Review of the Correlation between Earthquake Damage of Underground Structures and Ground Motion Parameters

Renhui Dai\textsuperscript{1*}, Qingrui Lu\textsuperscript{1,2}, Shijun Chen\textsuperscript{1}, Zengliang Wang\textsuperscript{1} and Hongfei Zhang\textsuperscript{1}

\textsuperscript{1} School of Civil and Architectural Engineering, East China University of Technology, Nanchang, Jiangxi Province, 330013, China

\textsuperscript{2} Department of structural and geotechnical engineering, Politecnico di Torino, Turin, Italy

\* Corresponding Author: Renhui Dai; email: pe_dairenhui@126.com

Abstract. The ground motion parameters are the results of the seismic dynamic calculation. The review of investigation on the performance of large size underground openings during past seismic events has been presented, and different factors such as peak ground acceleration, peak ground velocity, seismic magnitude etc. on the effect of damage have been examined. The research results are of great significance for the analysis of seismic damage of underground structures.

1. Introduction

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 1976 Tangshan, China earthquake, the 1995 Kobe, Japan earthquake, the 1999 Chi-Chi, Taiwan earthquake, and the 1999 Kocaeli, Turkey earthquake, and some more recent earthquakes such as the 2004 Niigata, Japan earthquake, and the 2008 Wenchuan, China earthquake. Especially, the Daikai subway station collapse as the first collapse of an urban underground structure due to earthquake forces, rather than ground instability, significantly changed our belief that underground structures had the ability to sustain earthquakes with little damage\cite{1}.

Information on the performance of underground openings during earthquakes is relatively scarce, compared with that on the performance of surface structures. Some ground motion parameters have been devoted to the investigations of damage performances.

2. Peak ground acceleration (PGA)

In earthquake engineering, according to Dowding & Rozen, PGA is one of the most widely accepted index of the ground shaking intensity and damage\cite{2}. Ground motions with high peak accelerations are usually, although not always, more destructive than motions with lower peak accelerations \cite{3}.

Damage cases of tunnel structures documented by Dowding & Rozen, as shown in Figure 1 which was revised by Bäckblom, suggest that no damage should be expected if the peak surface accelerations are less than about 0.2g, and only minor damage will be experienced between 0.2 and 0.4g \cite{2,4}. Sharma & Judd updated the previous database and concluded that no damage or minor damage occurred for PGA less than 0.15g, as shown in Figure 2\cite{5}. And according to the extended database of Owen & Scholl, little damage would be expected for rock tunnels for peak ground accelerations below 0.4g, as indicated in Figure 3\cite{6}.
Focusing on the damage induced by earthquake shaking other than by ground failure or fault movement, Power et al. removed the relatively poorly documented cases as well as those caused directly by the other two seismic effects, and simultaneously added some recent cases[7]. They concluded that ground shaking caused less damage for PGA less than 0.2g, some cases damaged ranging from slight to moderate damage with PGA between 0.2g and 0.5g, and some other cases suffered slight to heavy damage when PGA exceeded 0.5g, as shown in Figure4. Besides, the case of 1923 Kanto earthquake with PGA equal to 0.2g suffered heavy damage probably due to landsliding other than ground shaking.

ALA studied 217 bored tunnels which suffered strong ground motions and obtained the correlation of damage degree and peak ground acceleration, as shown in Table 1[8]. It is concluded that the general tendency is almost corresponding to previous conclusions. More recently, Corigliano updated the data derived from the post earthquake surveys after Chi-chi (Taiwan) and 2004 Niigata (Japan) earthquakes based on the database developed by Power et al, and showed that the influence of PGA on damage was not characterized by an increasing trend, due mainly to the uncertainty involved in the calculation of PGA based on empirical attenuation relations[9]. However, it can be inferred from Figure 5 that almost no damage occurred for PGA less than 0.15g, the threshold of PGA leading to moderate damage was 0.25g, while heavy damage occurred when PGA exceeded 0.35g.
It can be concluded from above that damage could be related to peak ground acceleration to some extent, which was confirmed by Dowding & Rozen by pointing out that the use of acceleration as an index of acceleration could result in a workable method for determining the imminence of gross levels of damage[2].

| PGA (g) | All Tunnels | DS=1 | DS=2 | DS=3 | DS=4 |
|---------|-------------|------|------|------|------|
| 0.07    | 30          | 30   | 0    | 0    | 0    |
| 0.14    | 19          | 18   | 1    | 0    | 0    |
| 0.25    | 22          | 19   | 2    | 0    | 1    |
| 0.37    | 15          | 14   | 0    | 0    | 1    |
| 0.45    | 44          | 36   | 6    | 2    | 0    |
| 0.57    | 66          | 44   | 12   | 9    | 1    |
| 0.67    | 19          | 3    | 7    | 8    | 1    |
| 0.73    | 2           | 0    | 0    | 2    | 0    |
| Total   | 217         | 164  | 28   | 21   | 4    |

Figure 5 Effects of PGA on damage (Corigliano, 2007).

3. Peak ground velocity (PGV)

According to Corigliano, velocity-time histories could better capture the intense, impulsive character of near-fault records than PGA, and the response of underground structures is governed by the imposed strain field[9], which may be correlated to the Peak Ground Velocity (PGV) through the following relationship:

\[ \text{PGS} = \frac{\text{PGV}}{C_a} \]

Besides, the peak particle velocity resulting from an earthquake of a given magnitude can be predicted to fall within reasonable narrow limits, compared with peak ground acceleration[10]. Carpenter and Chung also concluded that there existed closer relationship between peak velocity and damage than between peak acceleration and damage[11]. Therefore, the intensity of ground motion shaking for assessing seismic damage of underground structures is better quantified in terms of PGV at the free surface[9].

Dowding & Rozen concluded from relevant investigations that minor damage would occur with peak ground velocity ranging between 20 cm/s and 40 cm/s[2]. The study of Owen & Scholl suggested that the thresholds of minor damage and heavy damage are respectively 20 cm/s and 90 cm/s, as shown in Figure 6[6]. The correlation between PGV and case numbers for moderate damage level
obtained by Corigliano is shown in Figure 7[9]. Based on the relation for predicting PGV developed by Bray & Rodriguez-Marek, Corigliano correlated PGV and the damage level, as shown in Figure 8 [9,12], and showed that the moderate damage occurs with the PGV value ranging between 40 and 115 cm/s, which are higher than the values concluded by Owen & Scholl and Dowding & Rozen.

The reliability of the correlation between damage and PGV still needs to be further analyzed and verified due to that PGV is usually evaluated at the free surface and it is often estimated using attenuation laws which carry a certain level of uncertainty. However, the relation between PGV and damage can be used for preliminary assessment of stability of underground structures before performing more refined analysis[9].

![Figure 6 Calculated PPV and associated damage (Owen & Scholl, 1981).](image)

![Figure 7 Correlation between PGV and damage class B (Corigliano, 2007).](image)

![Figure 8 Comparison between PGV evaluated at free surface using Bray & Rodriguez-Marek (2004) relation and damage level (Corigliano, 2007).](image)

4. **Earthquake magnitude**

Magnitude characterizes the size of an earthquake by measuring indirectly the energy released, and current magnitude scales include: local magnitude scale, also known as Richter Scale ($M_L$); body wave magnitude ($M_B$), surface wave magnitude ($M_S$), duration magnitude ($M_D$) and moment magnitude ($M_W$).

Local magnitude ($M_L$) scale, developed in 1935 by Richter, was based on the responses of seismographs and their distance from the epicenter. Because of this, there is an upper limit on the highest measurable magnitude, and the local magnitude's estimate of earthquake size is also unreliable for measurements taken at a distance of more than about 350 miles (600km) from the earthquake's epicenter.
The moment magnitude ($M_w$) scale was introduced in 1979 by Hanks and Kanamori. This scale was based on the physical properties of the earthquake, specifically the seismic moment ($M_0$). Unlike other scales, the moment magnitude scale does not saturate at the upper end; there is no upper limit to the possible measurable magnitudes. However, this has the side-effect of low-energy earthquakes clustering together. For medium-sized earthquakes, the moment magnitude values should be similar to Richter values. It could be more reliable for both medium and large earthquake magnitudes, but is rarely used for smaller quakes.

Body wave magnitude ($M_B$), surface wave magnitude ($M_s$), and duration magnitude ($M_D$) are all scaled to give values similar to those given by the local magnitude scale; but because each is based on a measurement of one aspect of the seismogram, they do not always capture the overall power of the source. Specifically, some can be affected by saturation at higher magnitude values—meaning that they systematically underestimate the magnitude of larger events. But they are sufficient for the vast majority of observed events.

Concerning with seismic damage of underground structures, several studies were carried out to correlate the damage level to earthquake magnitude, and the previous correlation is mainly focused on Richter magnitude. According to Dowding & Rozen, as shown in Figure 9, no damage occurs for Richter magnitude less than 5, and rare heavy damage could be expected for Richter magnitude less than 7 [2]. Sharma & Judd also used the Richter magnitude to correlate the relevant damage degree to the earthquake intensity[5]. He concluded that the cases of reported damage increased with increasing Richter magnitude, while more than half of the damage reports were for events that exceeded magnitude 7. Corigliano correlated the damage cases to the moment magnitude and concluded that the level of damage increases as the earthquake magnitude increases, as shown in Figure 10[9].

For the assessment of the general damage tendency induced by earthquake, all the above magnitudes could provide satisfactory results. However, moment magnitude would be preferred to develop more accurate relations with other factors, since most underground damage would more likely occur for larger earthquakes.

5. Modified-Mercalli (MM) Intensity

For the quantification of underground damage using Modified-Mercalli (MM) Intensity, Dowding & Rozen concluded that the ‘no damage zone’ with acceleration up to 0.19g[2], is equivalent to $MM$ VI–VIII, while the ‘minor damage zone’ with acceleration up to 0.5g is equivalent to $MM$ VIII – IX. Significant damage to Japanese tunnels was observed predominately in locations where MM reached VIII.
6. Duration
According to Dowding & Rozen, duration of strong motion shaking during an earthquake is extremely important since it may cause fatigue failure and lead to large deformations [2], which are dependent on the total number of cycles induced by the ground shaking. Owen & Scholl also indicated that duration of strong seismic motion appeared to be an important factor contributing to the severity of damage to underground structures [6]. Due to a lack of relevant available damage cases, no correlation between duration and damage level could be presented here.

7. Frequency
The response of the ground layers in which underground structures are embedded is sensitive to frequency content, and it is important with respect to stability of underground openings [11]. Dowding & Rozen suggested that the destructive frequencies may be expected mainly at small distances from a causative fault because higher frequency components attenuate more rapidly than the lower frequency components [2]. The high frequency effect may also contribute to the local spalling of rock or concrete. Besides, the frequencies most likely to damage sub-surface openings are significantly higher (50–100 Hz) than the frequencies (2–10 Hz) that cause damage to surface facilities (Pratt et al., 1980).

8. Conclusions
Based on the above survey studies, the following conclusions could be obtained:
- The damage level of underground structures could be well correlated to ground motion parameters such as PGA, PGV and magnitude. PGV is preferred to characterize the earthquake effect compared with PGA.
- Damage level increases with the increase of earthquake magnitude.

Acknowledgements
This research was financially supported by national natural science foundation of China (51609093) and project supported by science and technology department of Jiangxi province (20161BBG70084). Special thanks are due to Corigliano of Eucenter (Pavia) for providing the seismic input data.

References
[1] Hashash, Y.M.A., Hook, J.J., Schmidt, B., Yao, J.I.C. (2001) Seismic design and analysis of underground structures. Tunnelling and Underground Space Technology, 16, 247-293.
[2] Dowding, C.H., Rozen, A. (1978) Damage to rock tunnels from earthquake shaking. American Society of Civil Engineers. Journal of the Geotechnical Engineering Division. Vol. 104(2 Feb): p. 175-191.
[3] Kramer, S.L. (1996) Geotechnical earthquake engineering. Prentice Hall, Upper Saddle River, NJ.
[4] Bäckblom, G., Munier, R. (2002) Effects of earthquakes on the deep repository for spent fuel in Sweden based on case studies and preliminary model results. Technical Report, TR-02-24, Swedish Nuclear Fuel and Waste Management Co.
[5] Sharma, S., Judd. (1991) Underground opening damage from earthquakes. Engineering Geology, vol. 30, pp. 263-276.
[6] Owen, G.N., Scholl, R.E. (1981) Earthquake engineering of large underground structures. Report no. FHWA/RD-80/195. Federal Highway Administration and National Science Foundation.
[7] Power, M.S., Rosidi, D., Kaneshiro, J.Y. (1998) Seismic vulnerability of tunnels and underground structures revisited. Proc of North American Tunnelling ’98. Newport Beach, CA: Balkema, Rotterdam, The Netherlands, p. 243–250.
[8] American Lifelines Alliance. (2001) Seismic fragility formulations for water systems. Part 1-2 – Guideline. ASCE-FEMA
[9] Corigliano, M. (2007) Seismic response of rock tunnels in near-fault conditions. Doctoral thesis, Politecnico di Torino.
[10] John, C.M., Zahrah, T.F. (1987) Aseismic design of underground structures. Tunnelling and Underground Space Technology, 2, (2).
[11] Carpenter, D.W., Chung, D.C. (1986) Effects of earthquakes on underground facilities. NUREG/CR-4609 p. 1–52, Lawrence Livermore National Lab.
[12] Bray, J.D., Rodriguez-Marek, A. (2004): Characterization of forward directivity ground motion in the near fault region. Soil Dynamic and Earthquake Engineering, 24, 815–828, 2004.
[13] Hanks, T.C., Mcguire, R.K. (1981) The character of high-frequency strong ground motion. Bull. Seismol. Soc. Am. 71, 2071–2095.
[14] Pratt, H.R., Stephenson, D.E., Zandt, G., Bouchon, M., Hustrulid, W.A. (1980) Earthquake damage to underground facilities. Rapid excavation and tunneling conference. Littleton, CO, USA, June 1980. Conf-800603-1, 48p. In Workshop on Seismic Performance of Underground Facilities, p. 43–74.