ADVANCING TUNNEL SEISMIC RESILIENCE

State-of-the-art design techniques support increasing use of underground space

May 8, 2023

Wataru Okada – CPEng, Technical Principal, Geotechnics and Tunnels, New Zealand
Stephen Klein – P. E., G.E., Senior Engineering Manager, United States
Bruce Downing – P.Eng., Senior Principal, Senior Geotechnical Engineer, Canada

Sections in this article:

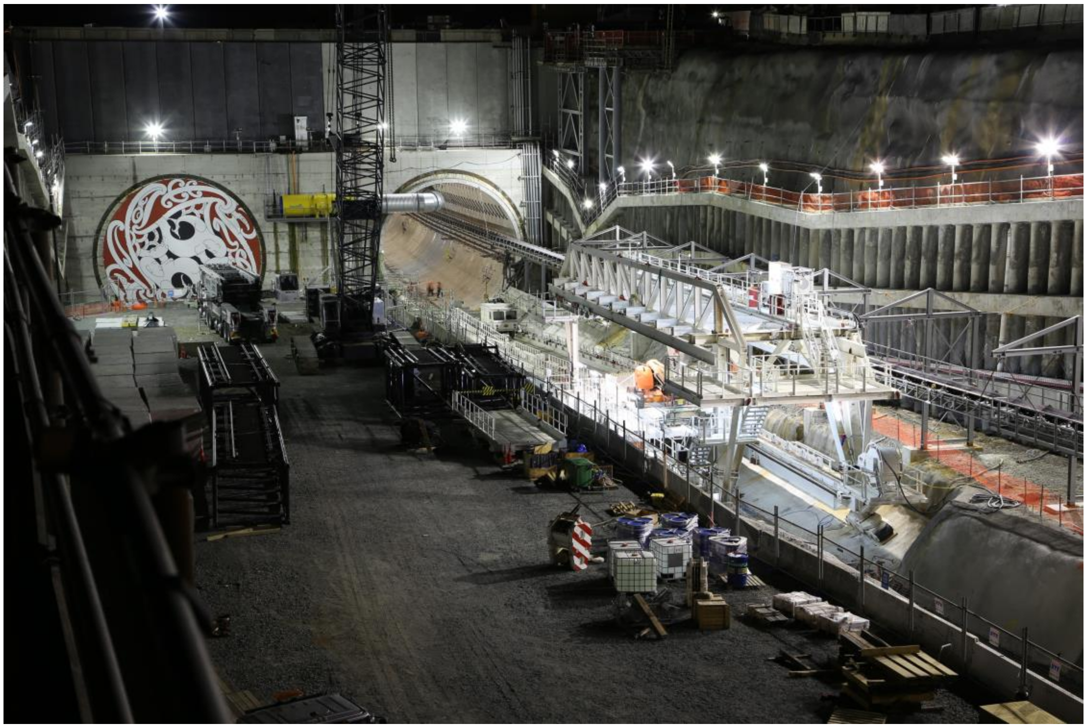

Image above: Waterview Tunnel, Auckland - courtesy of New Zealand Transport Agency

Tunnels cut across communities supporting essential services—from transportation to water systems. Yet, given their subterranean location, it is easy to overlook the important role of these structures in daily life and the factors that contribute to developing and maintaining them, especially throughout seismic events.

The following Q&A provides insights for developing seismic-resilient tunnels and adopting state-of–the-art seismic design techniques in projects.

HOW ARE SEISMIC DESIGN PRACTICES FOR TUNNELS EVOLVING?

Wataru Okada: Historically tunnels have performed relatively well in seismic events. Following recent major earthquakes, including Loma Prieta on California's Central Coast in 1989, Kobe in Japan in 1995 and Chi Chi in Taiwan in 1999, a significant amount of research has been devoted to understand the performance of tunnels during earthquakes, and this has led to the improvement of design practices for tunnels. The key feature of this research has been the recognition of the seismic behaviour of tunnels and soil structure interaction.

Today, designing for seismic resilience is rapidly becoming a widely accepted design approach in the tunnelling industry. Seismic resilience depends on risk mitigation through analyzing geological risk, creating redundancy in design, and enhancing the ability for the tunnel to recover speedily after seismic events, with minimal disruptions to ongoing operations. Geological risk—including faults, unstable ground and weak soils—can be mitigated early on in projects through route selection and then through design.

Tunnel structures have traditionally been designed for the maximum-agreed level of earthquakes, to prevent tunnel failure (ULS) while considering serviceability requirements to maintain operations following smaller more frequent earthquakes (SLS). The industry now recognizes the need to consider an intermediate state, or loss of function state (SLS2), in addition to ULS and SLS seismic loads for critical structures, to check that they have sufficient capacity to allow for rapid recovery after this event.

Post disaster recovery, access and emergency responses and temporary remediation, or infrastructure alternatives, are often key considerations when planning and designing tunnel structures. In some countries, design standards and guidelines are not keeping up with the most recent development in seismic design practices, requiring designers to stay abreast of international best practices while also fully complying with the local standards.

Stephen Klein: In the US, there are some standards for the seismic design of tunnels; however, many owners prefer to develop project-specific seismic design criteria that address their specific seismic performance objectives. These objectives are the key to providing a seismically resilient design and often stipulate that damage must be repairable, the time frame available for repairs, and the goal for resuming operations. We have developed such seismic criteria for several owners of rail systems including BART, LA Metro, SoundTransit, and the California High-Speed Rail Program.

An important consideration for a seismically resilient tunnel is adequate ductility. Ductility ensures the lining can deform without significant damage. This is the key to meeting performance objectives and returning the tunnel to service as soon as possible after a major seismic event. Strain limits are often specified to indicate how much inelastic behavior is acceptable. Some cracking is acceptable, but too much can lead to time-consuming repairs, increasing recovery time. Finding the right balance between the amount of inelastic behavior and the time to repair the tunnel is fundamental to achieving a resilient tunnel structure.

CAN YOU CITE SCENARIOS WHERE STATE-OF-THE-ART TECHNIQUES HAVE BEEN APPLIED?

Wataru Okada: City Rail Link in Auckland, New Zealand is one example of best practice that WSP adopted in tunnel design. Virtually the entire tunnel alignment is located in the East Coast Bays Formation, which has low strength but is largely competent rock; this choice was made so that the tunnel would not be built in weaker soils or a mixture of soil and rock. Sensitivity analyses were conducted to account for the variability of ground conditions and unexpected conditions. The sensitivity analysis included checking for a higher seismic event than is required by the design code to ensure collapse avoidance.

Figure 1- City Rail Link Karangahape Station Bored Tunnel, Auckland, New Zealand

Bruce Downing: Due to growing urban centres, greater demand for infrastructure, and the need to avoid impacts to sensitive surface environments, there is an increasing demand for tunnels; tunnels can play an important role in mitigating the impact of seismic hazards by providing more seismically resilient infrastructure. In Vancouver, Canada, Metro Vancouver (the regional utility) has recognized the need for a reliable water supply that is available after a very large earthquake and is therefore replacing major shallow marine crossings with deep tunnels in more stable soil deposits. Many of these projects, however, due to their location along river valleys with attendant poor soils, must accommodate large earthquake-induced deformations in the upper parts of the shafts and connections. WSP has been involved as the geotechnical engineer of record in several of these projects, and through careful assessment of the ground conditions (using extensive and sophisticated geotechnical investigations) coupled with state-of-the-art analytical methods (numerical modelling) is able to evaluate the ground deformations that are expected to occur, even for sites that are expected to undergo extensive liquefaction. These analyses are then used to determine means of mitigation, which may include ground treatment, structural strengthening of the shafts or tunnel, or both.

Figure 2 - Excavation of interlocking slurry wall panels in weak ground to create tunnel boring machine (TBM) launch shaft.

Figure 3 – TBM launch shaft

Stephen Klein: In California, WSP is working with the East Bay Municipal Utility District (EBMUD) on the Mokelumne Aqueducts Resiliency Project. The Mokelumne Aqueducts supply water to over 1.4 million residents of the East Bay through an aqueduct system extending from the Sierra Nevada Mountains to the San Francisco Bay Area. Approximately 10 miles (16 kilometres) of the aqueducts crossing the Sacramento-San Joaquin River Delta are pile-supported elevated pipelines, and this portion of the aqueducts is recognized to be vulnerable to seismic hazards due to liquefaction of the loose surficial soils and also excessive structural deflections during strong ground shaking. To meet the project’s resilience objectives, WSP is designing a 16.5-mile (26.6-kilometre) tunnel across the Delta and re-routing the existing aqueducts through this tunnel. The tunnel will be located in stable soils at a depth of about 120 to

150 feet (36.6 to 45.7 metres), which will allow this lifeline to maintain operations following large earthquakes.

In Turkey, the Eurasia Tunnel, which crosses beneath the Bosphorous Strait to connect the Asian and European sides of Istanbul, was designed to withstand a 7.25 magnitude earthquake. The differential displacements at the rock-soil interface in two places required the road tunnel lining to accommodate differential displacements up to 2 inches (5 centimetres) transversely and 3 inches (7.6 centimetres) longitudinally. WSP's solution, a first-of-its-kind for a large diameter segmentally lined tunnel, was to accommodate these differential displacements by designing a special, flexible seismic joint [Figures 4 and 5] that is installed between two segmental lining rings and is able to dissipate the large relative movements of this 40-foot (12-metre) diameter tunnel. The seismic joints allow the adjacent sections of tunnel to move longitudinally and laterally, relative to each other. This freedom of movement maintains the longitudinal compression of the lining so the gaskets around the circumferential joints remain compressed, eliminating the potential for leakage—a major risk for this tunnel under groundwater pressures exceeding 11 bars and at a depth of 300 feet (91.4 metres) below the Bosphorous Strait. This project, which won "Major Project of the Year" in 2015 from the International Tunnelling Association, is a good example of the unique challenges that develop in the seismic design of tunnels and the innovative solutions that are required to successfully meet these challenges.

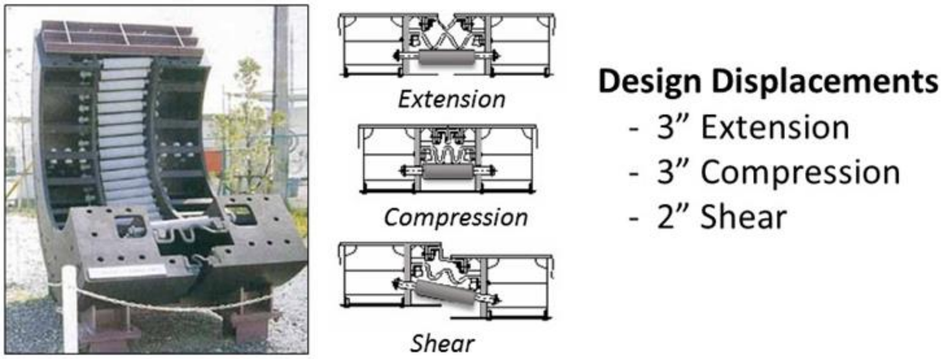

Figure 4 - Flexible seismic joint concept for the Eurasia Tunnel

Figure 5 - Special seismic joint installed in the Eurasia Tunnel

WHAT FACTORS ARE AFFECTING THE FUTURE OF THE INDUSTRY?

Bruce Downing: With increasing pressure on the use of urban spaces, and an increasing desire to ensure that infrastructure is designed to meet post disaster requirements (to withstand severe seismic shaking), there appears to be a clear trend toward greater use of underground space, which offers advantages in terms of seismic resilience and avoidance of surface intrusion, an environmental benefit. As the geotechnical conditions of these sites become more complex and challenging, there will be an increasing need for sophisticated means to evaluate the ground conditions and analyze the ground and tunnel response in the event of an earthquake.

Stephen Klein: In terms of emerging technology that could contribute to effective response, earthquake warning systems, which are currently being developed, might improve seismic resilience. For example, since 2012 California has been developing an earthquake early warning system. This system is designed to provide advance warning of an earthquake to critical facilities (hospitals, first responders, utility owners, transportation agencies) so they can take precautions to reduce damage and avoid the impacts of strong shaking. The system is currently operational but on a limited basis and is designed to provide up to 90 seconds of warning. This amount of warning could allow trains to be stopped at stations, providing easier evacuation if necessary. Power could be shutdown which might reduce post-construction downtime and operations to return to service more quickly. The potential benefits of this early warning system need to be evaluated more fully as such systems become more available.

Wataru Okada: As techniques are developed to support the increasing use of underground space, awareness will be essential for moving the industry forward. This needs to be achieved through the sharing of knowledge regarding the seismic behaviour of tunnels so that new techniques can be fully incorporated into industry practice, and by keeping communities informed regarding the advantages of utilizing underground space. Community awareness is important for developing public support for underground projects of all kinds in the infrastructure sector.

WSP's long history of designing projects and gaining and sharing knowledge related to tunnel design continues today through our ongoing international collaboration on projects and through our contributions to the development of international design guidelines to reflect current best practices.[1]

Authors

Wataru Okada – CPEng
Technical Principal, Geotechnics and Tunnels
New Zealand

Wataru.Okada@wsp.com

Stephen Klein – P.E., G.E.
Senior Engineering Manager
United States

Stephen.Klein@wsp.com

Bruce Downing – P.Eng.
Senior Principal, Senior Geotechnical Engineer
Canada

Bruce.Downing@wsp.com

---

[1] WSP supported the research of Joe Wang in 1993, Seismic Design of Tunnels, A Simple State-of-the-Art Design Approach, which has informed the industry standard in practice to this day, and has been involved in other recent design guidelines, including the Australian Tunnelling Society's Tunnel Design Guideline in 2020, the United States Department of Transportation FHWA Technical Manual for Design and Construction of Road Tunnels and the American Association of State Highway and Transportation Officials (AASHTO) LRFD Road Tunnel Design and Construction Guide Specifications.

About WSP

As one of the world's leading professional services firms, WSP exists to future-proof our cities and environment. We provide strategic advisory, engineering, and design services to clients in the transportation, infrastructure, environment, building, energy, water, and mining sectors. Our 66,000 trusted professionals are united by the common purpose of creating positive, long-lasting impacts on the communities we serve through a culture of innovation, integrity, and inclusion. Sustainability and science permeate our work. In 2022, WSP derived more than half of its $11.9 B (CAD) revenues from services that support the UN Sustainable Development Goals. The Corporation's shares are listed on the Toronto Stock Exchange (TSX:WSP). wsp.com