Guidelines for development around tunnels and seismic compliance of underground structures

By Jeffrey Yoders

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An analysis conducted for the Port Authority of New York and New Jersey, made public in 2006, showed that the PATH tunnels under the Hudson River were more vulnerable to a terrorist attack than previously thought and that a relatively small explosion could cause significant flooding of the entire rail system within hours. The work was based on analysis and computer modeling by the Lawrence Livermore National Laboratory and Rensselaer Polytechnic Institute.

The Hudson River PATH tubes, which suffered serious damage during the 9/11 attacks, were more vulnerable than most other tunnels that pass through New York and New Jersey because they lie in the soft riverbed of the Hudson, unlike other tunnels that were bored through bedrock. The worst case included in the analysis suggests that a bomb could easily have been carried aboard a train that could punch a 50-square-foot hole in one side of a tube, possibly breaching both sides of the tunnel and allowing 1.2 million gallons of water to pour in per minute and flood the system within hours. The analysis was based on a combination of tests of the cast iron from the tunnels and element analysis via computer modeling (Rashbaum and Neuemann, 2006).

In 2010, the PATH began a $600 million project to install steel reinforcing plates along the tunnel walls and flood-prevention gates at either end of the nearly 100-year-old tunnels.

While the PATH improvements are an extreme example — terrorists were found with maps of the system and other details of a thwarted attempt to bomb the system — it does illustrate how vulnerable tunnels and other underground structures can be to both natural disasters and manmade attacks.

Building around tunnels also is an increasingly important issue because of the increasing density of cities. During tunnel construction, such as the high-speed rail tunnel currently being built in Seattle, surface impacts can occur where removal of ground to form the tunnel causes some disturbance of the surrounding ground mass. Settlement along existing roads and footpaths may result from tunnel construction close to the surface and existing buildings may be adversely affected. Where these problems are anticipated through computer modeling and site analysis, mitigation methods can be put in place, either in the form of tunnel design and appropriate construction methodologies and/or combined with building underpinning. In extreme cases, tunnel alignment may have to be modified.

The reverse of this sequence occurs where a tunnel already exists and a new building is proposed. The problem then is to determine the influence of the proposed building on the tunnel. In this situation, the interaction between the building development and the tunnel may take one of three forms:

- excavation for basements will remove overburden weight adjacent to or above the tunnel and induce stresses in the tunnel lining;
- the building may impose additional loading on the tunnels; or
- a combination of the above and at different stages of construction (Nye, 2005).

This article presents an overview of some of the issues that arise when buildings are to be constructed near existing tunnels via case histories and the current state of seismic analysis and design for underground structures. While there are a number of technical challenges for construction near tunnels, another challenge is to satisfy the concerns of a wide range of stakeholders including the approving authority, the developer, and the owner of the underground infrastructure.

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Learning Objectives

After reading this article you should understand basic information about the following:

- Issues that arise when buildings are constructed near existing tunnels.
- How to plan for seismic design loads for an underground structure.
- How to measure the risk and rigidity of an existing tunnel for a natural disaster or manmade attack.
- How to accordingly strengthen or redesign an underground facility to withstand seismic activity.

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Methods of analysis

Prior to launching any numerical analysis of an existing tunnel for suitability of a new above-ground structure, a fundamental understanding of any problems with the proposed site must first be attained. The most common method of analysis is the finite element analysis method conducted via computer modeling. Other methods such as finite difference analysis also may be applied. Any numerical model is, of course, limited in that it is a representation of what the behavior might be. A full, 3D analysis, while preferable, is not always available or practical. Any finite element analysis and results must be supplemented by at least one or two alternatives and supported by field monitoring during construction (Nye, 2005).

For the building structural designer and tunnel/geotechnical engineer there are a number of variables that have to be obtained and assessed for the analysis. This required basic information is not necessarily limited to but should include the following:

- depth and breadth of the building excavations,
- distribution and magnitude of the building loads,
- geological model of the site,
- initial stresses in the ground and tunnel lining,
- depth and lateral location of tunnels relative to the building,
- height of groundwater table,
- relative stiffness of the tunnel lining to the surrounding ground, and
- shape of the tunnel and lining type.

Other variables apply if ground anchors/dowels are used to reinforce the rock or to compensate for ground removal (elastic rebound):

- sequencing of excavation and ground anchor/dowel installation,
- relative position and depth of ground reinforcement, and
- direction of stressing loads.

Tunnel protection

Apart from safety, the number-one driver for the protection of tunnels and underground structures is serviceability. The tunnel owner may provide criteria related to the design and construction of the building that allows limited cracking of the tunnel lining. Early in the last decade, several new developments were built on and around the existing Sydney Airport Line. Guideline documents had been prepared and issued to the prospective developers that allowed some minor cracking of the tube line's concrete lining; however, beyond a defined limit the developer was on the hook for the cost of repairs.

Construction is the highest risk to the tunnel and the tunnel environment. The most important thing a structural or geotechnical engineer can do for the team building the structure is provide accurate survey data and tunnel design drawings or 3D models. There have been cases where drilling rigs used for site investigation have penetrated tunnels.

The Sydney Airport Line was completed just prior to the 2000 Olympic Summer Games. Immediately after its completion, a large number of developer inquiries arrived for development along its 11-km route. The Airport Line consists of 6 km of 10-meter-diamater soft ground tunnel supported by segmental concrete lining and 2.5 km of rock tunnel with shotcrete walls and a concrete arch over its crown. There are four significant railway stations — two of them underground along the route and a fifth station constructed in an open cut. There have been at least 30 new developments along the route since its completion and the guidelines for development have been applied for all of them. The range of new and potential developments includes domestic residential, light industrial, and high commercial. Following is a typical list of issues that have to be addressed and information to be given in any assessment, approval, and monitoring for building works adjacent to the tunnels:

- verified surface survey details (may also require as-built survey of tunnel);
- site investigation data, properties of soil and rock;
- building structural and architectural drawings;
- tunnel lining and underground station details;
- design of tunnel protection methodology (including predicted effects);
- construction method details;
- construction program details;
- construction monitoring results where measured at surface and/or in tunnel (displacements, water levels, noise and vibration, ground stresses, and tunnel lining stresses);
- potential for electrolysis/corrosion;
- pre- and post-construction dilapidation surveys; and
- works as executed drawings. (Nye, 2005)

Obviously, the level of detail required will vary between each project depending on scale and complexity of the proposed development and its proximity to the underground structures. This major construction activity may cause cracking to tunnel lining no matter how well it is planned for. Table 1 shows the criteria for the Sydney Airport Line for when a crack is to be repaired.

The Sydney Airport Line guidelines further recognize the construction risk of building near a tunnel and stipulate:

1. All piling contractors must be made aware that the site is adjacent to a railway tunnel.
2. The position of the outside tunnel walls must be marked clearly on the ground in a visible manner.
3. The Sydney Railcorp, or its appointed representative, must be kept informed of piling progress on a daily basis.

These points could be applied to drilling associated with any site investigation works or other site works including dowel and ground anchor installation. See Nye (2005) for more details and case studies of development along the Sydney Airport Line.

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Seismic analysis of underground structures

Underground structures have features that make their seismic behavior distinct from most surface structures, most notably their complete enclosure in soil and/or rock and their significant length. This section describes how ground deformations are estimated and how they are transmitted to an underground structure, presenting methods used in the computation of strains, forces, and moment in the structure. Examples include application of these methods in underground structures in San Francisco, Los Angeles , and Kobe, Japan (Hashash, 2001).

Several studies have documented earthquake damage to underground facilities. The following general observations can be made regarding the seismic performance of underground structures:

1. Underground structures suffer less damage than surface structures.
2. Reported damage decreases with increasing overburden depth. Deep tunnels seem to be safer and less vulnerable to earthquake shaking than shallow tunnels.
3. Underground facilities constructed in soils can be expected to suffer more damage compared with openings constructed in competent rock.
4. Lined and grouted tunnels are safer than unlined tunnels in rock. Shaking damage can be reduced by stabilizing the ground around tunnels and by improving the contact between the lining and the surrounding ground through grouting.
5. Tunnels are more stable under a symmetric load, which improves ground-lining interaction. Improving the tunnel lining by placing thicker and stiffer sections without stabilizing surrounding poor ground may result in excess seismic forces in the lining. Backfilling with non-cyclically mobile material and rock-stabilizing measures may improve the safety of and stability of shallow tunnels.
6. Damage may be related to peak ground acceleration and velocity based on the magnitude and epicentral distance of the affected earthquake.
7. Duration of strong-motion shaking during earthquakes is of utmost importance because it may cause fatigue failure and, therefore, large deformation.
8. High-frequency motions may explain the local spalling of rock or concrete along planes of weakness. These frequencies, which rapidly attenuate with distance, may be expected mainly at small distances from the causative fault.
9. Ground motion may be amplified upon incidence with a tunnel if wavelengths are between one and four times the tunnel diameter.
10. Damage at or near tunnel portals may be significant due to slope instability.

Case studies of seismic performance of tunnels

Bay Area Rapid Transit (BART) system, San Francisco Bay Area — The BART system was one of the first underground tunnels to be designed with consideration for seismic loading. On the San Francisco side, the system comprises underground stations in fill and soft bay mud deposits. It is connected to Oakland via the transbay-immersed tube tunnel.

During the 1989 Loma Prieta Earthquake, the BART facilities sustained no damage and, in fact, operated on a 24-hour basis after the quake. This is because the system was designed under stringent seismic conditions. Special seismic joints were designed to accommodate differential movement at ventilation buildings. The system was designed to support earth and water loads while maintaining watertight connections and not exceeding allowable differential movements. No damage was observed at these flexible joints, although it is not known how far, exactly, the joints moved during the earthquake (Hashash, 2001).

Table 1: Criteria for the Sydney Airport Line for when a crack is to be repaired

Width of crack	Action
Less than 0.20 mm	Acceptable if no leakage occurs
Between 0.20 mm and 0.30 mm	Determined by length
	• Less than 300 mm — no further work required unless leaks occur
	• Greater than 300 mm — repairs required at cost of developer
Greater than 0.30 mm	Repairs required at cost of developer

The Alameda Tubes — The Alameda Tubes are a pair of immersed-tube tunnels that connect Alameda Island to Oakland in the Bay Area. These were some of the earliest immersed tube tunnels, built in 1927 and 1963 without the benefit of seismic design considerations. During the Loma Prieta event, the ventilation buildings observed some structural cracking. Limited water leakage into the tunnels also was observed, as well as liquefaction of loose deposits above the tube at the Alameda portal. Peak horizontal ground accelerations measured in the area ranged from 0.1 to 0.25 g. The tunnels, however, are prone to floatation due to potential liquefaction of the backfill (Hashash, 2001).

Los Angeles Metro — The Los Angeles Metro was operational during the 1994 Northridge Earthquake. The concrete lining of the bored tunnels remained intact after the earthquake. While there was damage to water pipelines, highway bridges, and buildings, the earthquake caused no damage to the Metro system. Peak horizontal ground accelerations were measured near the tunnels and ranged between 0.1 and 0.25 g, with vertical ground acceleration typically two-thirds as large.

Underground structures in Kobe, Japan — The 1995 Hyogoken-Nambu Earthquake caused a major collapse of the Daikai subway station in Kobe, Japan. The station design in 1962 did not include specific seismic provisions. It is the first modern underground structure to fail during a seismic event. The center columns of the station collapsed and were accompanied by the collapse of the ceiling slab and the settlement of soil coverage by more than 2.5 m.

During the earthquake event, transverse walls at the ends of the station and at areas where the station changed width acted as shear walls in resisting collapse of the structure. These walls suffered significant cracking, but the interior columns did not suffer as much damage under the horizontal shaking. In regions with no transverse walls, collapse of the center columns caused the ceiling slab to sink and cracks 150 to 250 mm wide appeared in the longitudinal direction. There was also significant separation at some construction joints and corresponding water leakage through the cracks. Few cracks, if any, were observed in the base slab (Hashash, 2001).

Center columns that were designed with very light transverse (shear) reinforcement relative to the main (bending) reinforcement suffered damage ranging from cracking to complete collapse. Center columns with zigzag reinforcement in addition to hoop steel did not buckle as much as those without reinforcement.

It is likely that the relative displacement between the base and the ceiling levels due to subsoil movement created the destructive horizontal force. This type of movement may have a minor effect on a small structure, but in a large one such as a subway station it can be significant. The non-linear behavior of the subsoil profile could also be significant. It is believed that the thickness of the overburden soil affected the extent of damage between sections of the station by adding inertial force to the structure. Others attribute the failure to high levels of vertical acceleration.

EQE (1995) made further observations about Daikai Station: "Excessive deflection of the roof slab would normally be resisted by: 1) diaphragm action of the slab, supported by the end walls of the station; 2) passive earth pressure of the surrounding soils, mobilized as the tube racks. Diaphragm action, however, was less than anticipated, due to the length of the station. The method of construction (cut and cover involving a sheet pile wall supported excavation with narrow clearance between the sheet pile wall and the tube wall) made compaction of backfill difficult to impossible, resulting in the tube's inability to mobilize passive earth pressures. In effect, the tube behaved almost as a freestanding structure with little or no extra support from passive earth pressure."

However, it is not certain that good compaction would have prevented the structural failure of the column. Shear failure of supporting columns has since caused similar damage in other earthquake events.

Underground Structures in Taiwan — Several Highway tunnels were located within the zone heavily affected by the Sept. 21, 1999, Chi Chi Chi earthquake (7.3 Richter) in central Taiwan. These are large, horseshoe-shaped tunnels in rock. All the tunnels inspected were intact without any visible signs of damage. The main damage occurred at tunnel portals because of slope instability. Minor cracking and spalling were observed in some tunnel lining. One tunnel passing through the Chelungpu fault was shut down due to a 4-m fault movement. No damage was reported in the Taipei Subway, which is more than 100 km from the ruptured fault zone.

Bolu Tunnel, Turkey — Twin tunnels were part of the expansion of a transportation line in the mountainous terrain west of Bolu, Turkey (between Istanbul and Ankara). They were built using the New Austrian Tunneling Method (NATM) where continuous monitoring of primary liner convergence is performed and support elements are added until a stable system is in place. The tunnel has an excavated arch section 15 m tall by 16 m wide. Construction was challenging because the alignment crossed several minor faults parallel to the North Anatolian Fault.

The Aug. 17, 1999, Koceali earthquake had minimal impact on the Bolu Tunnel. The closure rate of one monitoring station was reported to have temporarily increased for one week, then became stable again. Several hairline cracks previously observed in the final lining were continuously monitored for additional movement and showed no movement due to the earthquake.

The Nov. 12 , 1999, earthquake however, caused the collapse of both tunnels 300 m from their eastern portal. At the time of the earthquake, a 800-cm section had been excavated, and a 300-m section of unreinforced concrete lining had been completed. The collapse took place in clay gauge material in the unfinished section of the tunnels. The section was covered with shotcrete and had bolt anchors. Several mechanisms have been proposed for explaining the collapse of the tunnel. These mechanisms include strong ground motion, displacement across the gauge material, and landslide. The tunnel had to be re-excavated after it was cleaned out (Hashash, 2001).

See Hashash (2001) for more case studies.

Summary of seismic performance

The Daikai subway station collapse was the first collapse of an underground structure due to earthquake forces, rather than ground instability. Underground structures in the United States have experienced limited damage during earthquakes, but the shaking levels they've experienced to date have been much lower than the maximum anticipated events. Station collapse and anticipated strong motions in major U.S. urban areas raise great concerns regarding the performance of underground structures.

Several key elements may have helped in limiting the damage to the station structure and possibly prevented complete collapse. Transverse walls at the ends of the station and at areas where the station changed width provided resistance to dynamic forces in the horizontal direction. Center columns with relatively heavy transverse (shear) reinforcement suffered less damage and helped to maintain the integrity of the structure. The fact that it was underground instead of a surface structure may have reduced related damage.

Measurements of the seismic response of an immersed tube tunnel during several earthquakes show that the response of the tunnel is dominated by the surrounding ground response and not the inertial properties of the tunnel itself. Therefore, the focus of underground seismic design is on the free-field deformation of the ground and its interaction with the structure. The emphasis on displacement is in stark contrast to the design of surface structures, which focus on inertial efforts of the structure itself. This has led to the development of design methods such as the seismic deformation method that specifically consider the seismic deformation of the ground (Hashash, 2001).

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1. In a 2006 analysis, a 50-square-foot hole in the side of one of New York's PATH tubes was found to be:

a) The result of cracking in the lining.

b) Possibly able to breach both sides of the tunnel allowing 1.2 million gallons of water to pour in per minute and flood the system within hours.

c) Able to be mitigated only by gates at either end of the existing system.

d) Only capable of being created by a large explosion that would require a device that could not be carried onto a train.

2. Where a tunnel already exists and a new building is proposed, the interaction between the building development and the tunnel may take this form:

a) Excavation for basements will remove overburden weight adjacent to or above the tunnel and induce stresses in the tunnel lining.

b) The building may impose additional loading on the tunnels.

c) A combination of the above and at different stages of construction.

d) All of the above.

3. The most common method of analysis of a proposed building's effect on a nearby tunnel or other underground structure is:

a) Finite element analysis.

b) Finite differential analysis.

c) Geotechnical survey analysis.

d) All of the above.

4. Basic variables that need to be assessed by the analysis include:

a) Depth and breadth of the building excavations.

b) Relative stiffness of the tunnel lining to the surrounding ground.

c) Initial stresses in the ground and tunnel lining.

d) All of the above.

5. A typical list of issues that have to be addressed and information to be given in any assessment, approval, and monitoring for building works adjacent to a tunnel includes:

a) Verified surface survey details (may also require as-built survey of tunnel).

b) Analysis of rock formations in the area.

c) An environmental impact statement.

d) A scale model of the proposed development.

6. The Sydney Airport Line guidelines further recognize the construction risk of building near a tunnel and stipulate:

a) The position of the outside tunnel walls must be marked clearly on the ground in a visible manner.

b) Finite element analysis of the proposed building's impact on the tunnel must be performed.

c) A representative of the Sydney Railcorp must approve all drawings.

d) All of the above.

7. The following general observations can be made regarding the seismic performance of underground structures:

a) Underground structures suffer less damage than surface structures.

b) Underground facilities constructed in soils can be expected to suffer more damage compared with openings constructed in competent rock.

c) Damage may be related to peak ground acceleration and velocity based on the magnitude and epicentral distance of the affected earthquake.

d) All of the above.

8. San Francisco's BART system was designed for seismic loading and had these key features:

a) Special seismic joints were designed to accommodate differential movement at ventilation buildings.

b) Designed to shake with the movement of the surrounding silt.

c) Was built without joints or seams.

d) Escape routes designated for passengers.

9. During the 1989 Loma Prieta Earthquake, the Alameda Tubes:

a) Suffered no damage.

b) Suffered limited water leakage into the tunnels as well as liquefaction of loose deposits above the tube at the Alameda portal.

c) Suffered full collapse.

d) Suffered a partial collapse at an endpoint station.

10. During the 1994 Northridge Earthquake, the Los Angeles Metro:

a) Had cracks observed in its concrete lining but no leakage.

b) Had peak horizontal ground accelerations measured near the tunnels that ranged between 0.1 and 0.25 g.

c) Had major cracks with leakage in its concrete lining.

d) Suffered collapse of a portion of its concrete lining.

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