunnel Based on Overburden Depth**

The overburden depth varied from 0 to 1100 m, it was grouped into 3 categories for observation: shallow depth tunnel 0 – 300 m, medium depth tunnel 300 – 700 m and Deep tunnel 700 – 1100m, and the no. of damages per km for these overburden depths were taken. It was found that, for overburden depth of 0 – 300m, there were 7.36 damages per km, for 300-700m it was 31.17 and for 700-1100 m it was 4.01. From this, we get a pattern of damage occurrence. Here we can see that for high overburden depth (700 – 1100 m) the damages are very low as compared to lower overburden depths – 0-300 m and 300-700 m.

| Overburden Depth (m) | Length of Tunnel (km) | Counts of Cracks | % of Cracks |
|----------------------|----------------------|------------------|-------------|
| 0-300                | 5.976                | 44               | 7.36        |
| 300-700              | 5.294                | 165              | 31.17       |
| 700-1100             | 1.745                | 7                | 4.01        |

There are general findings from previous researches or theories that there are more damages to areas of less overburden depth. But here we see that the damage for 300 – 700 higher than that in 0 – 300m which is peculiar. This could be because of other influencing factors as type of rock. As can be seen in other discussions different rock type has different damage density. So it needs detail observation and analysis of particular rock type for corresponding overburden depth.

| Damage Degree | 0-300 | 300-700 | 700-1100 |
|---------------|-------|---------|----------|
|               | no    | %      | no       | %       | no | %    |
| Sl            | 22    | 50.00   | 85       | 51.52   | 5  | 71.43 |
| M             | 10    | 22.73   | 50       | 30.30   | 2  | 28.57 |
| Se            | 12    | 27.27   | 30       | 18.18   | 0  | 0.00  |
| total         | 44    | 165     | 7        |         |    |       |

**Figure 9.** Damage in tunnel based on degree of damage.
Here we can see (table 5 and figure 10) the detail inspection of damages for different overburden depth and the occurrence of degree of damages is obtained. In all of these half or more than half are slight damages, and then moderate and severe damages are lower in percentage.

![Figure 10. Degree of damages based on overburden depth.](image)

As expected for very high overburden depth there is less damage, for 700 – 1100 m there are no severe damages at all, but there are damages in 300-700m and severe damage percentage is 18.18, little lesser than 0-300 m. and the highest proportion for severe damage is for 0 – 300m being 22.27%.

4. Conclusion
From the result of previous researches and investigation of Melamchi tunnel some results which vary the traditional viewpoint regarding seismically induced damages on the basis of overburden depth is obtained. In Kobe earthquake, Chi Chi earthquake, Wenchuan Earthquake, a lot of underground structures were investigated. Most of them show that most damages occurred in shallow depth tunnels and less damages in deep tunnels. But some cases show that there were slight damages in shallow depth and severe damage in deep depth. Similarly, in Melamchi tunnel, after Nepal earthquake, tunnel damages were recorded in the region of deep overburden depth. So we just cannot neglect this result. Further study should be done in this perspective.

Generally it was observed that seismic damages occurred in deep tunnel structures which were located in poor geological conditions, particularly at active faults, fracture zones, interface between soft and hard rocks, and so on. This paper has proposed the need for further study in detail about the response of tunnels to seismic events and the requirement of appropriate design/mitigation methods. In particular, further research is required for better description and clarity of the mechanism of serious damage and corresponding aseismic measures in weak rock tunnels in areas of high overburden depth.

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