Seismic Design of Tunnels in the Sydney Region: Selection of Earthquake Parameters and Approach

Beatriz Estrada, Andrew de Ambrosis and Robert Bertuzzi

1. Corresponding Author. Associate Engineering Geologist, Pells Sullivan and Meynink Email: beatriz.estrada@psm.com.au

2. Principal, Pells Sullivan and Meynink. Email: andrew.deAmbrosis@psm.com.au

3. Principal, Pells Sullivan and Meynink. Email: robert.bertuzzi@psm.com.au

Abstract

The design of recent tunnels in the Sydney region has included the evaluation of tunnel performance under seismic conditions. The special characteristics of tunnels (underground, long structures) influence their response to earthquake ground shaking. These characteristics mean that tunnels typically experience a different seismic response to that of surface structures.

In Australia, there is no specific code for tunnel design. Similarly, there is no provision for tunnel seismic design in AS1170.4 (2007) or any other Australian Standard. Consequently, the seismic design of tunnels requires specific considerations and approach. Accordingly, for the design of recent tunnels in the Sydney region, a two-level design criterion has been adopted. The first level is aimed at continuous operation and the second at life safety. The two-level design approach requires the definition of two design earthquakes.

The characteristics of the ground motion associated with the two design earthquakes are used to estimate the tunnel deformation (i.e. axial deformation, curvature deformation and racking deformation) under seismic conditions by using close form elastic solutions and numerical analysis. This paper describes the selection of the design earthquakes, the earthquake parameters used in the analysis and their application to the adopted methodology.

Keywords: seismic design, tunnels, Sydney, design earthquakes

1. INTRODUCTION

Traditionally the design of Sydney tunnels has not specifically considered seismic parameters. The reasoning was that a sound and comprehensive static tunnel design, involving appropriate factors of safety, would be enough to withstand the seismic shaking expected to occur in Sydney during the life of the tunnel. In recent years however, tunnel design in Sydney has evolved to specifically consider and include earthquake loading. The transition to actively include earthquake loads has imposed many challenges, including:

1. The selection of design earthquakes parameters. This can be challenging, due to the lack or vague definition of design earthquakes for tunnels in the available standards or guides (i.e. Austroads Guide to Road Tunnels, 2015; AS117004 - 2007)
2. The uncertainties associated with earthquake generation in intraplate regions such as Australia.

This paper focuses on the selection of earthquake design parameters used to evaluate tunnel performance for recent tunnelling projects in Sydney. Examples of the methodology used for the evaluation of tunnel performance are also presented.

2. SEISMOTECTONIC CONTEXT OF THE TUNNELS AND EARTHQUAKE ACTIVITY

The tunnelling projects considered by this paper are located in the Sydney Metropolitan area within the Sydney Basin. The basin comprises a thick sedimentary sequence of Permian-Triassic aged rocks (290 Ma – 200 Ma). The Sydney Basin experiences infrequent seismicity in comparison with other regions around the world as a consequence of its location away from plate tectonic boundaries. It has different levels of earthquake activity within its geographical extension. Greater levels occur at the south and west of the Sydney Basin.

Figure 1 shows the schematic location of the considered tunnels and the earthquake activity in the Sydney Basin from the earthquake catalogue collected by Allen et al (2011). The recorded earthquake activity shows:

1. All earthquakes with magnitude greater than three have been recorded more than 20 km from the tunnels.
2. Historical data shows that the maximum recorded magnitude in the Sydney Basin is (M_L) 5.6.

In the Sydney Basin it is difficult to link earthquakes with causative faults due to uncertainty in earthquake locations and incomplete knowledge of faults characteristics.

The majority of earthquakes occur under the Blue Mountains and have been associated with the Lapstone Structural Complex - LSC (Gibson, 2005; Clark, 2010). The LSC is approximately 25-30 km from the western end of the considered projects. A paleoseismological study by Clark (2010) estimates that maximum earthquake magnitudes ~M_w7.0 might occur on the LSC with an average frequency of between 1-2 million years (Clark, 2010).

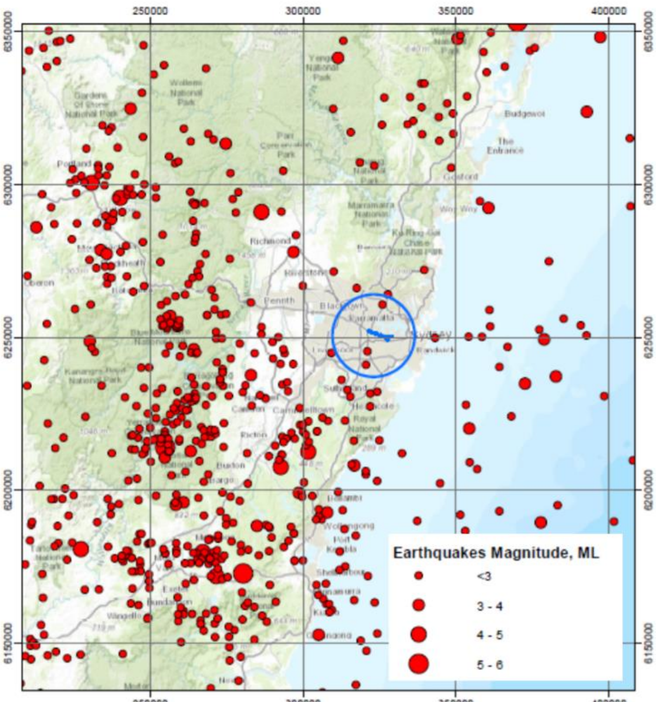

Figure 1. Recorded earthquake activity in the Sydney Basin. The schematic location of the tunnel alignments is shown as a blue line. The blue circle represents a distance of 20 km from the alignment.

Similarly, earthquake activity can also occur on other faults scattered across the Sydney Basin. Geological and seismological data collected from mining and tunnel excavations in the region were used by Berryman et al., (2009) to estimate the recurrence of damaging earthquakes on individual faults. Berryman et al. (2009) estimate that earthquakes with magnitude M_L5-6.0 occur on individual faults in the Sydney Basin once every several million years.

Based on the recognition that the recurrence on individual faults is likely to be in the order of millions of years (Berryman et al., 2009; Clark, 2010), a low seismic hazard is implied for the Sydney tunnels. This conclusion is in keeping with site investigations conducted for the considered projects, as no evidence of activity was observed on the faults located along the tunnel alignments.

3. SEISMIC DESIGN OF TUNNELS

The special characteristics of tunnels (underground, long structures) influence their response to earthquake ground shaking. These characteristics mean that tunnels typically experience a different seismic response to that of surface structures. There are several considerations that influence the seismic design of tunnels, including:

- The vast majority of Sydney tunnels are located in competent rock (i.e. competent shale or sandstone). During an earthquake, the tunnel moves together with the surrounding ground.
- Wave propagation imposes transit deformation in tunnels, not inertial forces as in surface structures. Therefore the design must ensure that the structure can sustain those deformations.
- The effects of rock-structure interaction can play an important role in tunnel performance during earthquake shaking. The relative stiffness of the tunnel support system and the surrounding ground influences the response.

- The earthquake excitation affecting the tunnel can be represented by a vertically propagating horizontally polarised shear wave incident from the bedrock (Wang, 1993; Pescara et al., 2011).
- Earthquake accelerations from AS1170.4 – 2007 correspond to motions expected on the ground surface. However, earthquake ground shaking decreases with depth and consequently earthquake shaking is expected to be lower at tunnel depth (Power et al., 1996).
- Response of tunnel to seismic shaking can be explained in terms of three principal types of deformation (Wang, 1993; Hashash et al., 2001):
  - axial
  - curvature
  - ovaling/racking deformation (Figure 2)
- Axial and curvature deformations are induced by components of seismic waves that propagate along the longitudinal axis and/or by spatially varying ground motions resulting from local soil/site effects.
- Ovaling/racking deformation is caused by seismic waves propagating perpendicular to the tunnel longitudinal axis.

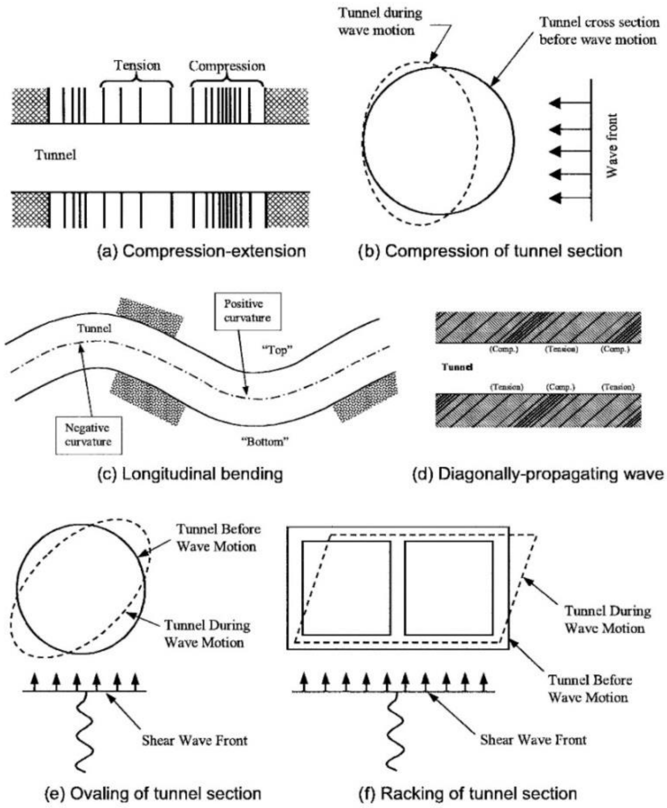

Figure 2. Deformation modes of tunnels due to seismic waves (Hashash et al., 2011).

4. SELECTION OF DESIGN EARTHQUAKES

The considered tunnel projects adopted a two-level seismic design criterion. The first level design is aimed at continuous operation and a second design level is aimed at life safety (no collapse). The two-level design approach requires the definition of two design earthquakes: the Operating Design Earthquake (ODE) and the Maximum Considered Earthquake (MCE), which had previously been referred to as the Maximum Design Earthquake (MDE).

Due to the lack of specific definitions for the ODE and the MCE for tunnels in Australia, the definitions by Hashash et al. (2001) have been adopted.

Accordingly, the ODE is assumed to be the earthquake that can be expected to occur at least once during the design life of the tunnel (e.g. an event with probability of exceedance between 40-50%). Considering a design life of tunnels of 100 years, the ODE is an earthquake with return period between 150 and 200 years. Hence, the ODE is selected as the earthquake expected with a return period of 200 years.

Similarly, the MCE is the defined as the maximum level of shaking that can be experienced at the site from deterministic seismic hazard assessment (earthquake scenarios) or the event with a 3-5% probability of exceedance during the life of the facility. Therefore, for the Sydney region the MCE is selected as the earthquake with return period of 2500 years (equivalent to an earthquake with 4% of probability of exceedance in the design life of the tunnels, 100 years).

Table 1 shows the expected peak ground acceleration (PGA) values associated for bedrock in Sydney with return periods representing the ODE (200 years) and the MCE (2,500 years) according to the current Australian Standard for Earthquake Load (AS 1170.4 -2007).

TABLE 1.
EXPECTED PGA ASSOCIATED WITH ODE AND MDE (BASED ON AS 1170.4 – 2007)

ODE PGA	MCE PGA
0.056 g	0.144 g

5. EARTHQUAKE SCENARIOS

The ground motion associated with the MCE can also be estimated by assessing earthquake scenarios.

For the considered tunnelling projects the selection of the earthquake scenarios was based on the seismotectonic setting of the Sydney Basin, the recorded earthquake activity and the current knowledge of geological faults in the region.

Two earthquake scenarios were assessed:

1. M_w 7.0 earthquake generated at the LSC (at ~30 km from the western end of the tunnel alignments).
2. M_w 6.0 earthquake generated at a distance of 20 km from the tunnel alignments.

The following parameters were included in the assessment of the earthquake scenarios:

- The (non-cratonic) ground motion prediction equations (GMPE) developed by Somerville et al. (2009) for Australia and the GMPE developed for Eastern North America (ENA) by Atkinson and Boore (2006). The ENA equations are included because they were developed from a similar tectonic setting to Australia.

- The causative faults were modelled to have reverse displacement (based on the current compressive stress regime of the eastern Australia). The tunnel alignment was assumed to be located on the hanging wall.
- The site was assumed to be shale or sandstone rock and was represented by shear wave velocities (Vs) greater than 800 m/s.

Table 2 shows the PGA and peak ground velocity (PGV) estimated from the earthquake scenarios. The mean and 84th percentile values are shown for a site condition with Vs>800 m/s.

TABLE 2
ESTIMATED PGA AND PGV VALUES (BASED ON EARTHQUAKE SCENARIOS)

EARTHQUAKE SCENARIO	PGA [G]		PGV [CM/S]
	Mean	84th percentile	84th percentile
Mw 7.0 on the LSC	0.12 (average)[1]	0.23 (average)[1]	19
Mw 6.0 at 20 km	0.11	0.2	9

[1] Average value calculated along the tunnel alignment.

The PGA values estimated from both earthquake scenarios are roughly equivalent to the PGA values based on AS1170.4 – 2007 with the selected MCE (i.e. 0.144 g). Consequently, the selection of the MCE as the event with 2500 years return period was deemed appropriate.

It has been reported that in addition to PGA, other type of ground motions such as PGV and peak ground displacement (PGD) also correlate to earthquake damage to underground structures (Hashash et al., 2001).

Table 3 present the PGA, PGV and PGD values associated with the selected ODE and the MCE. The selection of the PGV was based on the PGV/PGA ratios estimated from the earthquake scenarios and also by Wilson et al (2008) who reported that in AS 1170.4 -2007 a PGA value of 0.1g is equivalent to a PGV of 7.5 cm/s.

Similarly, the selection of the PGD was based on results from processing of earthquake acceleration time histories from earthquakes with similar characteristics to those expected in Sydney and also from the PGD/PGA ratios proposed by Powers et al (1996).

TABLE 3
PGA, PGV and PGD ASSOCIATED WITH THE OBE AND MDE

DESIGN EARTHQUAKE	RETURN PERIOD, YEARS	PGA (g)	PGV (cm/s)	PGD (cm)
ODE	200	0.056	4.2	1.7
MDE	2500	0.144	10.8	4.3

6. SEISMIC DESIGN APPROACH

The above earthquake parameters were used as input to assess the seismically induced axial, curvature and raking deformation of the tunnels. This section shows examples of the general methods applied to evaluate the performance of the tunnels under seismic loads but is not intended to provide the detailed procedure used for the analysis.

Closed Form Solutions for Axial and Curvature Deformation

A simplified closed form elastic solution is used to estimate the tunnel's axial and curvature deformations. This simplified method assumes the tunnel as an elastic beam subjected to the same seismic wave amplitudes at all locations. The maximum strain at the critical incidence angle of the seismic wave is used in the calculations (Hashash et al., 2011). An example of the equations used in the analysis is presented below:

The longitudinal strain (ε_{ab}) due to S-waves

$$\varepsilon_{ab} = \left(\frac{V_s}{C_s} sin\phi cos\phi + \frac{r a_s}{C_s^2} \cos^3 \phi \right)$$

Where:

- r is the equivalent radius at tunnel cross section of interest
- C_S is the S-wave velocity
- V_s is the peak ground velocity (PGV) for MCE at tunnel depth
- a_s is the peak ground acceleration (PGA) for MCE at tunnel depth
- ϕ is the angle of incidence of wave with respect to the tunnel taken as 0.74 radians to maximise strain.

Numerical Modelling for Raking Analysis

Raking of the tunnel lining imposed by seismic waves is assessed by numerical modelling. The following input parameters are included in the analysis:

- The geometry of the cross section of the tunnel
- The site specific geotechnical ground conditions
- The properties of the tunnel lining
- The calculated shear (horizontal) displacements based on the maximum free-field shear strain applied to the tunnel boundaries. The shear displacement is a function of the shear wave velocity and the PGV.

Figure 3 shows an example of the numerical model used for raking analysis.

A full dynamic analysis, using earthquake time histories representing the design earthquakes was not undertaken for the considered projects. According to Wang (1993) and Hashash et al (2001), the use of the closed form elastic solutions and numerical analysis is adequate when the earthquake shaking intensity is low and/or the ground is very stiff. Consequently, the methodology applied for the seismic design of recent tunnels in Sydney is considered to be appropriate for Sydney conditions. Notwithstanding this, full dynamic analyses are being considered for future development.

Material Name	Color	Elastic Type	Young's Modulus (MPa)	Poisson's Ratio	Material Type
Residual soil		Isotropic	325	0.3	Elastic
Shale IV/V		Isotropic	950	0.3	Elastic
Shale III		Isotropic	3170	0.25	Elastic
Shale I/II		Isotropic	6270	0.25	Elastic

Liner Name	Color	Type	Young's Modulus (MPa)	Poisson's Ratio	Material Type	Thickness (m)
Shotcrete		Standard Beam	32000	0.2	Elastic	0.25

Joint Name	Color	Slip Criterion	Tensile Strength (MPa)	Peak Cohesion (MPa)	Peak Friction Angle (deg)	Normal Stiffness (MPa/m)	Shear Stiffness (MPa/m)
Slip interface		Mohr_Coulomb	0	0	20	2000	1000

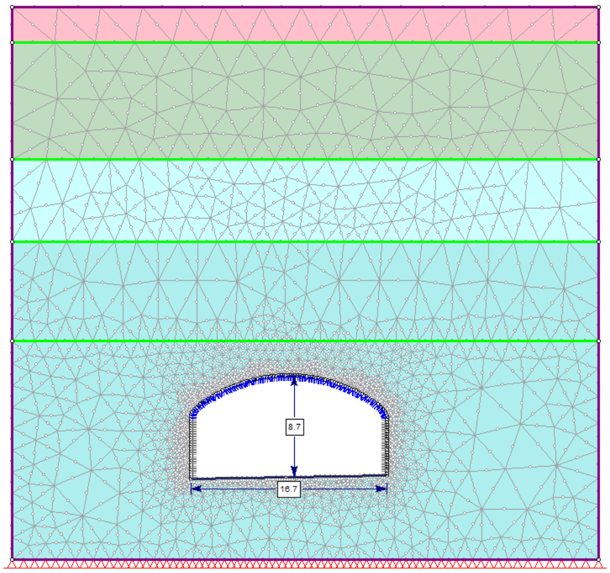

Figure 3. Example of model geometry used for numerical analysis of racking deformation.

7. CONCLUSIONS

Recent tunnelling projects in the Sydney region have included the evaluation of tunnel performance under earthquake loads in their design. The selection of appropriate design earthquakes was challenging due to: the lack of or vague definitions of design earthquakes for tunnels in Australia and the uncertainties imposed by the long recurrence characteristics of the earthquakes in the Sydney region.

For the considered projects, two design earthquakes were contemplated: the ODE and MCE. The MCE was selected as the earthquake with 2500 years return period. The selection of this event was complemented with site specific assessments of earthquake scenarios.

The earthquake parameters associated with the ODE and MCE were used to evaluate the seismically induced axial, curvature and raking deformation in the tunnel by applying close form solutions and numerical analysis.

It is expected that full dynamic analyses are the next step in the seismic design of Sydney tunnels.

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