Earthquakes and Vancouver Tunnels

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Abstract:

Use of underground space is important in Vancouver because of both the increasing population density and the complex geography. Since 1912, a total of thirteen major tunnels have been constructed for transportation and utilities. This work has employed a variety of construction techniques to accommodate the range of ground conditions encountered. In total, eight different tunnelling methods have been used ranging from drill and blast in the granite along the North Shore, to compressed air in the highly permeable glacial deposits on the west side of the city, to cut and cover methods for near surface highway transportation tunnels. When reviewing the stability of these existing tunnels or designing new tunnels, consideration needs to be given to seismic loads induced by Earthquakes. This paper reviews the recent experience of tunnel performance in the 1989 Loma Prieta, 1994 Northridge and 1995 Hyogeken-Nanbu earthquakes and discusses the implications of this experience to tunnels in the Vancouver area.

Introduction

Use of underground space is important in Greater Vancouver because of both the increasing population density and the complex geography. Since 1912 a total of thirteen major tunnels have been constructed for transportation and utilities. This work has employed a variety of construction techniques to accommodate a wide range of geological conditions. In total, eight different tunnelling methods have been used, ranging from drill and blast in the granite on the north Shore, to compressed air in the highly permeable glacial deposits on the west side of the city.

Vancouver is also in a high seismic risk zone, and there is a need that the tunnels be able to withstand earthquake ground motion without serious damage. To date all of the tunnels have successfully withstood the minor earthquakes that have occurred in the past century, but they have not yet been subjected to a major earthquake. In comparison, tunnels in both Japan and California have been subjected to severe ground shaking, and some have been damaged. This paper reviews damage records from the 1989 Loma Prieta, 1994 Northridge and 1995 Hyogeken-Nanbu earthquakes in California and Japan, and discusses the implication of this information to tunnels in Vancouver.

Vancouver Tunnels and Geology

The following is a summary of the geology of Vancouver, and tunnelling methods that have been employed in this wide variety of conditions (Wyllie *et. al.*, 1998). Table 1 lists 13 tunnels that have been constructed since 1912, together with two proposed tunnels for which investigation work and preliminary designs have been prepared. The locations of these tunnels and the approximate geology of the area are shown on Figure 1.

Geography and Geology of Vancouver

Vancouver's geographic conditions include steep mountains along the North Shore and Fraser Valley, a deeply incised coastline and the complex watercourses of the Fraser River delta. Geologic conditions range from the very strong, massive granite forming the mountain ranges, to very weak sandstones and shales in the western part of the city, and extensive, highly variable glacial and river deposits. Figure 1 shows the approximate distribution of the main rock and soil types, the characteristics of which are as follows:

Table 1

Basic Information For Vancouver Tunnels

Reference Number	Owner	Function	Length	Construction	Year of Construction
1	BC Rail	Single Track Rail	~1,370 m	**D &B**	1974
2	GVWD	Water	984 m	D & B	1932
3	CN Rail	Single Track Rail	500 m	Cut & Cover	1928
4	BC Transit	Stacked Track LRT	1,400 m	D & B / Road Header	1985
5	GVSDD	Sewer	8,140 m	TBM	Late 1960's
6	GVSDD	Sewer	4,600 m	Compressed Air & Dewatering Wells	1962
7	MoTH	6 Lane Vehicle	724 m	Cut & Cover	1990
8	CN Rail	Single Track Rail	3,280 m	D & B	1968
9	GVWD	Water	472 M	Trenching / D & B	1976
10	MoTH	4 Lane Vehicle	2,000 m	Sunken Tube	1957
11	GVWD (Coquitlam)	Water	655 m in Rock 142 m in Soil	D & B Steel Sets and Spiles	1912, 1987
12	GVWD (Proposed)	Water	1,700 m	D & B	Future
13	GVRD	Water	890 m	TBM	1998
14	City of Vancouver	Sewer	895 m	Microtunnel	1996
15	GVSDD (Proposed)	Sewer	2,375 m	Earth Pressure Balance Machine	Future

Abbreviations:

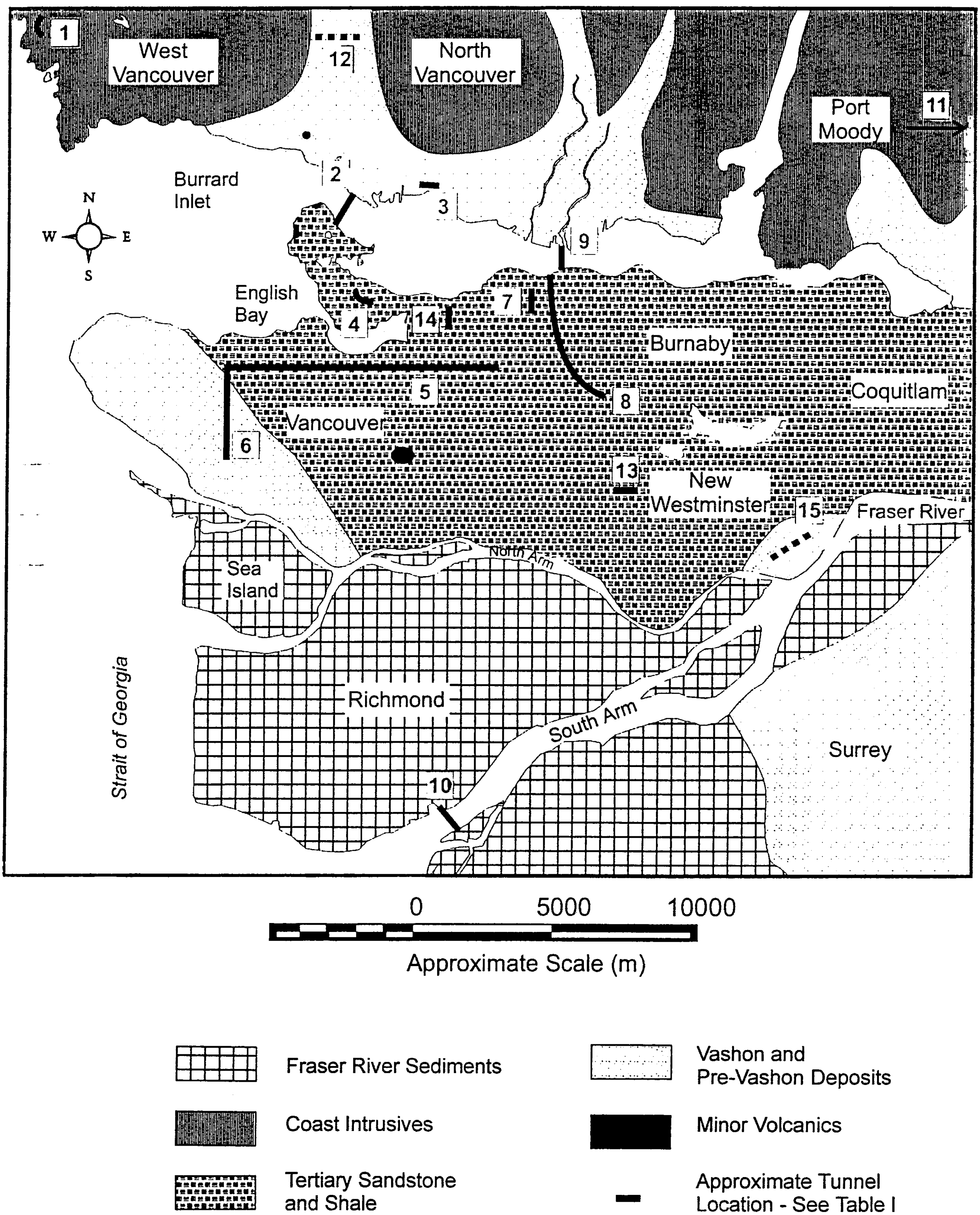
D & B - Drill and Blast

TBM - Tunnel Boring Machine

- **Coast Intrusive Rocks:** various compositions of granite are part of the Coast Plutonic Complex that stretches from the Fraser River to the Yukon border. These granites are very strong, massive rocks, which are generally unweathered as the result of glaciation. Faults are likely to be encountered along deeply incised valleys.
- **Sedimentary Rocks**: sandstone, siltstone, sandy shale and conglomerate formed as a result of sediments deposited by streams flowing south and southwest off local mountains about 70 million years ago. The sandstones and shales are generally very weak to weak, but contain few discontinuities. Weathering occurs as a near surface degradation process. The conglomerate is usually massive and strong.
- **Recent Glacial and Non-Glacial Deposits**: clays, silts, sands and gravels were deposited by glacial and non-glacial events about 12,000 to 1.6 million years ago. These materials range from dense boulder tills to

Figure 1

Vancouver Tunnel Locations and Simplified Geology at Tunnel Depth



a variety of sands and silts that can be loose and highly permeable.

- **River Deposits**: sand, silt and mud transported by the Fraser River developed most of the landforms in the Fraser Lowlands.

A particular feature of the sedimentary, glacial and river deposits is that the distribution of the different materials is highly variable and they occur as discontinuous lenses, the dimensions and locations of which are unpredictable.

Tunnelling Methods

In order to accommodate the wide range of geographic and geologic conditions described above, a variety of tunnelling methods have been employed. These methods are listed on Table 1, and are summarized as follows:

- **Drill and blast** - in the North Shore granites which are generally strong and massive, drill and blast methods have been used in such tunnels as the B.C. Rail Horseshoe Bay tunnel and the rock portion of the Coquitlam water tunnel. Support in these tunnels has been limited to scaling and rock bolting, with shotcrete applied to fault and shear zones. For tunnels constructed earlier than the 1940's in the weak but massive sedimentary rocks, drill and blast methods were also used.
- **Tunnel boring machine** - TBM's have been used for the Eighth Avenue sewer tunnel, and the Central Park watermain tunnel. Both these tunnels were driven in the sedimentary rocks, which are ideal for this method of construction. Both these tunnels were permanently supported with concrete linings.
- **Compressed air** - the only use of compressed air has been for the Highbury sewer tunnel in the glacial deposits. These materials are highly variable, and often unconsolidated. The tunnelling method was to lower the water table by surface pumping, and then to hand mine the tunnel under air pressure. The tunnel was lined with cast iron rings.
- **Microtunnelling** - microtunnelling was used to drive a sewer tunnel at the south end of Clarke Drive. The machine was designed to accommodate materials ranging from sand to gravel to boulders which is common for the glacial materials.
- **Road-header** - roadheaders were used for the underground stations and the running tunnel for the Skytrain between the Waterfront and Stadium stations. This equipment could readily cut the weak sandstone, and maintain close tolerances required for the inclined escalator shafts and stations tunnels.
- **Sunken tube** - the Dease Island tunnel is a concrete sunken tube comprising six 344 m long segments. It was placed on a layer of gravel in a trench dredged in river sediments. Gravel was then placed around the completed tunnel to fill the trench back up to original grade.
- **Cut and cover** - the lower Londsdale rail tunnel and the Cassiar Connector road tunnels are both reinforced concrete structures which were constructed in open lower excavations. Foundation conditions likely vary from till to sedimentary rock for the Cassiar Connector, to marine deposits for the Londsdale rail tunnel.
- **Sub-sea tunnelling** - the Lions Gate water tunnel was driven by drill and blast methods in sedimentary rock below the seabed. On the North Shore, the shaft accessing the tunnel was excavated through sands and gravels forming the delta deposits of the Capilano River.

Records of Earthquake Damage to Tunnels

Documentation of earthquake damage always shows that surface structures are more extensively damaged than tunnels. The reasons for this are as follows:

- ground motions are amplified as they pass from the bedrock to the surface, so tunnels will be subjected to lower accelerations than buildings on the surface;
- tunnel linings and the rock surrounding the tunnel are compressed so the amount of movement is restricted; and
- the relatively small dimensions of tunnels compared to high rise buildings, means that their natural frequency is generally less than the ground motion frequency.

Both Japan and California are located in high risk seismic zones, and also have highly developed urban infrastructure that includes tunnels. Recent earthquakes such as Loma Prieta in San Francisco (1989), Northridge in Los Angeles (1994) and Hyogoken-Nanbu in Kobe (1995) all caused extensive damage, primarily to surface structures, that has been carefully documented. In addition, earlier work by Dowding et. al. (1978) surveyed damage to tunnels in many parts of the world.

The following is a summary of the damage to tunnels by these more recent earthquakes.

Loma Prieta, San Francisco (1989)

The Loma Prieta Earthquake was a Magnitude 7.1 earthquake on the Richter scale, with the epicenter some 96 km distant from San Francisco Bay area in the Santa Cruz Mountains, along a segment of the San Andreas fault. Shaking intensity was VIII on the Modified Mercalli Intensity scale over an area 48 km long by 24 km wide encompassing an area from Los Gatos to Watsonville to Santa Cruz. Within the San Francisco Bay area free-field, peak horizontal accelerations were as high as 0.26 g and the duration of strong shaking was 10 seconds. The fault rupture penetrated upward to 6.4 km from surface, but did not break the ground surface (Housner, 1990).

While extensive damage was done to surface structures in the San Francisco Bay area, very little damage was noted to any of the tunnels. An example is the Bay Area Rapid Transit (BART) Trans-bay Tube. This submerged tube tunnel system was largely undamaged in the earthquake, while a segment of the Bay Bridge located in close proximity to the tunnel collapsed. The only damage to the Trans-bay Tube appears to have been 19 mm of differential movement at a flexible construction joint between the tunnel box and a ventilation tower on the Oakland side (Clough et al, 1994). There was no movement at a similar interface on the San Francisco side. The reasons for movement only being observed on the Oakland side are not obvious.

Northridge, Los Angeles (1994)

The Northridge earthquake was a Magnitude 6.4 event, which occurred in the San Fernando Valley, located approximately 32 km west - northwest of Los Angeles at a focal depth of 19 km. As with the Loma Prieta Earthquake, no surface rupture is known to have occurred, although significant surface disruption occurred resulting in the collapse of buildings and bridges, as well as the severing of utilities. A preliminary assessment of peak ground accelerations indicated the horizontal free-field component ranged from 0.16 g to 1.82 g within a 40 km radius of the epicenter (Hall, 1994).

While the Northridge earthquake caused severe surface disruption, very little damage appears to have occurred to tunnels in the area.

Hyogoken-Nanbu, Kobe (1995)

The Hyogeken-Nanbu Earthquake was the most destructive near-field earthquake to hit Japan since the Fukui earthquake of 1948 (Yoshimi, 1996). The magnitude 7.2 event caused very extensive surface damage to the Kobe area and killed more than 5000 people. Particular features of the earthquake were :

- The ground motions were much stronger than had been experienced in Japan before, particularly in the vertical component;
- The earthquake occurred in a densely populated area with a highly developed network of surface and underground infrastructure; and
- Extensive liquefaction occurred in the well graded residual soils underlying the City.

The earthquake was a strike slip type fault movement which resulted in peak horizontal ground accelerations of up to 0.8 g near and around the fault rupture zone and peak horizontal ground accelerations as high as 0.25 g at a distance of 54 km from the epicenter (Ejiri et al, 1996).

Unlike the Loma Prieta and Northridge Earthquakes, damage did occur to underground structures, the most severe of which was the collapse of the Daikai Subway Station cut and cover box. This was the first underground subway structure ever to collapse as a result of an earthquake. In addition to Daikai Station, damage also occurred at four other subway stations and three other tunnel boxes (Iida et al, 1996).

The collapse of Daikai Station is believed to have been caused by a large horizontal force acting transversely across the box. It is postulated that the source of the horizontal force was differential ground movement between the top of the box at a depth of 4.8 m and the base of the box at a depth of 12 m (Iida et al, 1996). The stratigraphy of the site consisted of loose sandy silts, overlying coarse sands, soft marine clays and dense gravels. The depth to the top of the dense gravel was approximately 17 m at the location of the collapse.

Damage was also reported in 24 of the 107 driven tunnels in the area which had been excavated by mechanical methods or drill and blast. Of the 24 tunnels, ten required some form of remedial work to the existing lining after the earthquake. Of these, only one resulted in a complete collapse of the tunnel, due to a slope failure above the portal. While the extent of damage was far more severe than for the Loma Prieta and Northridge Earthquakes, it was still relatively minor, when compared to the catastrophic damage caused on surface.

All of the driven tunnels which were damaged were located within 10 km of the epicenter, but no correlation could be found between damage severity and distance from the Earthquake's epicenter. However, most of tunnels which were damaged did cross known faults and fracture zones and the damage tended to occur at these locations (Asakura and Sato, 1998). Daikai Station was located 15 km from the epicenter, again in close proximity to a known fault.

Types of Damage to Tunnels in Earthquakes

Based on the case histories collected by Dowding and Rozen (1978) and later by Asakura and Sato (1998), a pattern emerges in terms of the type of damage which may be experienced in an underground excavation, due to earthquake shaking. The most common types of damage to tunnels appear to be as follows:

- Slides and rock falls at portals;
- Differential displacement of the tunnel and lining caused by fault movement;
- Cracking or spalling of the lining due to increased rock loads due to ground squeeze in areas of poor ground or due to ground collapse where voids have formed behind the lining;
- Failure of a lining whose load carrying capacity has decreased due to deterioration over time of the lining materials themselves; and
- Horizontal ground loads caused by differential ground displacements acting on buried structures near surface.

Figure 3

Earthquake Damage in Tunnels Related to Surface Acceleration

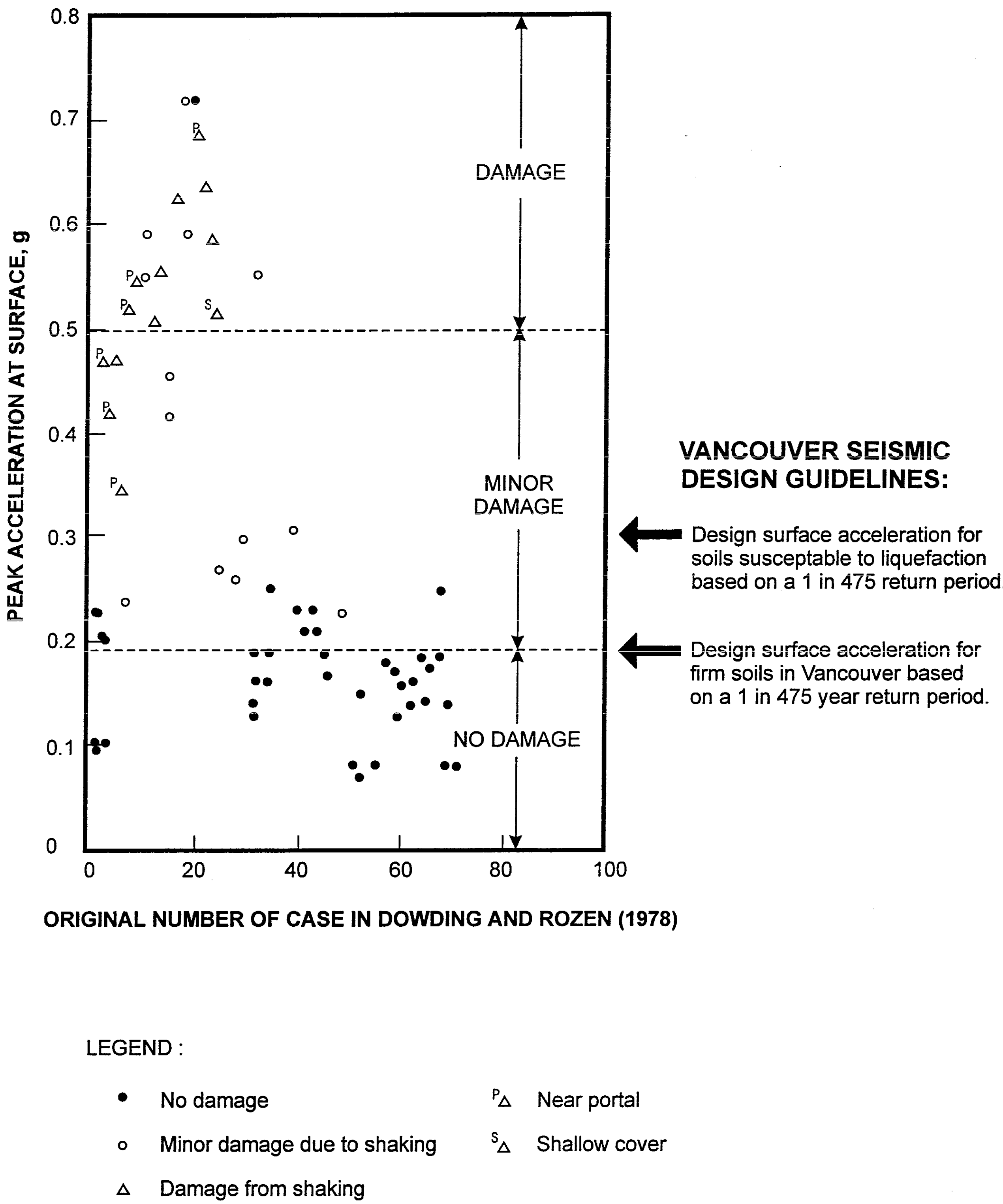
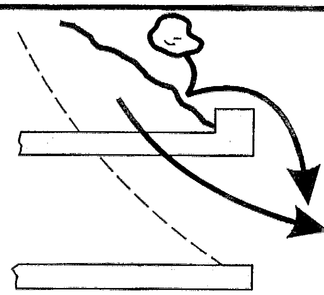
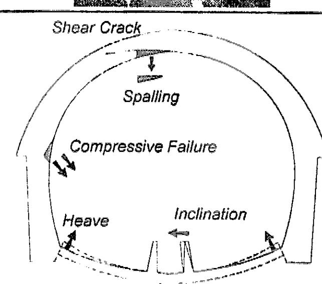
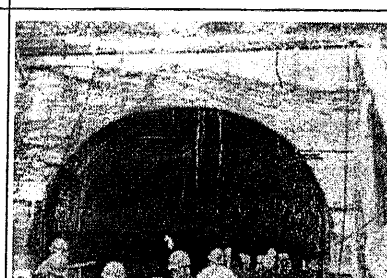


Figure 2

Examples of Tunnel Damage Induced During The Hyogoken-Nanbu Earthquake

Landslides and Rockfalls at Portal		*The downstream portal of the Egegana River Tunnel was completely destroyed when the slope above the portal failed.*
Fault Displacement		*Failure of tunnel lining within a clay rich fault zone in the Bantaki Tunnel.*
Squeezing Ground		*Lining failure modes observed in the Rokko Tunnel due to Earthquake induced loading in known fracture zones.*
Voids Behind Linings and/or Deterioation of Original Structure		*Cracks in Higashigama Tunnel portal. The cracks are believed to be extensions of existing features. The portal was originally constructed in 1928.*
Ground Movement Near Surface		*Collapse of the Daikai Station Cut and Cover Box. Up to 2.5m of vertical settlement occurred when 35 of the center columns collapsed.*

After Asakura and Sato, 1998 and Iida et al, 1996.

Examples of these types of failures are given in Figure 2, all taken from the 1995 Hyogeken-Nanbu Earthquake. In addition to the types of damage, general statements can also be made regarding the likelihood of damage given the magnitude of the event and distance of the tunnel from the epicenter. The data collected by Dowding and Rozen (1978) suggests little damage will occur to rock tunnels for ground surface accelerations less than 0.4 g, and very little or no damage will occur below 0.2 g (Figure 3). In a similar study by Yoshikawa (1981), it was concluded that damage to tunnels within 10 km of the epicenter was likely for a Magnitude 7 event and within 30 km for a Magnitude 8 event on the Japanese Meteorological Agency (JMA) scale.

Potential effect of earthquakes on Vancouver tunnels

The current design horizontal peak ground acceleration for Vancouver is 0.2 g for firm ground (National Building Code, 1990), which is usually upgraded to 0.3 g in soils prone to liquefaction. These peak ground accelerations are based on a 1 in 475 year event frequency. Based on the damage thresholds shown on Figure 3, it would appear that the likelihood of severe damage to Vancouver tunnels situated in rock is low for such events.

From the case histories discussed above, the following observations can also be made for the Vancouver area:

- **Rock falls and landslides at portals** - tunnels on the North Shore may be located with steep slopes at the portals. Because the rock is strong, the occurrence of landslides is unlikely, but rock falls may occur where loose rock or boulders are present on the slope face. Extensive study has been carried out in California on earthquake induced rock falls and landslides which has shown that the greatest hazard of rock falls occurs at slope angles greater than 25 degrees in poorly lithified rock, with closely spaced, open joints associated with water (Keefer, 1992 and Jibson, Harp and Michael, 1998).
- **Fault displacement** - at present no active faults have been located in the Greater Vancouver area. It is therefore unlikely that any of the Vancouver tunnels will be sheared by fault movement and suffer lining damage.
- **Voids behind linings** - prior to about 1940, tunnels with concrete linings were free-standing structures, with timber or loose masonry packing in the void space between the rock and the lining. Over time the packing can rot or loosen, resulting in loss of support to the rock surrounding the tunnel. This condition can result in rock falls impacting the lining, particularly at the portals where the ground motion is greatest. This was an issue on the downtown Skytrain tunnel, which was originally constructed in the 1930's as a rail tunnel, and in 1983 was converted for use by Skytrain. Here the voids behind the original lining were grouted to improve the structure's resistance to ground shaking.
- **Failures in areas of poor quality rock** - there is a potential for damage where tunnels pass through major seams of loose, broken rock. It is likely that the hazard would be highest near the portals where ground motions are the highest. The types of damage that could occur include ground collapse in unlined tunnels, and spalling and cracking of the lining in lined tunnels.
- **Horizontal ground loading** - based on the Daikai Subway Station collapse, it appears near surface underground structures such as portals, shaft collars and cut and cover boxes, which are situated in loose soils prone to liquefaction can suffer severe damage in a large earthquake event. In Vancouver, loose soils situated in low lying areas adjacent to river courses are the most likely to liquefy in a magnitude 7 or 8 earthquake (Fitzell et al, 1995). Underground structures located in these soils therefore need to be able to resist the large differential horizontal loads which can be applied to the structure during such an event.

Conclusions

Detailed documentation has been made of damage to tunnels due to earthquakes in Japan, while in contrast, tunnels in California have not been damaged in two recent earthquakes. The experience of these two density developed urban areas can be used to assess the possibility of damage to existing tunnels in Vancouver, and to help in the design of tunnels that may be constructed in the future. It would appear that the possible causes of damage to Vancouver tunnels in the event of an earthquake would be falls at portals, liquefaction, cracking of linings in areas of very poor ground, and falls in voids behind linings.

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