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Earthquakes and Seismic Faulting: Effects on Tunnels

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Abstract: A study of tunnels in areas affected by strong earthquakes in the last 50–100 years revealed at least three cases of tunnels damaged by earthquake shaking or offset by seismic faulting, including the Bolu (Turkey) twin tunnels, which collapsed during the 1999 Düzce earthquake. These data indicate that tunnels cannot be considered as structures invulnerable to earthquakes. Furthermore, the tectonic offset of tunnels shows that certain observed seismic surface ruptures are not necessarily indicative of tectonic faulting and represent only secondary local ground instability effects.

Key Words: earthquake, elastic dislocation analysis, faulting, offset, tunnel

Depremler ve Sismik Faylanma: Tüneller Üzerindeki Etkileri

Özet: Son 50–100 yıl içinde büyük depremlerden etkilenen bölgelerdeki tüneller üzerine yapılan bir çalışma deprem sarsıntısından veya sismik faylanma ile kesilerek hasar gören 1999 Düzce depreminde çöken Bolu (Türkiye) ikiz tünellerini de içeren, tünellerde en az üç durum ortaya koymuştur. Bu veriler tünellerin depremlerde kolayca hasar görebilecek yapılar olduğunun düşünülmediğini göstermiştir. Ayrıca, tünellerdeki tektonik atım, gözlenen sismik yüzey kırıklarının tektonik faylanmanın göstergesi olmadığını ve sadece ikincil lokal zemin duraysızlığının etkileri olduğunu yansıtır.

Anahtar Sözcükler: deprem, elastik dislokasyon analizi, faylanma, ofset, tünel

Introduction

Among the major constructions hit by the 1999 Düzce Mw=7.2 earthquake (Turkey) were the twin Bolu tunnels, still under construction. This was a very intriguing and unusual event, because tunnels, in contrast to freestanding structures (buildings, bridges, dams etc.), are considered constructions practically invulnerable to earthquakes; a hypothesis already tested in numerous earthquakes, including the 1989 Loma Prieta earthquake (Mw=7.1) and the 1995 Kobe earthquake (Mw=6.9). The 1989 Loma Prieta earthquake in particular did not affect the Bay Area Rapid Transit System, the main transportation between the East Bay and San Francisco that survived this earthquake, while the Bay Bridge was seriously damaged and closed for nearly a month (McNutt 1989). Furthermore, during the 1995 Kobe earthquake, damage was limited to the collapse of three of the 10 stations of the Kobe underground rapid transit system, as a result of high lateral forces and the collapse of the vertical elements of the large-span underground structure (EQE 1995); from a structural point of view, however, such constructions are obviously very different from tunnels.

The question arising therefore is whether the earthquake damage in the Bolu tunnel represents an exception to a rule, or whether the apparently well-accepted hypothesis for minor seismic risk affecting tunnels should be re-evaluated. In order to answer this question, we examined numerous tunnels in tectonically and seismically active areas. The preliminary results of this study indicate that tunnels in such areas are vulnerable not only to seismic shaking, but also to tectonic deformations.

Methodology

Our research was mainly based on bibliographic data and Internet research. We focused on areas which have been affected in the last 50–100 years by strong earthquakes associated with seismic faulting, and then searched for underground structures which might cross these faults. All types of tunnels have been examined: railroad tunnels usually constructed since the last decades of the 19th century; road tunnels, usually constructed since the 1930s; and water conveyance tunnels.

Results

The preliminary results of this ongoing study are presented below and summarised in Table 1.

Bolu Tunnels – 1999 Düzce Earthquake, Turkey

The 16-m-wide and 3.2-km-long twin Bolu tunnels are part of the new İstanbul-Ankara highway. Their lines cross the North Anatolian Fault Zone (NAFZ), along a 200–300-m-wide shear zone consisting of highly plastic clay of poor strength. The squeezing of this weak rock mass and extreme deformation up to 720 mm were observed during the opening of the tunnel (Brox & Hagedorn 1999). The 1999 Düzce earthquake (Mw=7.2) associated with the NAFZ caused a collapse within the clay zone ~300 m from the portals, which was temporarily supported with shotcrete 25 cm thick and rock bolts 6 to 9 m long (Erdik 2000; GEES 2002). However, as this tunnel is practically at the eastern end of the rupture of the surface faults activated in 1999 (Akyüz *et al.* 2002) it is rather unlikely to have been tectonically offset. Its failure is probably due to high, near-fault seismic intensity or local ground instability that might have been produced during the earthquake (Dalgıç 2002).

Wrights Railway Tunnel – 1906 San Francisco Earthquake

The Wrights railway tunnel (southern Santa Cruz Mts., California) was constructed between 1876 and 1880 and was abandoned in 1940. This 1920-m-long tunnel crosses the San Andreas Fault Zone (SAFZ) at about 120 m from one of its portals (Figure 1). After the 1906 San Francisco earthquake (Mw=7.7) the tunnel, above which two parallel seismic surface ruptures were observed, was closed for more than 1 year due to the collapse of a ~100-m-long part crossing the fault zone. Based on a geodetic survey during its reconstruction in 1907, it was concluded that the tunnel was offset by 1.5 m (Figure 1), and this estimate was widely used as a representative value of the 1906 SAF slip. However, Prentice and Ponti (1997), based on elastic dislocation analysis in an elastic half-space, computed an up to 1.7–1.8 m lateral offset of the tunnel axis. Furthermore, on the basis of the dislocation analysis, the hypothesis of two subparallel surface faults was rejected, and it was concluded that one of the two parallel surface 1906 ground ruptures above the Wrights tunnel reflected local ground instability effects.

The Kern County Tunnel – 1952 Kern County Earthquake

A railway tunnel crossing the White Wolf Fault (WWF) was seriously damaged during the 1952 Kern County earthquake (Mw=7.5) associated with this fault (SCECDC 2002). After the earthquake both a compressive and a lateral component of displacement were detected on the ground surface along the WWF: rails, both inside and at the entrance of the tunnel, were bent (Figure 2), while locally the displaced rail was thrust by the 46-cm-thick tunnel lining (Figure 3).

Discussion and Conclusion

The data presented above indicate that the widely accepted idea that tunnels are invulnerable to earthquakes appears to be illusive. Tunnels excavated in tectonically inactive areas such as NW Europe are not vulnerable to seismic faults and shaking, but for tunnels

Table 1. Offset or collapsed tunnels due to seismic faulting.

Tunnel	Earthquake	Mw	Fault	Offset type	Offset Amplitude (m)	Reference
Wrights tunnel	1906 San Francisco earthquake	7.7	San Andreas Fault Zone	strike slip	1.7 to 1.8	Prentice & Ponti 1997
Urban Kern Country railway tunnel	1952 Kern Country earthquake	7.5	White Wolf Fault	reverse + strike slip	1.3	SCECDC 2002
Twin Bolu tunnels (İstanbul-Ankara highway)	1999 Düzce (Turkey) earthquake	7.2	North Anatolian Fault Zone	strike slip	collapse	GEES 2002

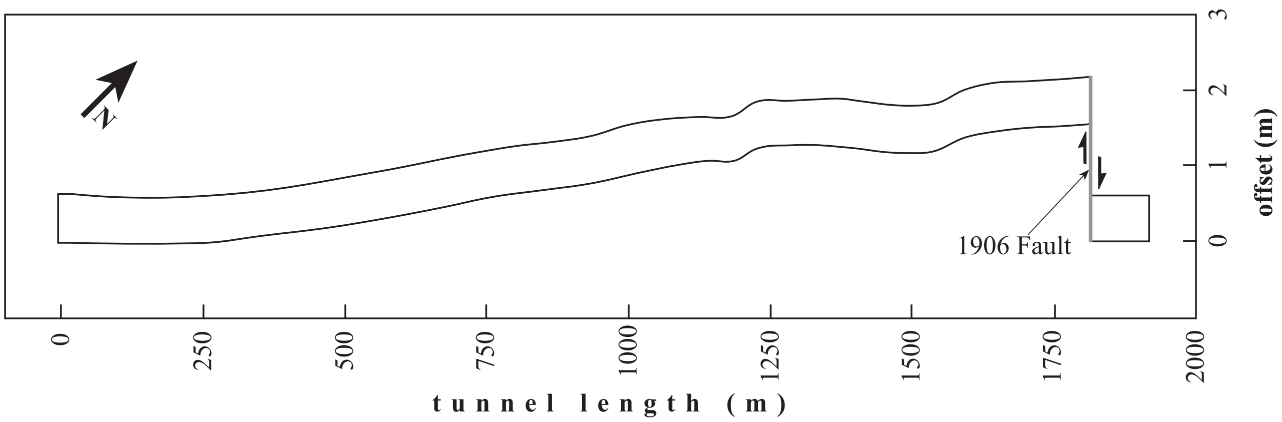

Figure 1. Plan of the Wrights tunnel offset by the 1906 San Francisco earthquake based on a 1908 geodetic survey. The pattern of the tunnel deformation and an elastic dislocation analysis indicate that a second surface rupture observed above the tunnel reflected only secondary effects (after Prentice & Ponti 1997).

Figure 2. Kern County urban railway tunnel. A view from the entrance of the tunnel showing bent rails near a zone of intense fracturing along the White Wolf Fault. Source: SCECDC 2002.

Figure 3. Bent rails inside the Kern County urban railway tunnel. The White Wolf Fault had a both compressive and lateral dislocation during the 1952 Kern County earthquake. Indicative of this type of fault dislocation is the fact that the rails are bent and continuous underneath the tunnel wall, showing that the wall was lifted up enough for the rail to slide underneath. Source: SCECDC 2002.

in tectonically active areas earthquakes and faulting represent important causes of failure, both during their construction (e.g. Bolu tunnels) and their operating (e.g. Kern County tunnel and Wrights tunnel) period.

Furthermore, a study of reactivated faults crossing tunnels at a depth of a few tens to several hundred metres below surface gives the rare opportunity to study the difference in the pattern between surface and deeper deformation; a deformation pattern that cannot certainly be seen in trenches cut at a depth of a few metres. In the case of the Wrights tunnel for instance, the fault offset at the depth of the tunnel indicates that some of the observed surface ruptures reflect only secondary ground instability effects accompanying the main fault rupture and are not directly related to seismic faulting at depth; a conclusion already obtained for other causes on the grounds of geodetic data as well (in Stiros & Drakos 2000).

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