The use and performance of precast concrete tunnel linings in seismic areas

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Abstract: Many large cities around the world are subjected to seismic ground shaking. As these cities grow, more and more tunnels will be constructed to facilitate the movement of people, goods, and services. The purpose of this paper is to discuss the use and performance of precast concrete tunnel linings (PCTL) in seismic areas. Use of one-pass PCTL has become the most favoured lining type for closed-face soft ground tunnelling, due to the overall value added to the project. However, the seismic behaviour of PCTL segments is not well understood, and the volume of published work on the subject is relatively thin. This paper is intended to bridge the gap between the theory of PCTL design and the performance of the lining during earthquake shaking.

An extensive literature search was conducted to find tunnel inspection reports from various earthquakes that have occurred in urban areas over the past 25 years. PCTL performance in earthquakes is then reviewed based upon available data. Because earthquake reconnaissance reports typically focus on poor performance, and the performance of PCTL tunnels has been good, there are only a few published inspection reports available. Another reason why case histories are not common is that PCTL were not widely used until the 1980s. Nevertheless, case histories of PCTL performance in the Kobe (1995), Athens (1999), and Hualien (2002) earthquakes are available. Lessons learned from these reports, and similarities between PCTL performance in earthquakes are presented.

PCTL segments have inherent advantages over other tunnel linings when subjected to earthquake shaking. These advantages are discussed and related to the case histories noted above. A discussion of important considerations and information needed from future earthquake reconnaissance reports and seismological data needed for design of PCTL in seismic areas is included.

Résumé: Plusieurs grandes villes du monde sont soumises à des secousses sismiques. Au cours de leur développement, de plus en plus de tunnels seront construits pour faciliter le déplacement des gens, des biens et des services. L'objectif de cet article est de discuter de l'utilisation et du rendement des revêtements de tunnel en béton préfabriqué (appelés en anglais precast concrete tunnel linings ou PCTL) dans les zone sismiques. L'installation instantanée du PCTL lors du creusement est devenue le type d'installation de prédilection pour l'excavation souterraine de tunnels en sol mou (closed-face), en raison de la valeur qu'il ajoute à un projet. Toutefois, le comportement sismique du PCTL n'est pas bien compris, et il existe peu de documentation écrite à ce sujet. Cet article vise à combler la lacune entre la théorie de la conception du PCTL et le rendement de ce revêtement durant les tremblements de terre.

Une vaste recherche bibliographique a été menée pour trouver des rapports d'inspection de tunnels se trouvant dans des zones urbaines touchées par des séismes au cours des 25 dernières années. La performance du PCTL lors des tremblements de terre est alors évaluée avec les données existantes. Comme les rapports de reconnaissance se penchent habituellement sur les piètres rendements et que les tunnels en PCTL font bonne figure, peu de rapports d'inspection sont disponibles. Le PCTL n'a commencé à être largement utilisé qu'au début des années 1980, ce qui peut également expliquer le faible volume de documentation. Néanmoins, quelques monographies sont disponibles sur la performance du PCTL lors des tremblements de terre à Kobe (1995), à Athènes (1999) et à Hualien (2002). Les leçons tirées de ces rapports ainsi que les similarités entre le rendement des PCTL lors des tremblements de terre sont présentées.

En comparaison des autres revêtements de tunnel, les segments du PCTL comportent des avantages inhérents lorsqu'ils sont soumis à des secousses sismiques. Dans l'article, ces avantages seront abordés et mis en relation avec les monographies énumérées ci-dessus. L'article examine également l'information qui devra être rapportée dans d'éventuels rapports de reconnaissance sur les tremblements de terre et les données sismologiques requises pour la conception de PCTL en région sismique.

Keywords: Earthquakes, seismic response, tunnels.

INTRODUCTION

Tunnel linings perform well in earthquakes because they are constrained by the ground around them. Between 1960 and 1990, the use of precast concrete segments replaced steel or cast iron segments as the most widely used lining for tunnels in soft ground. PCTL tunnels perform particularly well in earthquakes because of their circular, largely symmetrical shape, and because they are jointed and have ample flexibility.

The study has established a list of hundreds of applications of PCTL in seismically active areas by comparing historical earthquake records and seismic hazard maps with the location records of tunnels using PCTL systems. PCTL systems have been extensively used in seismically active locations in Japan, Venezuela, Puerto Rico, Iran, Taiwan, Mexico, Turkey, Spain, Italy, Greece, the United States and elsewhere. PCTL systems continue to be specified for bored tunnel construction in seismic areas.

This study summarizes the observed and documented performance of PCTL systems (particularly transit tunnels) where such systems have been subjected to significant seismic ground motions.

PRECAST CONCRETE TUNNEL LINING SYSTEMS

When utilizing a closed face tunnel boring machine (TBM) in soft ground (soils) beneath the water table, it is necessary to install a lining concurrent with TBM advance to stabilize the ground and limit groundwater inflow into the tunnel excavation (see Figure 1). Gasketed, pre-cast concrete segmental rings are frequently used as a single-pass lining. When using a single-pass system, the lining installed in the TBM tail shield acts as both initial and final support and is utilized as a reaction block that the TBM can thrust against to continue the installation process.

Precast concrete tunnel linings were used for the first time in Great Britain in the 1930s, in North America in the mid 1960s, and entered widespread use in the 1980s. The driving reason for use of precast concrete instead of cast iron lining was the cost. The cost differential was initially small, but precast concrete lining segments are now roughly one-third to one-fourth of the cost of comparable cast iron or steel segments. By 1990, precast concrete segments became the most widely used lining for tunnels in soft ground. The cost advantage of precast concrete lining segments has increased with the high shove forces needed for increasingly larger closed face TBMs. PCTL systems are the most suitable system for public transit projects, including highway and rail, due to their construction efficiency and superior long-term performance.

The adoption of PCTL lining systems for tunnels in the United States has been slower than in Europe, Japan and elsewhere. It is only in the past two decades that PCTL systems have gained widespread use throughout the United States including seismically active areas such as Seattle, Portland, San Diego and Los Angeles for sewage, water transport, and highway and transit applications. PCTL systems are currently being designed for highway and rail transit applications in seismic zones, including the San Francisco Bay, San Diego, and Los Angeles areas.

Figure 1. Precast Concrete Tunnel Segments (PCTL) Being Loaded onto a Segment Car

In addition to seismic areas in the United States, PCTL systems have been extensively used in seismically active locations in Japan, Venezuela, Puerto Rico, Iran, Taiwan, Mexico, Turkey, Spain, Italy, Greece, and elsewhere. Due to the flexible nature of PCTL segmental systems relative to the stiffness of the ground mass, the circular tunnel shape and the depth of the tunnels; they have demonstrated excellent performance when subjected to shaking during seismic events. PCTL systems continue to be specified for bored tunnel construction in seismic areas.

The flexibility of the individual segments themselves is achieved through steel reinforcing bars (rebar) or steel fibre reinforcing and flexibility of the overall structural system is achieved through joints between the segments that accommodate deformations with little or no damage. In addition, joint contact areas contain packing materials that cushion segments and preclude high contact stresses. When they occur, tensile strains are accommodated by ring pre-compression due to ground and TBM thrust loadings. Inter-segment connecting devices such as dowels, bolts, and guide-rods (largely used for convenience during construction) maintain segment alignment and provide a level of redundancy with respect to stability of the segment positions. Assembled segments in a tunnel are shown on Figure 2.

Figure 2. Assembled PCTL Segments in a Tunnel

STUDY CRITERIA

An extensive literature search was conducted to evaluate the use of PCTL tunnels in seismic areas and PCTL performance in seismic events. Project specific literature search criteria were developed to match key criteria relevant to this study, which include the following:

- Projects designed before 1980 were generally not reviewed. This criterion was used because PCTL were not widely used before about 1980, and the design and fabrication of PCTL has changed significantly since that date.
- Tunnels smaller than 3 metres (9.8 feet) in diameter were not reviewed as PCTL lining systems are not installed as frequently in smaller tunnels.
- Tunnels in areas that have not exhibited significant seismicity were not reviewed. This includes most of Europe, the Eastern United States, Eastern Canada and other areas.
- For the purposes of this study, earthquakes smaller than magnitude 6.0 were not reviewed unless they caused significant shaking or damage in urban areas. For the purpose of this study, the term "significant seismic event" refers to earthquakes larger than magnitude 6.0. This study typically uses the term "magnitude" to refer to the moment magnitude (M_w) measurement of earthquake shaking unless otherwise noted.
- Only tunnels located in areas with peak horizontal ground accelerations (PHGA) in excess of the 0.16g contour, were considered further. The 0.16g contour was based on a 10% probability of being exceeded in 50 years by a probabilistic seismic hazard analysis (PSHA). This probability equates to a 475 year return period. Accelerations were obtained from Global Seismic Hazard Maps available from the United States Geological Survey (USGS), California Geological Survey (CGS), and the Global Seismic Hazard Assessment Program (GSHAP). These maps are discussed further below.

Tunnel Data Sets Reviewed

Tunnel locations and details regarding construction and performance were reviewed from a variety of sources. The three main groups of data reviewed for this study are outlined below:

- TBM production records and tunnel construction logs from companies that manufacture TBMs, including Kawasaki Corporation, Herrenknecht AG, and Lovat Incorporated. The Kawasaki data set includes some 720 records. A majority of these records are for PCTL tunnels constructed in seismic areas. This data set is also specific to tunnels constructed in soft ground. A separate data set from Kawasaki exists for rock tunnels, but this data set was not reviewed as part of this study.
- Tunnel data included in a draft report entitled "Summary and evaluation of procedures for the seismic design of tunnels" (Power et al, 1998). This data includes 204 tunnels constructed using a variety of lining types that experienced shaking in earthquakes.
- Data compiled by Hatch Mott MacDonald (HMM) from a variety of sources, including project design records, articles from various industry publications, and technical papers. This data includes 184 PCTL tunnels constructed around the world during the past 12 years.

Earthquake Data Reviewed

Once tunnel locations were established, they were cross-referenced against earthquakes to identify tunnels that experienced significant seismic ground motions. As part of this process, earthquake reconnaissance reports were reviewed. Earthquake reconnaissance reports are prepared by a variety of organizations, and prove invaluable for studies that relate to seismic performance of structures, in addition to the evaluation of other seismic hazards. In contrast to other structures, documentation in the literature of the observed performance of tunnels in seismic events is somewhat limited. This is for two reasons:

- Most tunnels in seismically active regions have not yet experienced significant-enough seismic events to warrant inspection; and
- Inspection and documentation during significant seismic events only cover instances of significant damage – generally, facilities where no damage occurred go unreported.

To establish the performance of mined tunnels (soft ground and hard rock using PCTL and other lining systems) during seismic events, significant earthquakes in urban areas were identified as part of this study. Urban centres reviewed for this study were located in the following countries grouped by continent:

Asia
China, India (Northwest), Iran, Japan, Indonesia, Philippines, Taiwan, Turkmenistan, Turkey
Europe
Greece, Italy (Peninsula), Spain, Portugal
North America
Canada (west coast), Mexico, USA (west coast)
South America
Colombia, Venezuela

Mined tunnels in general (i.e. with or without PCTLs) have historically performed very well during seismic events. In order to demonstrate the inherent stability of tunnels in seismic events, earthquake reconnaissance reports were reviewed to evaluate the post-seismic event condition of tunnels that experienced shaking. A summary of results of tunnel performance is included on Table 1.

Table 1. Summary of Tunnel Performance during Selected Seismic Events

Date	Earthquake Location	Magnitude*	Earthquake Tunnel Damage Assessment	Source(s)
11/23/80	Campania-Basilicata, Italy	7.0 (M_s)	No damage	Stratta et al, 1981
9/19/85	Michoacan, Mexico	8.1	No damage to Underground Metro in Mexico City	Ayala and O'Rourke, 1989
10/17/89	Loma Prieta, CA	6.9	No reports of damage to tunnels	Power et al, 1998
4/25/92	Petrolia, CA	7.2	No PCTL tunnels existed in area, other tunnels were damaged	Power et al, 1998
7/12/93	Hokkaido, Japan	7.7	No reports of damage to tunnels†	Power et al, 1998
1/17/94	Northridge, CA	6.7	No damage to PCTL tunnels	This study‡
1/17/95	Kobe, Japan	6.9	No reports of damage to PCTL tunnels, other tunnels were damaged	Power et al, 1998 (p.30)
8/17/99	Izmit (Kocaeli), Turkey	7.4	No reports of damage to tunnels	EERI, 2000
9/7/99	Athens, Greece	5.9	No reports of damage to tunnels	EERI, 1999
9/21/99	Chi Chi, Taiwan	7.5	No reports of damage to PCTL tunnels, other tunnels were damaged	EERI, 2001
2/28/01	Nisqually, Washington, USA	6.8	No reports of damage to tunnels	This study‡
10/23/04	Niigata Prefecture, Japan	6.6	Several tunnels were damaged, final report not available§	EERI, 2005

* Magnitudes are M_w = moment magnitude, unless otherwise noted.
† Damage to a talus shed (which is part of the portal to the Shiroito Tunnel) is reported in the EERI reconnaissance report (EERI, 1995b). The talus shed collapsed due to a rockfall larger than that which the shed was designed for. This is sometimes incorrectly referred to as a tunnel collapse.
‡ No damage to tunnels was described or noted in reconnaissance reports and other literature reviewed for this study.
§ Several tunnels were reportedly damaged in the Niigata Ken Chetsu earthquake of October 23, 2004. A review of photographs in preliminary reports does not show any PCTL lined tunnels. However, these photographs are not comprehensive and the final reconnaissance report was not available at the time this paper was prepared.

PCTL USE IN EARTHQUAKE PRONE URBAN AREAS

To illustrate the frequency of PCTL use in earthquake prone areas, a selection of transit tunnels was reviewed. PCTL linings are currently planned, or are already in use in most major transit systems in seismically active areas around the world. A map showing global seismicity (Figure 3) was used as the basis for selection of the geographical areas to focus on. A few significant examples of PCTL use in seismic zones are listed on Table 2, showing the widespread use of PCTL worldwide. Most of these tunnels were identified using information obtained from three TBM manufacturers: Lovat of Canada, Herrenknecht of Germany and Kawasaki of Japan. Other manufacturers could have been added, but ample cases were derived from these manufacturers to develop the conclusions described in this study.

Table 2. Recent Use of PCTL for Transit Tunnels in Seismically Active Areas

Project	**Type**	**Location**	**Diameter**	**Year**	**PSHA Ground Acceleration***	**Reference**
Taipei Metro	Metro	Taiwan	6 m (19.7 ft) OD	1987-1996	>0.48g	World Tunnelling, 1994b
Athens Metro	Metro	Greece	8.5 m (27.9 ft)	1991-1999	0.24g	T&T International, 1996
Barcelona Metro	Metro	Spain	10.9 m (35.8 ft)	2002	0.16g	T&T International, 2002
Turin Metro	Metro	Italy	6.9 m (22.6 ft)	2003	0.16g	T&T International, 2003
Tehran Metro	Metro	Iran	6.0 m (19.8 ft)	1997	>0.48g	Lovat News Release
Shiraz Metro	Metro	Iran	6.0 m (19.7 ft)	2004	0.41g	T&TC, 2004
Metropolitano de Lisboa	Metro	Lisbon, Portugal	9.8 m (32.1 ft) OD	Under construction	0.16g	Lovat News Release
Passante Ferroviario	High-speed railway	Bologna, Italy	9.4 m (30.8 ft)	2001	0.41g	Lovat News Release
Istanbul Metro Extension	Metro	Istanbul, Turkey	6.5 m (21.3 ft) OD	Under construction	>0.48g	Lovat News Release
Marmaray Bosphorus Crossing	Rail	Bosphorus, Turkey	8.0 m (26.2 ft) OD	Under construction	>0.48g	Lovat News Release
Ankara Metro Sogutozu-Kizilay	Metro	Ankara, Turkey	5.9 m (19.3 ft) OD	Under construction	0.24g	Lovat News Release
Metro Caracas Linea 3	Metro	Caracas, Venezuela	5.8m (19 ft) OD	Under construction	0.4g	Lovat News Release
LA Metro Gold Line	Metro	Los Angeles, CA	5.8m (19 ft) OD	Under construction	Design levels: 0.41and 0.79g Result from mapping: 0.70g	Law/Crandall (2003)

* This column indicates results of Probabilistic Seismic Hazard Assessment (PSHA) mapping from a variety of sources for an event with a 10% probability of being exceeded in 50 years, unless otherwise noted.

Ground accelerations noted on the above tables are based on available probabilistic seismic hazard acceleration (PSHA) maps. Probabilistic seismic hazard evaluation techniques were developed to assess hazards based on possible earthquake magnitudes, source-site distances, and probabilistic analyses. PSHA was first developed by Cornell (1968) and is further described in a 1997 SSHAC report, in addition to numerous other papers. PSHA maps are commonly available through GSHAP, CGS, USGS, and other agencies. The GSHAP maps were developed under the auspices of the United Nations and are available at http://www.seismo.ethz.ch/GSHAP/. CGS maps cover the State of California and are available through the CGS webpage (see Figure 4). A sample PSHA map from CGS, centred around San Jose, California is shown on Figure 4. Resulting accelerations from PSHA analyses are referenced to probabilities for a given recurrence interval of seismic event. To facilitate comparison between the various maps, accelerations were based on a 10% probability of being exceeded in 50-years, which corresponds to a recurrence interval of 475-years. The accelerations in Table 2 from PSHA analyses are ground surface accelerations and some attenuation of these motions can be expected at tunnel depth.

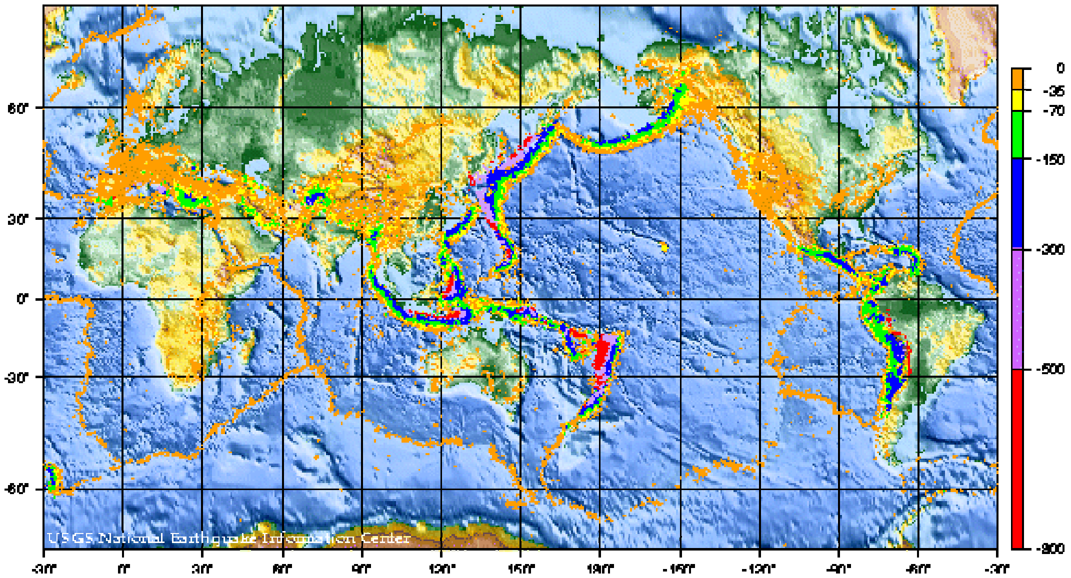

Figure 3. Global Seismicity From 1990-2000
Source: USGS, http://wwwneic.cr.usgs.gov/neis/general/seismicity/world.html

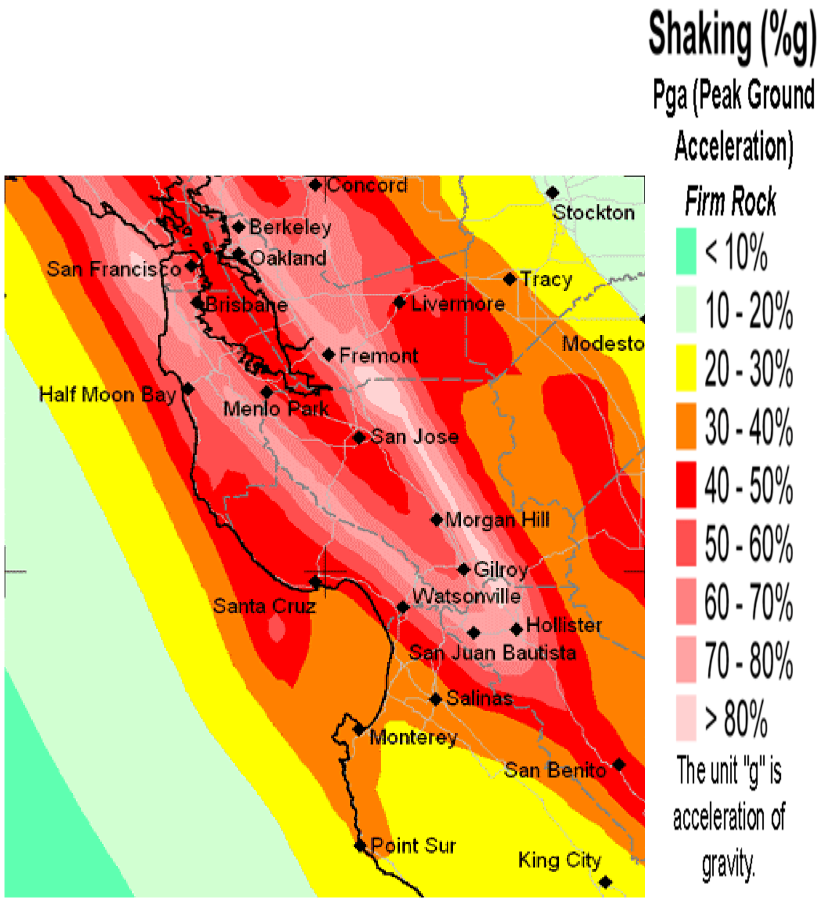

Figure 4. PSHA Map of San Jose Area
Based on the USGS/CGS Probabilistic Seismic Hazards Assessment (PSHA) Model, 2002 (revised April 2003), 10% Probability of Being Exceeded in 50 years. Source: CGS, http://www.consrv.ca.gov/cgs/rghm/pshamap/pshamain.html

PCTL EARTHQUAKE PERFORMANCE - CASE HISTORIES

While selected TBM construction records exist from tunnel boring machine manufacturers, these records largely do not include details regarding the tunnel lining system. As a result, tunnel inspection reports often need to be compared with installation records and other sources to determine the lining type.

Once a list of PCTL tunnels in seismic areas was established, tunnels were cross-referenced to seismic events. A list of significant seismic events that occurred in these areas over the past 25 years was developed to assist with identification of specific tunnel projects that experienced seismic ground motions. Tunnels in the vicinity of previous seismic events were examined in more detail to estimate peak ground surface accelerations in the vicinity of the tunnel. Available reconnaissance reports and technical papers were reviewed to ascertain whether tunnels were inspected, and if so, the condition of the tunnel after the seismic event. The result of this search yielded case histories of PCTL tunnels that had experienced significant seismic ground motions. Four of these case histories are summarized on Table 3 below and are discussed in more detail in following sections. It became evident during this study that there is very limited documentation of PCTL performance in seismic events, despite the fact that many more than four PCTL tunnels are likely to have experienced ground motions comparable to those shown on Table 3.

Table 3. PCTL Earthquake Performance Case Histories

Tunnel	Earthquake	Earthquake Date	Surface Horizontal Acceleration Near Tunnel (g)	Post Event Tunnel Condition	Source(s)
LA Metro	Northridge	1/17/94	0.4	No Damage	Monsees and Elioff, 1999 and EERI, 1995
Isobe Dori Shield Tunnel	Kobe	1/17/95	0.5*	Some Spalling at Segment Joints	JSCE, 1995
Athens Metro	Athens	9/7/99	0.25†	No Damage	EERI, 1999
Taipei Metro	Hualien	3/31/02	0.20	No Damage	Taipei Times, 2002

* A range of accelerations are available - see discussion below.
† This acceleration was measured within a Metro station.

LA Metro

Strong shaking occurred in the LA Metro tunnels resulting from the Northridge Earthquake of 1994, which struck at 4:31AM local time and had a moment magnitude of 6.7. The earthquake caused 57 fatalities and over 5,000 injuries. Property damage was estimated at $20 billion, the costliest natural disaster in the history of the United States at that time. The hypocentre of the earthquake was located in the San Fernando Valley, approximately 32 km (20 miles) northwest of Los Angeles (EERI, 1995).

Earthquake design criteria for the LA Metro was developed for both Operating Design Earthquake (ODE) and Maximum Design Earthquake (MDE) events. The shaking during the Northridge Earthquake corresponded to the ODE event, and there was no damage to the PCTL lining system that was under construction in the Los Angeles Basin portion of the new LA Metro Red Line segment. PCTL tunnelling in the San Fernando Valley did not start until after the earthquake. The Red Line was designed to have a two-pass lining, due to the presence of hazardous gasses along the alignment. The internal lining had not been installed at the time of the earthquake so earthquake loading of the tunnel lining was borne solely by the PCTL.

The maximum shaking measured within the Red Line tunnels was 0.27g for this event. (EERI, 1995 and Monsees and Elioff, 1999). The 0.4g surface acceleration estimate indicated on Table 3 is derived from a shake map by Stewart et al, which is included as Figure 5 below (EERI, 1995). The acceleration within the tunnels is lower than 0.4g due to attenuation that occurs with depth. This figure includes the location of the Red Line, which is located entirely underground, superimposed on the original base map.

Isobe Dore Shield Tunnel

The Isobe Dore Shield Tunnel was under construction at the time of the Kobe Earthquake of January 17, 1995. The Kobe Earthquake had a moment magnitude of 6.9, and struck directly beneath the densely populated City of Kobe. The earthquake caused over 5,500 fatalities and over 26,000 injuries. Property damage was estimated at US$200 billion (EERC, 1995).

The Isobe Dore Shield Tunnel, owned by Kansai Electric Power Company, was under construction at the time of the Kobe Earthquake. Installation of the 4.95 m diameter PCTL tunnel had been completed along the length of the tunnel (931 m) at the time of the earthquake. The design included construction of a concrete invert, although construction of the invert had not started at the time of the earthquake. Therefore, earthquake ground motions were resisted solely by the PCTL lining. Cracks 0.2mm wide were observed in the shafts, but the tunnel itself remained intact, with only some spalling observed after the event. The damage report stated the following (JSCE, 1995, p.152): *"…there was some spalling in the grooves in the segments between segment rings; otherwise the structure remained undamaged…"*

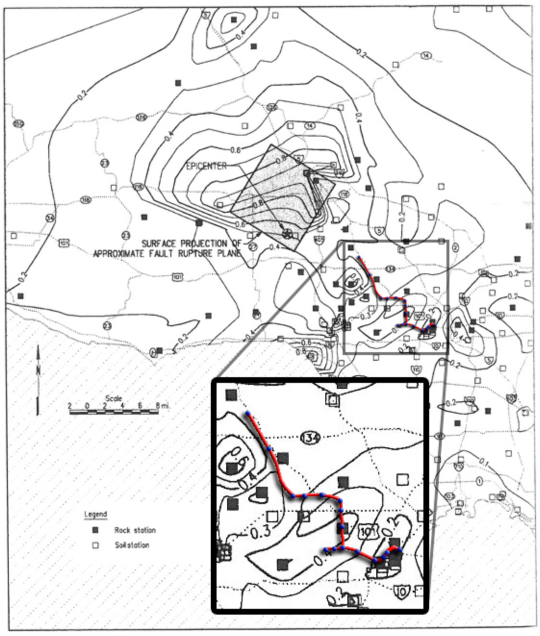

Figure 5. Northridge Earthquake Shake Map with Metro Red Line Tunnel Locations
Base map source: EERI, 1995, after Stewart et al, 1994

Figure 6 shows the post-earthquake condition of the tunnel during the inspections. Accelerations in the vicinity of the tunnel vary. Ground conditions at the tunnel consisted of very dense gravel with groundwater 1.8 to 3.0 metres (6 to 10 feet) below the ground surface (JSCE, 1995). The tunnel depth ranged from approximately 21 to 28m (69 to 92 feet) below the ground surface with a riser section from approximately 17 to 21 metres (56 to 69 feet) below the ground surface. Shake maps indicate a horizontal PGA of approximately 0.5g, so this is the value reported on Table 3 above. This value is likely to be conservative, as most nearby strong motion stations reported readings well in excess of 0.5g.

Figure 6. Post Earthquake Inspection of the Isobe Dori Shield Tunnel, Kobe, Japan
Source: JSCE, 1995

Athens Metro

No damage was reported to any of the Athens Metro tunnels in the Athens Earthquake of September 7, 1999 (EERI, 1999a). The earthquake, which had a moment magnitude of 5.9, struck at 2:56PM local time with an epicentre located in the northwest portion of Athens. The earthquake caused 147 fatalities and hundreds of injuries. (ITSAK, 1999). Although it had a magnitude less than 6.0, the Athens Earthquake is included in this study because significant damage occurred.

Unfortunately, the closest strong motion recordings were from around 10 km from the epicentre. Data from 14 strong motion recordings between 10 and 20 km from the epicentre indicate peak horizontal ground accelerations ranging from 0.04 to 0.35g (a recording of 0.53g is regarded to be anomalous due to site specific ground motion amplification). EERI noted that peak ground accelerations may have exceeded 0.5g in the epicentral area. The Athens Metro tunnels are known to be constructed using PCTL and limited information regarding the segment design for the tunnels is to be found in World Tunnelling (World Tunnelling, 1994a).

Several of the strong motion recording stations were located in Metro stations. The largest horizontal level of shaking of 0.25g, measured within the Sepolia Station, is reported on Table 3 above. Accelerations in other stations close to the epicentre may have been higher, but were not recorded during the event.

Taipei Metro

The Chi-Chi earthquake had a moment magnitude of 7.6 and struck at 1:47 am local time on March 31, 2002. The epicentre was located near the town of Chi-Chi in central Taiwan. The earthquake caused 2,415 fatalities and 1,441 injuries. Total damages, including property damage and lost productivity, were estimated at US$20 to 30 billion (EERI, 1999b). While the epicentre was 150km (90 miles) South of the capital city of Taipei, significant seismic ground accelerations were recorded in Taipei and the Taipei Metro system experienced ground motions resulting from the earthquake.

The Taipei Times reported that the Metro was stopped for inspection at the time of the earthquake. Metro Service was restored by 7:30 pm on the same day (Taipei Times, 2002). Peak horizontal ground acceleration was measured from a seismograph, Station TAP022, in downtown Taipei. (Taiwan Institute of Earth Sciences, 2002). The peak ground acceleration from this station is reported on Table 3 as 0.2g. The Metro tunnels are known to be constructed using PCTL, and limited information regarding the segment design for the Taipei Metro is included in World Tunneling (World Tunneling, 1994b).

PCTL DESIGN CONSIDERATIONS

PCTL are robust systems when subjected to seismic loading for several reasons. PCTL are subjected to significant loads during construction due to thrust loads exerted by the tunnel boring machine. Higher than specified concrete strengths may be used to reduce curing time so that more segments can be produced with fewer precast segment moulds. The result is that the compressive strength and thickness of the lining are typically more than sufficient to resist the static and seismic loads imposed on them. Tensile strain induced by seismic waves passing through the ground can be distributed to the joints between the PCTL segments, thereby minimizing tensile stresses within the segments themselves.

For purposes of evaluating tunnel performance, the intensity of ground shaking is typically quantified by peak ground acceleration (PGA), peak ground velocity, peak ground displacement, and strong motion duration. For initial assessments of potential seismic effects, PGA at the ground surface is usually used as an index of the shaking intensity, because acceleration is the parameter usually recorded and most readily estimated at the ground surface. A classic presentation of the performance of different types of tunnels that experience shaking is plotted against peak horizontal ground acceleration by Power et. al. (1998), with further updates by Asakura and Sato (1998). While performance of PCTL was not specifically investigated by these authors. Instead, PCTL performance is grouped within the larger category of reinforced concrete linings. It is apparent from these studies that significant damage to concrete lined tunnels is not typically experienced where peak ground acceleration is less than 0.4 to 0.5g. It is also apparent that reinforced concrete lined tunnels perform better than unreinforced concrete lined tunnels. The seismic performance of PCTLs summarized on Table 3 can be used to supplement the data from Power et al (1998) and Asakura and Sato (1998) specifically for PCTLs. This data, although very limited, indicates the generalized threshold between none to slight damage in terms of PGA may be in the vicinity of 0.5g for PCTLs.

Where a seismic analysis of PCTL is warranted, the anticipated ground displacement at tunnel depth is most important to design. Ground displacement can be higher within 15 to 20 km of the epicentre where near field ground motion effects must be considered. The most critical seismic design case often results from the combination of static loads and seismic load induced by vertically propagating shear waves. Free field peak shear strain, seismic deformation modulus and poisson's ratio of the soil are geotechnical parameters needed for a basic analysis.

INFORMATION NEEDED FROM FUTURE EARTHQUAKE RECONNAISSANCE REPORTS

It would be useful to develop standard tunnel reconnaissance procedures for use by post-earthquake reconnaissance teams. Such a procedure would be a guideline for reconnaissance, not a directive, as each tunnel is unique, and the range of items that could be noted in a reconnaissance is variable and cannot be predicted. However, the collection of certain types of data would prove very useful over time as more and more records are gathered. Ultimately, these records could be compiled into a tunnel earthquake performance database, which would prove useful as a design aid for future work. It is important to note that it is generally not possible during a reconnaissance to gather large amounts of data or conduct geotechnical and geological explorations. As a result, it is important that the required data be limited to that which is of sufficient importance to warrant use of limited reconnaissance time in the field.

The most important data that could be collected can be grouped into two main categories; (1) information related to tunnel design and construction and (2) information needed to estimate ground motions at the tunnel itself. A third category is also presented below for information that would be useful, if time permits during the reconnaissance programme. Item two is quite important because information regarding ground motions is typically given at seismographs that are often not within tunnels. If enough geologic and geotechnical and location information is provided in the reconnaissance report, estimates of ground motions within the tunnel itself can be made. Consideration was given to data needed to estimate ground deformation or strain, as this is an important parameter needed to evaluate post-earthquake tunnel performance.

Information related to tunnel design and construction includes the following:

- Tunnel lining type,
- Documentation of tunnel inspection results, *even if good performance is observed* (good performance is typically not documented today),
- Tunnel use (highway, rail, utility, etc...),
- Longitude and latitude, street address, or other identifiable location data of tunnel portals. This would facilitate future research and comparison with maps by outside researchers, who may not have the time or resources to conduct subsequent site reconnaissance. This is typically not done today.

Information needed to estimate the ground deformation at the tunnel itself includes:

- Subsurface conditions at the tunnel,
- Ground motions, location, and ground conditions at the nearest seismograph, including enough information to estimate peak particle velocity and free field seismic shear strain,
- Distance from at least one identifiable part of the tunnel (portals, midpoint, or other identifiable locations) to the nearest seismograph(s),

Time permitting, documentation should also include:

- Tunnel length and diameter,
- Depth to bedrock,
- Tunnel owner,
- Construction details (locations of plans or construction records) and construction method, and
- Lining as-built drawing showing PCTL general arrangement, thickness, concrete strength, reinforcing, and connection details, and
- Summary of external design load cases.

SEISMOLOGICAL DATA NEEDS

Questions still exist regarding the attenuation of ground motions from the surface to tunnel depth. Although rules of thumb have been developed by Power et al, 1998, and others, there is not a substantial amount of research regarding this subject. However, the issue is of significance in PCTL design, especially for PCTL tunnels where substantial changes in acceleration can occur through the soil column. This is because, in cases where seismic loads control PCTL design, PCTL could be designed to accommodate the lower level of shaking that occurs at depth, rather than shaking that would be expected at the surface.

Procedures and software have been developed to account for the variation in ground motions with depth, although these are not always used in seismic tunnel design. Development of additional case histories would be useful in assuaging the concerns of owners of transit tunnels in seismic areas regarding the integrity of the structure in a seismic event. Establishment of additional seismographs underground would be useful as additional case histories are established. Such seismographs exist in Greece and other areas, but are not standard in tunnels in all seismic zones. Seismographs are relatively inexpensive, although they need to be connected to external power and data lines. They should be considered for installation in all new transit tunnels in earthquake prone areas.

CONCLUSION

In general, tunnels perform well in earthquakes because they are constrained by the ground around them and are not subjected to inertial effects like above-ground structures. PCTL tunnels perform particularly well in earthquakes because of their circular, largely symmetrical shape, and their flexibility relative to the ground surrounding them. The research conducted for this study has confirmed that PCTL tunnels perform well when subjected to seismic ground motions, based on four case histories and a lack of reported damage to many more PCTL tunnels that have been subjected to similar shaking. Only one instance of slight damage to a PCTL tunnel was found in an extensive search of the performance of PCTL tunnels during seismic events. Literally hundreds of tunnels have been built using PCTL linings in seismically active areas around the world. The widespread use of PCTL together with inherent advantages in load carrying capacity, flexibility, cost effectiveness and seismic performance, make PCTL the ideal lining type for large single-pass bored tunnel projects that are designed to withstand strong seismic ground motions.

Since PCTL tunnels are frequently built in seismic areas, development of standard post-earthquake tunnel reconnaissance guidelines would greatly facilitate future tunnel earthquake design. Additional seismological data relating to ground motions experienced at tunnel depth could be used to further refine the state of the practice for seismic PCTL design in soft ground. Similar research could be conducted for tunnels in rock as well.

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